Pumping Strategies in Data-Sparse Environments: Insights from the Eastern Mancha System, Spain

Vanessa A. Godoy[a,], James J. Butler Jr.[b], J. Jaime Gómez-Hernández[a]

[a]*Research Institute of Water and Environmental Engineering, Universitat Politècnica de València, Valencia, Spain*
[b]*Kansas Geological Survey, University of Kansas, Lawrence, KS, USA*

Abstract

Study Region The Eastern Mancha System, located within the Júcar River Basin District in eastern Spain, is one of the country's largest carbonate aquifers. This semi-arid Mediterranean region supports extensive irrigated agriculture and faces persistent groundwater deficits, with annual withdrawals exceeding natural recharge by approximately 35 Mm^3.

Study focus This study applies the Water Balance Approach (WBA), originally developed for the Kansas High Plains Aquifer, to evaluate pumping reduction strategies in a data-sparse Mediterranean aquifer. Using 14 years (2010-2023) of water-level records from 35 monitoring points and indirect estimates of annual groundwater use, we establish a linear relationship between average annual water-level change and total pumping. This relationship is used to quantify pumping volumes required for stable water levels and to assess the impact of different management targets.

New Hydrological Insights for the Region The analysis shows that current pumping of 310 Mm^3/year results in an average annual decline of 0.17 m, while near-term stabilization requires only a 1.6% reduction to 305 Mm^3/year, while the Júcar Water Authority's target of 275 Mm^3/year would yield approximately 1 m/year rise in levels. These results demonstrate that modest pumping cuts could achieve stability, preserving agricultural productivity and groundwater sustainability. The study confirms that the WBA is a practical, transferable

tool for rapid groundwater assessment in data-limited Mediterranean aquifers.

Keywords: Groundwater management · Water balance approach · Aquifer sustainability · Irrigation pumping · Data-sparse environments · Spain

1. Introduction

Groundwater depletion in aquifers supporting irrigated agriculture represents one of the most pressing water resource challenges of the 21st century [1, 2]. This global phenomenon is particularly acute in semi-arid regions where surface water resources are limited and agricultural production depends heavily on groundwater extraction. Spain exemplifies this challenge, where groundwater resources face substantial pressure from multiple factors, including agricultural irrigation, urbanization, industrial activities, and tourism [15, 18]. These pressures are intensified by prolonged droughts and climate change, which diminish recharge rates and heighten water scarcity concerns.

In the Júcar River Basin District in Spain, which encompasses all rivers, aquifers, and other water bodies within a broad area in eastern Spain, 35% of aquifers are currently experiencing depletion according to the Júcar River Basin Management Plan for the 2022-2027 cycle [9]. This depletion, driven largely by agricultural practices that began intensifying in the 1970s, challenges the long-term sustainability of agricultural production and regional economic stability. The situation is particularly critical in the Eastern Mancha System, where annual groundwater withdrawals of approximately 310 Mm^3 exceed the estimated natural recharge of 275 Mm^3, creating a persistent deficit that threatens the aquifer's future viability.

Extending the lifespan of these aquifers, along with the agricultural output and regional economies they sustain, has become increasingly important for water resource managers and policymakers. The most straightforward solution is to reduce pumping, but determining the appropriate level of reduction in the absence of alternative water sources presents significant challenges. Traditional approaches rely heavily on numerical groundwater models, which require extensive parameterization and geological data [16]. While these models provide detailed insights into aquifer behavior, they can be time-consuming to develop and calibrate, potentially delaying critical management decisions [10, 18]. Moreover, the uncertainty inherent in model parameters and conceptual frameworks can limit confidence in their predictions, particularly in data-sparse environments where detailed hydrogeological information is limited.

In contrast, the Water Balance Approach (WBA) offers a simpler, more direct method to link historical data with future predictions [7]. This approach examines the correlation between annual pumping rates and average annual water-level changes within an aquifer, providing a linear relationship that can be used to assess the sustainability of current pumping practices and determine necessary reductions to stabilize or increase water levels [5, 6, 22]. The method's strength lies in its simplicity and direct reliance on observable data, making it particularly valuable as a complementary tool for preliminary assessment of aquifer conditions under stress.

Butler and colleagues at the Kansas Geological Survey developed and applied this approach to the Kansas High Plains Aquifer (HPA), a vital water source for agriculture in the central United States, where decades of intensive pumping had led to significant declines in groundwater levels [7]. Their study demonstrated that modest reductions in irrigation pumping (less than 22%) could stabilize water levels across much of the HPA over the near-term (years to a few decades), offering a practical and efficient tool for groundwater management. The success of this method in the HPA, which benefits from extensive datasets including over 1,440 water level monitoring points and 27,700 flowmeters [14, 22], raised important questions about its applicability to data-scarce regions.

Subsequent research has investigated the data requirements for effective application of the WBA, revealing that, as long as the data is unbiased and representative, it is possible to forecast short-term aquifer responses to proposed pumping reductions using much less extensive water level and water-use data than what is available in the Kansas HPA [3]. This finding opens the possibility of applying the method to aquifer systems worldwide where data availability is more limited, potentially providing water managers with a rapid assessment tool even in challenging data environments.

The Eastern Mancha System presents an ideal case study for testing the applicability of the WBA in a data-sparse Mediterranean environment. While both the Kansas HPA and the Mancha aquifer are heavily relied upon for agricultural irrigation, there are key differences between the two systems. The HPA covers a vast semi-arid region characterized by deep, unconfined aquifers with relatively simple hydrogeological structures, whereas the Eastern Mancha system is a more complex hydrogeological structure with multiple aquifer units and strong interaction with surface water from the Júcar River [17]. Additionally, the data availability in the Mancha system is significantly more limited, with 35 monitoring points compared to over 1,400 in Kansas, and water use estimates derived from indirect methods rather than direct metering.

Despite regional differences, the core principle of the Water Balance Approach, a linear relationship between total water extraction and average aquifer-level decline, remains applicable, provided that key assumptions are satisfied. These include seasonally pumped aquifers evaluated annually, adequate spatial scales with sufficient monitoring well density, and water table depths exceeding tens of meters [7]. Although the method is typically applied to areas of several hundred square kilometers, successful applications have been demonstrated in areas as small as 256 km [4], with the critical requirement being an adequate well density to ensure minimal annual variation in specific aquifer storage and reduce the impact of anomalous local measurements. The Eastern Mancha System meets all these conditions, indicating that the WBA can be effectively adapted to this Mediterranean setting.

This study aims to demonstrate the applicability of the Water Balance Approach to groundwater management in data-sparse environments by applying it to the Eastern Mancha System. Specific objectives include: (1) establishing the linear relationship between annual pumping and water level changes using available monitoring data, (2) calculating the pumping value that would lead to stable water levels, (3) assessing the pumping reductions required to achieve various management targets, (4) evaluating the uncertainty in these estimates given the limited data availability, and (5) discussing the implications for sustainable groundwater management in similar Mediterranean aquifer systems.

The results of this analysis will provide water managers in the Júcar basin with quantitative guidance for sustainable pumping strategies while demonstrating the broader applicability of the WBA method to data-limited environments worldwide. This work shows that simple, data-driven approaches can complement more complex numerical models in supporting evidence-based groundwater management decisions.

2. The Water Balance Approach

The Water Balance Approach represents a fundamental application of the aquifer water balance principle to assess the sustainability of groundwater pumping in irrigated agricultural systems [7]. This section provides a comprehensive overview of the theoretical foundation, underlying assumptions, and practical implementation considerations for the method, with particular attention to its application in data-sparse environments.

2.1. Theoretical Foundation

The method is based on the principle that the change in water volume stored in an aquifer is equal to the net inflow minus the total pumping. This fundamental water balance relationship can be expressed as:

$$\Delta WL \times A \times S_{aq} = I - Q, \tag{1}$$

where ΔWL represents the average change in water level within the aquifer area over a given time interval, measured in length units [L]; A is the surface area of the aquifer being considered, measured in square length units [L^2]; S_{aq} is the average specific yield for unconfined aquifers or storativity for confined aquifers, which is a dimensionless quantity; I indicates the net inflow into the aquifer area during the time interval, measured in volume units [L^3]; and Q is the total volume of water pumped from the aquifer area during the time interval, also measured in volume units [L^3].

The net inflow term I is defined as the difference between total inflow (which includes recharge from precipitation, return flows from irrigation, and lateral inflow from other units) and natural outflow (which includes discharge to streams, evapotranspiration, and lateral outflow to other units). This net inflow is equivalent to the "capture" term commonly used in groundwater depletion assessments [5, 12, 13], representing the additional water that becomes available to pumping wells through induced changes in the natural flow system.

Rearranging equation 1, the average water level change can be expressed as a linear function of the total extracted groundwater:

$$\Delta WL = \frac{I}{A \times S_{aq}} - \frac{1}{A \times S_{aq}} Q, \tag{2}$$

which can be simplified as:

$$\Delta WL = b - aQ, \tag{3}$$

where $a = \frac{1}{A \times S_{aq}}$ and $b = \frac{I}{A \times S_{aq}}$ are constants that can be determined through linear regression analysis of historical water level and pumping data.

When the specified conditions are met and reliable data on water levels and usage are available, a plot of ΔWL versus Q should exhibit a clear linear relationship. Once the linear relationship is established through regression analysis, it becomes a powerful tool for calculating the impact of proposed changes in total pumping on average water levels and determining the pumping rate (Q stable) required to maintain stable water levels ($\Delta WL = 0$):

$$Q_{stable} = \frac{b}{a} = I_{ua} \times A, \tag{4}$$

where $I_{ua} = I/A$ is the net inflow per unit area.

3. The Eastern Mancha System

The Eastern Mancha System represents one of the most significant groundwater resources in Spain, covering an area of approximately 7,260 km^2 in southeastern Spain and encompassing portions of the provinces of Albacete, Ciudad Real, Cuenca, and Valencia. It is characterized by a central wide plain named Albacete–Cuenca Plain, at an average elevation of 700 m above sea level, delimited by rounded reliefs that increase in tectonic complexity towards the system boundaries. The system is located within the Jcar River Basin District and includes one of the largest carbonate aquifers in the country [17]. The Jcar River constitutes the main fluvial system and the primary groundwater discharge component under steady-state conditions. Figure 1 shows the study area within the broader context of the Jcar River Basin District in Spain.

The System is characterized by a Mediterranean-continental, semi-arid climate with mean annual precipitation of approximately 350 mm, varying spatially from 280 mm yr^{-1} in the south to 550 mm yr^{-1} in the north [17]. High inter-annual variability characterizes the precipitation regime, with dry years recording as little as 150 mm and humid years reaching 750 mm. Agriculture is the predominant land use, with approximately 1,000 km^2 converted to irrigated agriculture since the mid-1970s using groundwater as the primary water source [11]. Currently, approximately 310 Mm^3 of groundwater are pumped annually, with 98% used for agriculture. Groundwater withdrawals exceed the estimated natural recharge of

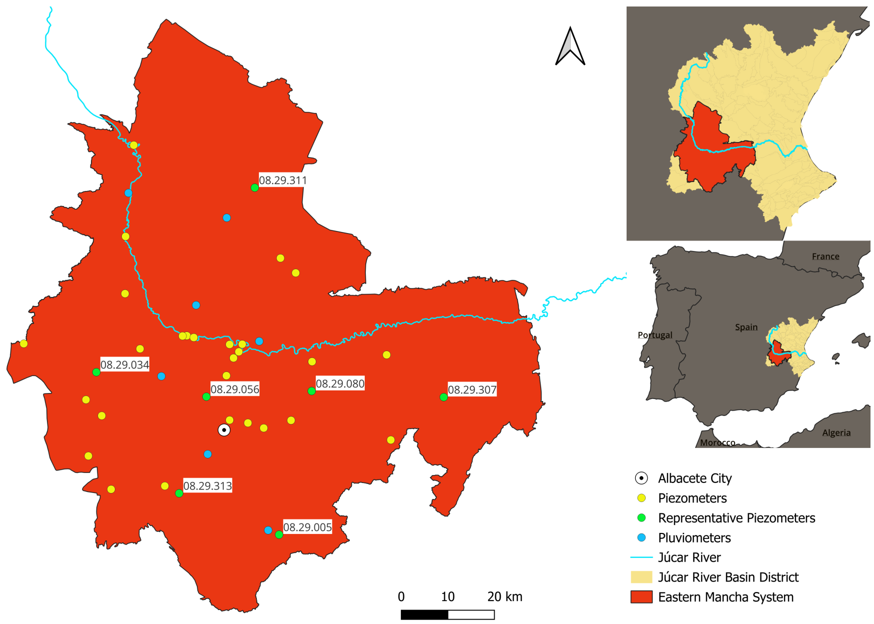

Figure 1: Location of the Eastern Mancha System within Spain, showing its position within the Jcar River Basin District.

275.3 Mm^3 yr^{-1}, creating a persistent deficit that has led the Jcar Water Authority to classify the system as being in poor quantitative status [9].

The hydrogeological framework of the Eastern Mancha System has been the subject of extensive multidisciplinary research over the past decades. Comprehensive studies have included detailed geological mapping, geophysical surveys, hydrochemical characterization, pumping tests, and numerical modeling [16, 17, 19]. This body of work has established a robust conceptual understanding of the structure, functioning, and water resources of the system, serving as a reference framework for the management of water by the Jcar Water Authority. The following synthesis draws upon these detailed investigations to describe the main hydrogeological features of the system.

The System presents a complex three-dimensional architecture formed by thick Mesozoic and Cenozoic sedimentary sequences affected by regional tectonics at the junction of the Iberian Range and the External Prebetic domains. Nine hydrostratigraphic units (HU9-HU1, from bottom to top) have been identified and classified as aquifers, aquitards, or aquicludes according to their hydraulic behaviour [17]. The basal impermeable formationsKeuper evaporites (HU9) and Lower Jurassic marly limestones (HU8)define the regional aquifer base. Above these, the main water-bearing units correspond to Jurassic and Cretaceous carbonates (HU7, HU5, HU3), composed of fractured and karstified limestones and dolostones that constitute the principal productive aquifers. These carbonate units are locally confined by marly and sandy aquicludes (HU6 and HU4), creating vertical compartmentalization in certain areas. The upper part of the sedimentary sequence comprises Miocene marly limestones (HU2) and detrital Tertiary-Quaternary deposits (HU1), which form semi-permeable or locally productive horizons depending on facies distribution and karstification degree. Overall stratigraphic thickness exceeds 1,000 m in the central and eastern sectors.

The spatial distribution and connectivity of these hydrostratigraphic units are strongly controlled by tectonic structures, resulting in the subdivision of the system into several hydrogeological domains [17]. These domains correspond to distinct hydrostructural blocks defined by fault systems, each exhibiting characteristic piezometric behaviour, hydraulic properties, and hydrochemical signatures. The Northern Domain (ND) is dominated by Triassic and Jurassic carbonate formations (HU7) bordering the Jcar River valley, where these units crop out or are close to the surface, facilitating recharge and discharge processes and maintaining strong hydraulic connection with the river. The Central Domain (CD), located around Albacete, encompasses the thickest and most continuous development of both Jurassic carbonates (HU7) and Miocene limestones (HU2), but also Upper Cretaceous carbonates (HU3), functioning as the main storage and production zone of the system. Here, intense karstification and fault-related fracturing enhance vertical connectivity between HU7, HU5, and HU2, creating a highly transmissive multi-layered aquifer system. To the south, progressive tectonic compartmentalization subdivides the system into the El Salobral–Los Llanos (SLD), Pozocañada (PCD), Moro–Nevazos (MND), and Montearagn–Carceln (MCD) domains. In these areas, fault-bounded blocks limit lateral continuity of the carbonate aquifers, while the variable presence and thickness of confining units (HU6, HU4) reduce vertical connectivity between HU7, HU5, and HU3. Consequently, these southern domains behave as partially independent groundwater flow systems with differential responses to external stresses. Figure 2 presents a simplified geological map of the Eastern Mancha System showing the spatial distribution of the main hydrostratigraphic units, the location of hydrostructural domains, major fault systems, and the position of representative cross-sections. Figure 3 illustrates three hydrostratigraphic cross-sections (I-III). Both figures are reproduced from Sanz et al. [17] with permission.

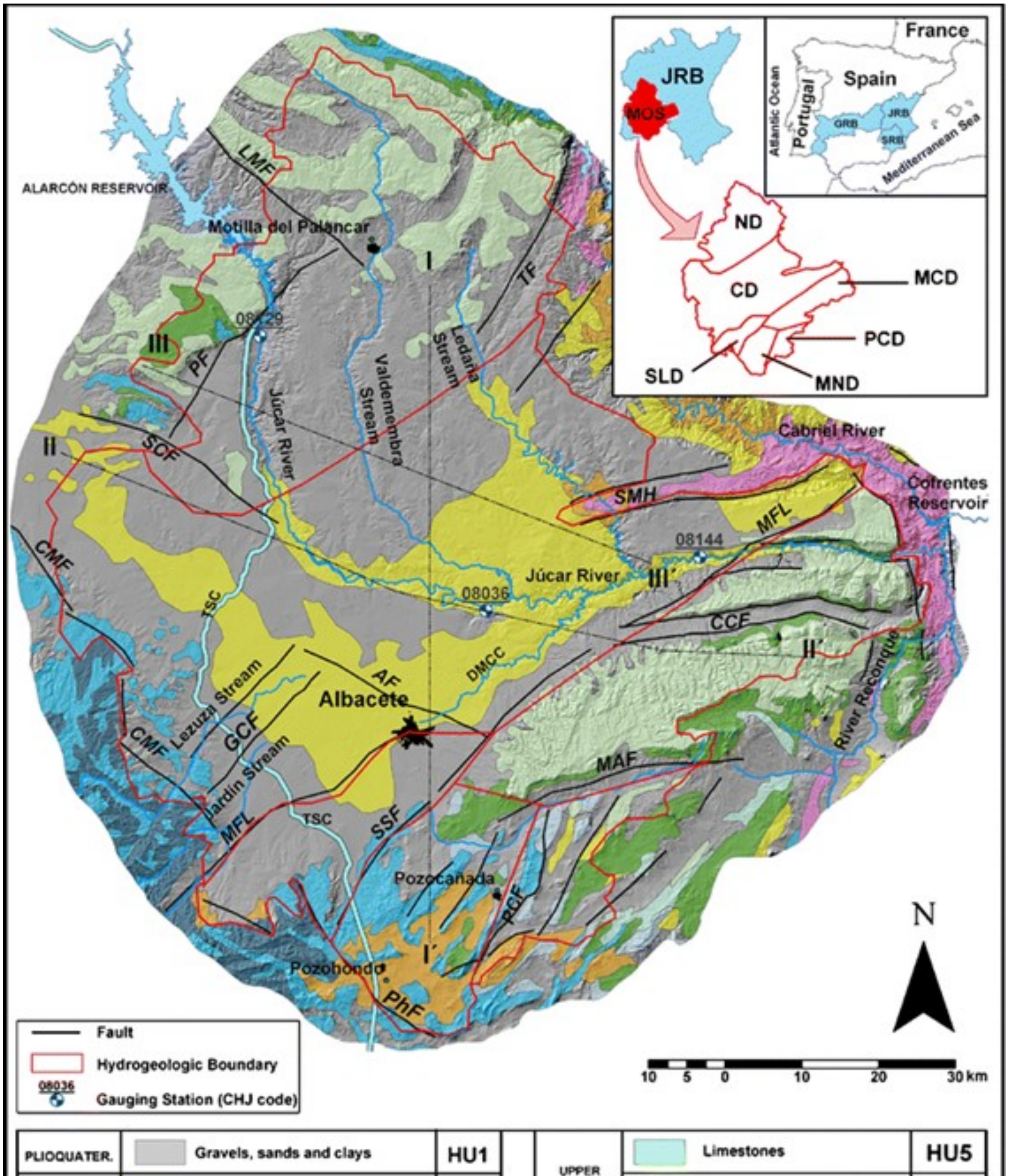

Figure 2: Simplified geological map of the Eastern Mancha System showing the spatial distribution of the main hydrostratigraphic units, the limits of the hydrostructural domains, major fault systems, and the positions of representative cross-sections. Adapted from Sanz et al. [17].

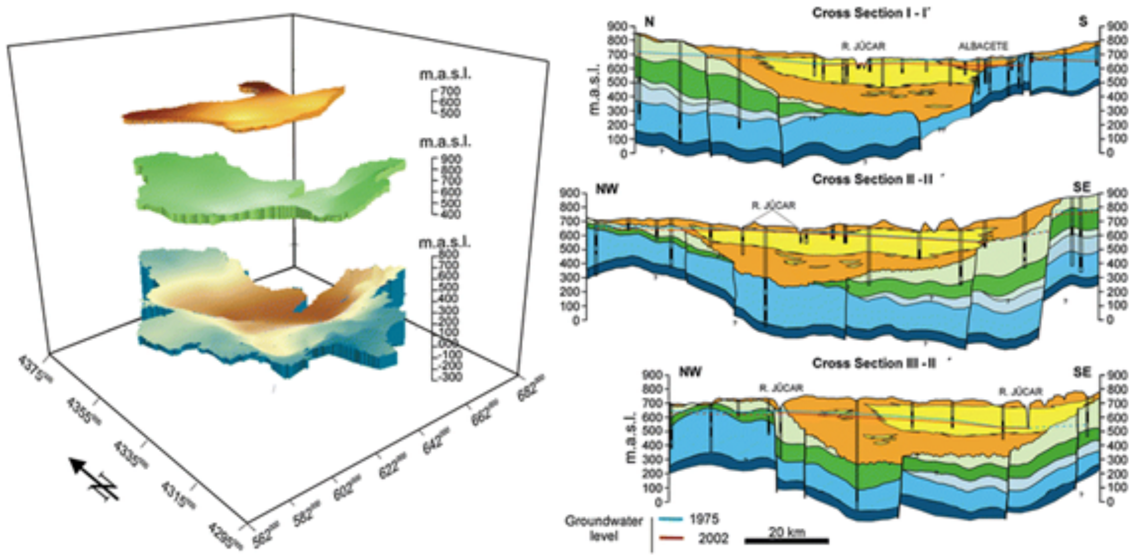

Figure 3: Three-dimensional rendering of the main hydrostratigraphic units next to cross-sections I to III marked in Figure 2. The three-dimensional geometry, structural relationships between units, and tectonic control on domain segmentation can be observed. Adapted from Sanz et al. [17].

4. Application of the Water Balance Approach

This section presents the detailed application of the Water Balance Approach to the Eastern Mancha System, including data preparation, quality control procedures, statistical analysis, and quantitative results.

4.1. Data Collection and Preparation

For the calculation of ΔWL, we selected 35 monitoring points from the broader network of observation wells maintained by the Jcar Water Authority. These monitoring points were chosen based on the completeness and length of their time series, spatial distribution across the aquifer system, and data quality. The density of the monitoring network provides approximately one monitoring location per 200 km^2, which, while less dense than the Kansas High Plains Aquifer network, is sufficient for regional-scale analysis, although local variations may not be fully captured.

The monitoring wells are distributed across different hydrogeological domains. Most of the piezometers (71%) are located within the Central Domain (CD) the most productive area of the systemwhile 11% are situated in the Northern Domain (ND), 9% in the Salobral–Los Llanos Domain (SLD), 6% in the Montearagón–Carcelén Domain (MCD), and 3% in the Moro–Nevazos Domain (MND). The smaller domain, Pozocañada (PCD), is not represented in the monitoring network. The Central Domain, the most extensive one (approximately 3,500 km^2), includes piezometers monitoring primarily the aquifer units of the Middle Jurassic (HU7) and Middle Miocene (HU2), which constitute the main water-bearing horizons of the system. The spatial distribution of monitoring wells is shown in Figure 1, with selected representative piezometers in each domain indicated. Figure 4 presents the temporal evolution of water levels (WL, in m a.s.l.) alongside the cumulative deviation from mean monthly precipitation (CDP, in mm) for these representative wells. The progressive divergence between water levels and precipitation, particularly evident after 2018, indicates intensified groundwater abstraction that exceeds natural recharge across all domains.

Water levels are typically measured monthly or bimonthly in the Júcar River Basin District. For this study, we selected measurements taken in mid-January from 2010 to 2023, corresponding to a period three to four months after the end of the irrigation season. This timing was chosen to minimize the influence of interannual variability in the cessation of irrigation pumping. Some time series contained gaps, which were addressed using the Multiple Imputation by Chained Equations (MICE) method [21].

Groundwater abstraction data were obtained from the Jcar Water Authority, which estimates irrigation volumes using a remote sensing methodology originally developed by Castaño *et al.* [8]. This approach combines multitemporal satellite imagery with crop classification algorithms to identify irrigated areas and applies crop-specific irrigation rates defined by the Provincial Agricultural Technical Institute of Albacete (ITAP), based on long-term experimental studies of crop water requirements.

The methodology by Castaño *et al.* has been extensively validated in the Eastern Mancha System through field verification of more than 344 randomly selected plots covering 85.5 km^2.

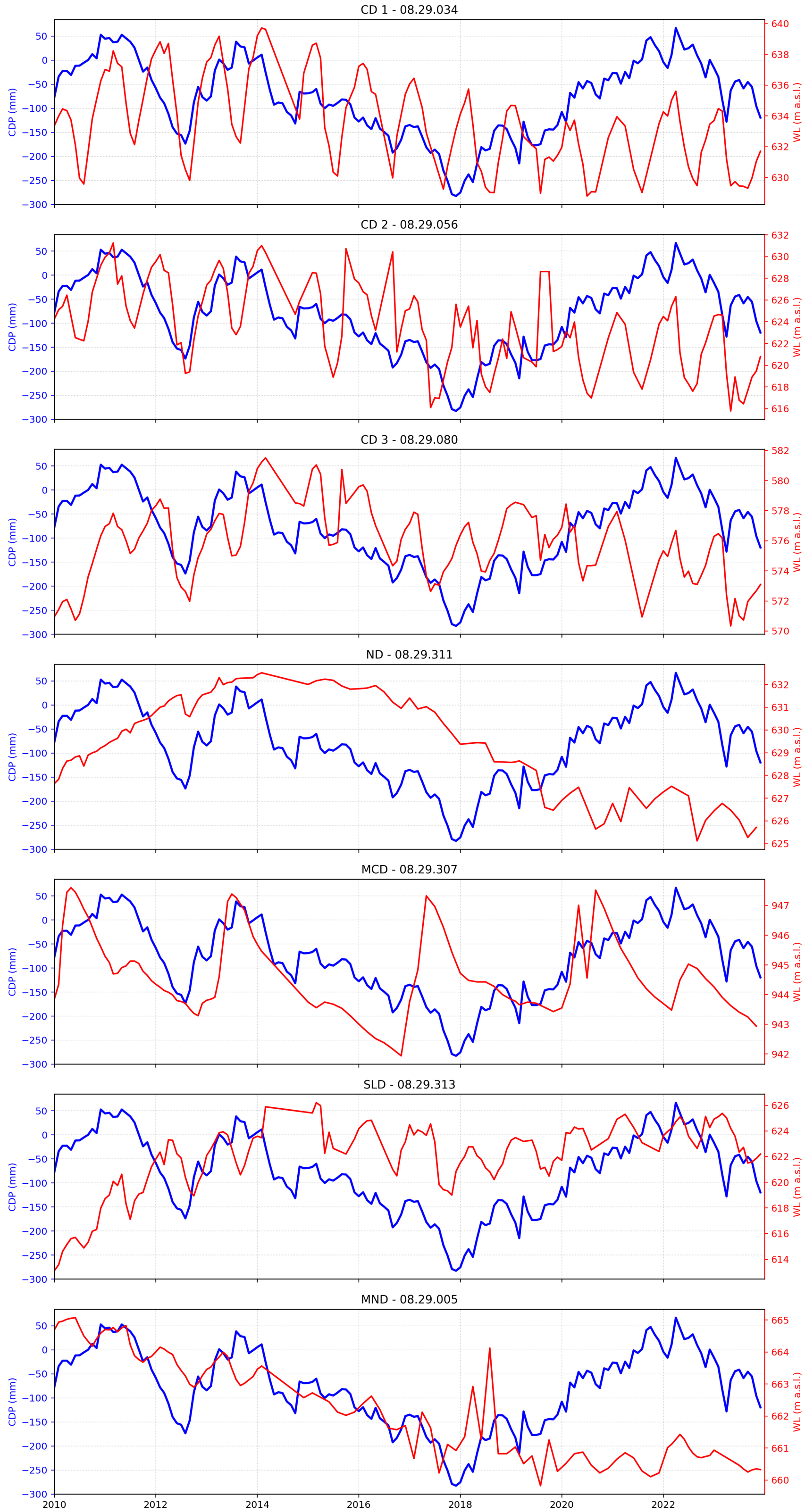

Figure 4: Time-series evolution of piezometric levels (WL) and cumulative deviation from mean monthly precipitation (CDP) for representative wells in each domain. The overall divergence between both curves, especially after 2018, reveals an intense groundwater use throughout the different domains.

Validation results demonstrated very high accuracy, with a larger than 96% match between observed and classified crop types, and misclassification rates between irrigated and non-irrigated plots below 1%.

Cross-validation with aquifer storage variations further confirmed the robustness of the estimates, showing that the method explains over 95% of the observed changes in groundwater storage within isolated hydrogeological domains. Additionally, the methodology integrates correction coefficients derived from experimental plot monitoring to convert theoretical irrigation requirements into actual applied volumes, accounting for regional irrigation efficiencies and management practices.

For detailed information on image pre-processing, NDVI-Kc relationships, geometric correction procedures, and classification algorithms used to derive water use data in the Eastern Mancha System, readers are referred to the complete description in Castaño *et al.* [8].

4.2. Statistical Analysis and Data Validation

Given the complexity of the system, which includes both confined and unconfined aquifers, we first assessed whether their annual water-level changes could be considered part of the same population. To do so, we performed independent two-sample t-tests (Students t-test) comparing the mean values of corresponding variables in each dataset. A significance level of 0.05 was adopted, with the null hypothesis stating no difference in means between the two groups. P-values above this threshold indicated no significant difference, allowing us to treat the datasets as a single population. All statistical analyses were conducted using Python (SciPy library). Figure 5 illustrates the water-level changes based on aquifer confinement interpretation.

A statistical t-test yielded a p-value of 0.71 and a t-statistic of -0.37, indicating no significant difference between water-level changes in confined and unconfined aquifers. Therefore, the data can be analyzed together without distinguishing between aquifer types.

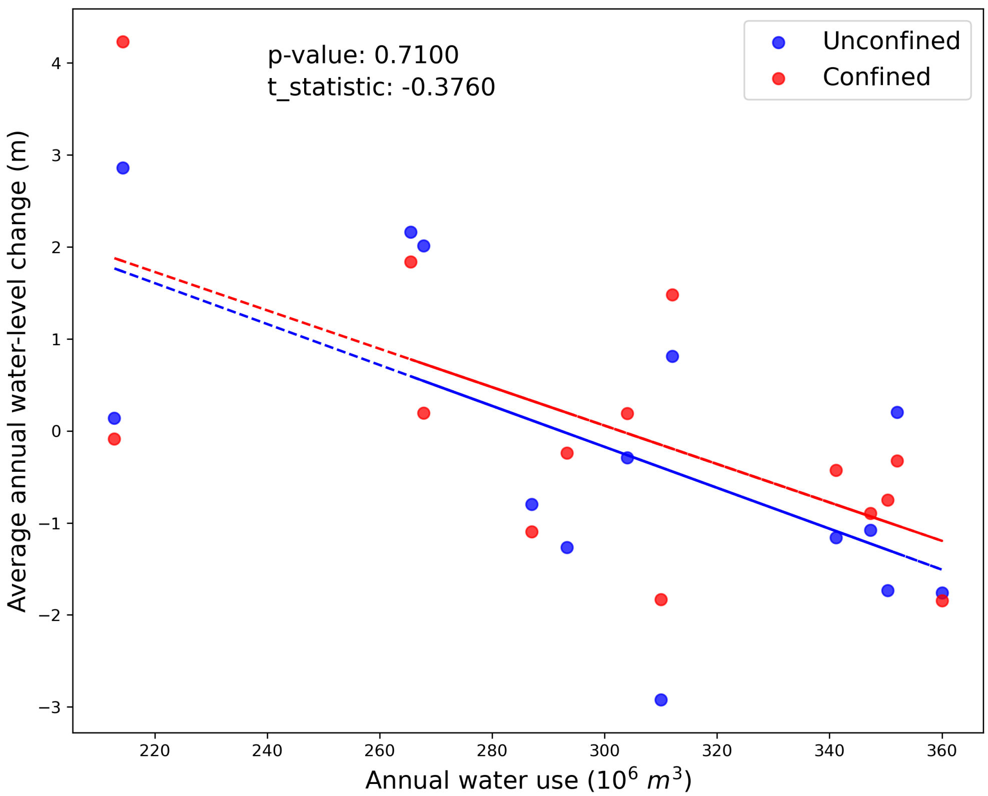

Figure 5: Comparison of annual water-level changes between confined and unconfined aquifer areas. Statistical analysis (t-test: p-value $= 0.71$, t-statistic $= -0.37$) indicates no significant difference between the two populations, supporting combined analysis.

Due to the indirect nature of groundwater use estimates, we introduced annual precipitation as an independent variable to assess the internal consistency of the dataset and identify potential outliers. Precipitation data from seven meteorological stations were used to compute area-weighted averages representing regional climatic conditions.

Given that the aquifer is primarily exploited for agricultural purposes, precipitation is expected to influence groundwater abstraction through its control on irrigation demand. In wetter years, reduced irrigation requirements should lead to lower groundwater pumping and smaller water-level declines (or even increases), while dry years would correspond to increased abstraction and larger declines. We developed linear regression models as an exploratory tool to test whether these irrigation-driven patterns are detectable in the data, using precipitation as the predictor of (i) average annual water-level change and (ii) total annual groundwater use. These models were expressed as:

$$\Delta WL = a \cdot P + b \tag{5}$$

$$WU = c \cdot P + d \tag{6}$$

where ΔWL is the average annual water-level change (m), WU is the total annual water use (10^6 m^3), P is the annual precipitation (mm), and a, b, c, and d are regression coefficients estimated via ordinary least squares.

Model performance was evaluated using the coefficient of determination (R^2), and studentized residuals were examined to detect years with anomalous behavior.

The analysis revealed significant uncertainty in 2011. When this year was included, the regression yielded an R^2 of 0.33 for annual water use and 0.83 for water-level change, suggesting potential inconsistencies in the reported abstraction data. This interpretation is further supported by a studentized residual of -2.95, confirming 2011 as an outlier in the climate-response relationship.

It is likely that the substantial precipitation in 2010 had a delayed effect on groundwater levels, resulting in smaller-than-expected declines despite relatively high abstraction. This decoupling between water use and water-level response indicates that 2011 may not be a reliable year for evaluating the relationship between climate and aquifer dynamics.

Additionally, the complex interaction between the aquifer and the Jcar River may further complicate the water balance relationship. During wet periods, enhanced river-aquifer interaction could partially offset pumping-induced declines, creating apparent inconsistencies in the linear relationship between groundwater abstraction and aquifer response [8].

Uncertainty was also observed in 2023, an exceptionally dry year in which reported water use was lower than predicted by the model. When both 2011 and 2023 were included, the regression yielded an R^2 of 0.73 for annual water use, which improved to 0.81 upon their removal. Although this suggests possible inconsistencies in the 2023 abstraction data, the studentized residual of -1.25 did not exceed the commonly used threshold of ± 2.00 for identifying statistical outliers.

Consequently, only the year 2011 was initially excluded from the final analysis.

Figures 6 and 7 show the predicted versus measured values for annual water use and water-level change, respectively, after removing 2011 from the dataset.

4.3. Water Balance Analysis Results

After data preparation and quality control, the final dataset comprised 12 years of observations (2010 and 2012-2023) used for the analysis. This period was selected based on both data availability and methodological considerations. Prior to 2008, the monitoring network was too limited to represent the aquifer system adequately, with only 0-21 wells compared to 35-38 wells operating from 2008 onwards. Moreover, the years 2007-2008 coincide with the implementation of the OPAD (Public Offer for Right Acquisition) campaign by the water

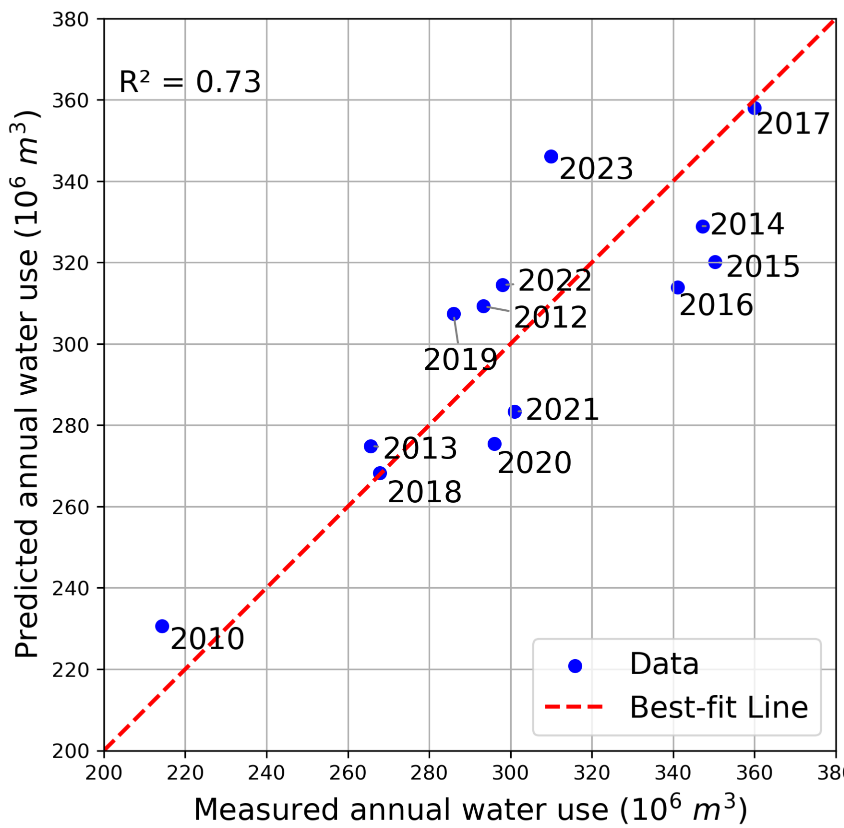

Figure 6: Validation of annual water use estimates using precipitation-based regression model ($R^2 = 0.73$). The good correlation provides confidence in the indirect water use estimation methodology for most years (2011 excluded).

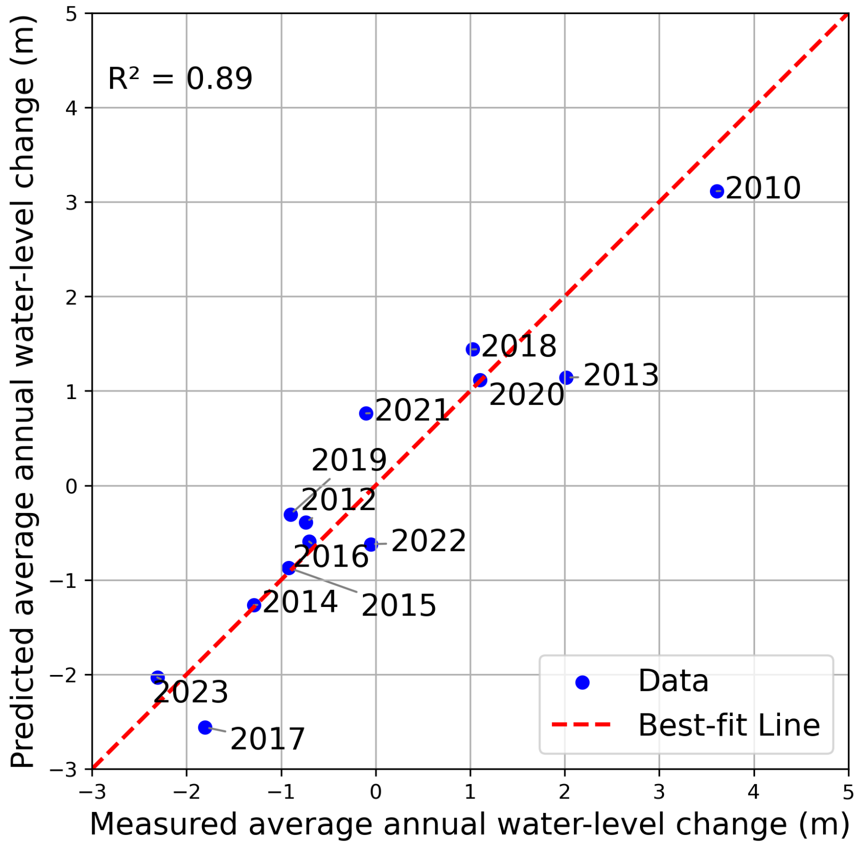

Figure 7: Validation of annual water-level changes using precipitation-based regression model (R^2 = 0.89). The strong correlation supports the quality of water level measurements and their representativeness of regional aquifer conditions (2011 excluded).

authorities, which sought to replace groundwater use with alternative water sources through the public acquisition of water rights. Including pre-2008 data would therefore introduce a systematic bias associated with these management interventions. Although a longer time series could enhance the statistical robustness of the regression, the selected 12-year period represents the most reliable basis for establishing the water-balance relationship under consistent management conditions and adequate spatial coverage.

Given the extreme hydrological conditions observed in 2023, particular attention was paid to that year in the regression analysis. Figures 8 and 9 present the results with and without the 2023 data point, respectively.

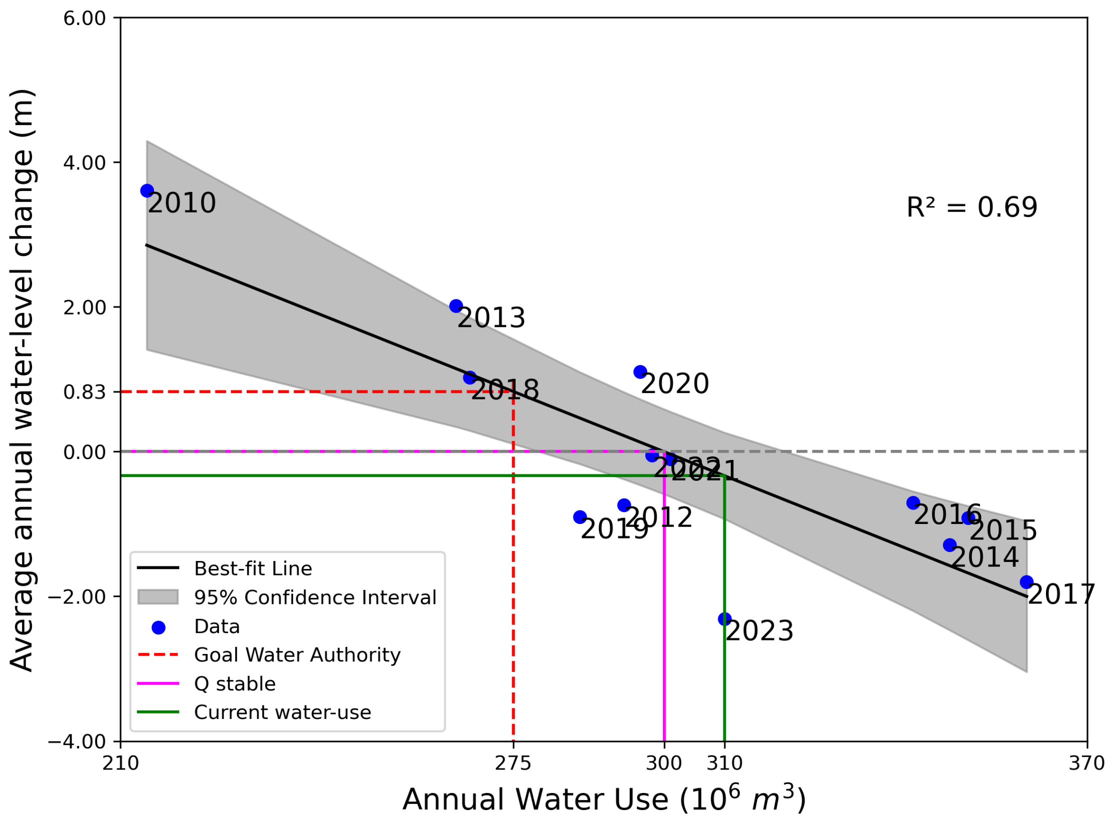

Figure 8: Water Balance Approach analysis for the Eastern Mancha System showing the linear relationship between annual water use and average annual water-level change ($R^2 = 0.69$). The plot includes 95% confidence intervals, current groundwater use level, the Jcar Water Authority target, and the Q-stable threshold indicating the required pumping level to stabilize water levels.

The year 2023 stands out in the graph due to its exceptionally low precipitation and significant deviation from the overall trend. This data point lies completely outside the 95% confidence interval of the regression model, suggesting that the linear method may not adequately capture the system's behavior under extreme drought conditions.

This deviation appears to result from systematic underestimation of groundwater abstractions by the remote sensing methodology during the severe drought of 2023. Based on the observed substantial water level decline, the established linear relationship would predict significantly higher water use than reported by the teledetection data. The discrepancy likely stems from well-documented limitations in NDVI-based crop classification under extreme drought stress. Water-stressed vegetation exhibits reduced NDVI values that can lead to misclassification in remote sensing applications [20]. Literature indicates that drought monitoring using vegetation indices alone can produce misleading results when irrigated areas are not properly accounted for, as stressed but irrigated crops may be misinterpreted as non-irrigated [20]. This systematic underclassification of actually irrigated areas likely contributed to underestimating total groundwater abstractions and causing the 2023 data point to fall well outside the expected linear correlation.

To evaluate the impact of this anomaly, the regression was recalculated excluding the 2023 data point. When 2023 is excluded, the coefficient of determination (R^2) increases from 0.69 to 0.78, suggesting that the model better captures the relationship between pumping and water-level change. However, the fitted linear relationship remains nearly unchanged, which confirms that the trend is robust and primarily influenced by the remaining years in the dataset.

When including 2023, the regression yields the following relationship:

$$\Delta WL = 9.99 - 0.033 \times Q \tag{7}$$

This equation indicates that a groundwater use of:

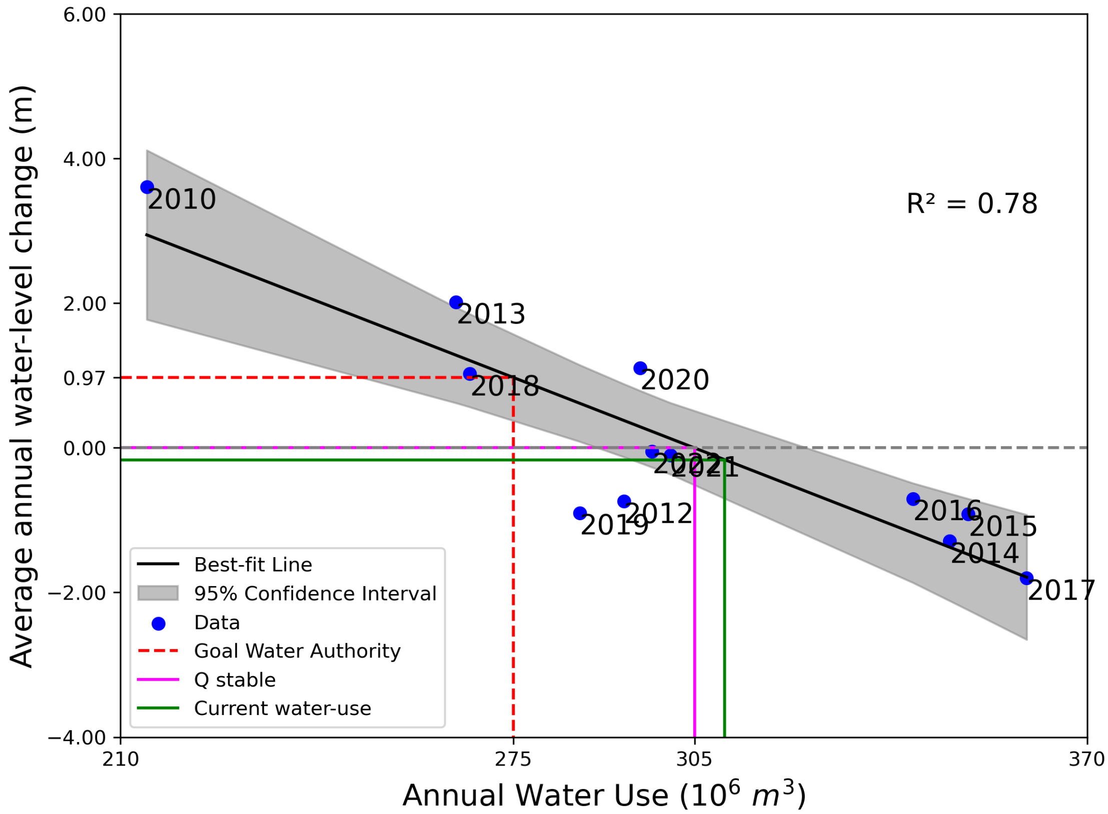

Figure 9: Linear regression between annual groundwater use and average water-level change excluding the year 2023 ($R^2 = 0.78$). The model becomes slightly less conservative, allowing higher pumping volumes to achieve stable water levels.

$$Q_{\text{stable}} = \frac{9.99}{0.033} \approx 300 \text{ Mm}^3/\text{year} \tag{8}$$

would result in stable average water levels ($\Delta WL = 0$). In contrast, the regression excluding 2023 gives:

$$\Delta WL = 9.91 - 0.032 \times Q \tag{9}$$

yielding a slightly more permissive estimate for stabilization:

$$Q_{\text{stable}} = \frac{9.91}{0.032} \approx 305 \text{ Mm}^3/\text{year} \tag{10}$$

This comparison shows that the removal of 2023 produces a slightly less conservative model, meaning that a higher volume of water can be abstracted while still maintaining stable water levels. Nevertheless, the overall structure of the regression remains consistent.

In this scenario, reducing groundwater use from the current level of approximately 310 Mm^3/year to 305 Mm^3/year would achieve stable conditions on average, representing a reduction of 5 Mm^3/year or 1.6%. The 95% confidence interval for the Q_{stable} estimate ranges from 285 to 315 Mm^3/year, reflecting the uncertainty in the regression analysis.

From a management perspective, maintaining the current level of abstraction (310 Mm^3/year) would lead to an average water-level decline of 0.17 m per year. Meeting the Jcar Water Authority target of 275 Mm^3/year would instead result in average annual water-level increases of 0.97 m, thus supporting aquifer recovery. Achieving an annual recovery of one meter would require reducing groundwater withdrawals to approximately 274 Mm^3/year, equivalent to an 11.6% reduction from current levels.

5. Discussion

The successful application of the Water Balance Approach to the Eastern Mancha System provides important insights into both the specific management challenges facing this aquifer and the broader applicability of the method to data-sparse environments worldwide.

5.1. Interpretation of Results

The strong linear relationship ($R^2 = 0.78$) between annual water-level changes and groundwater abstraction volumes demonstrates that the fundamental assumptions of the WBA are met, despite the data-sparse context and the complex hydrogeological setting. This is a particularly significant finding, as it confirms that the method can be effectively applied to Mediterranean aquifer systems, which differ substantially from the High Plains of the Central United States settings where it was originally developed.

The calculated Q_{stable} value of 305 Mm^3/year suggests that the Eastern Mancha System is much closer to sustainable abstraction levels than its official classification as being in poor quantitative status might imply. Current pumping, estimated at approximately 310 Mm^3/year, exceeds the sustainable threshold by only 5 Mm^3/year, or 1.6%, indicating that relatively modest reductions could be sufficient to stabilize water levels for the near-term. This stands in contrast to many overexploited aquifers worldwide, where achieving sustainability often requires much more drastic reductions, typically on the order of 20-50%.

The analysis also shows that the years 2010, 2013, 2018, and 2020 were characterized by positive water-level changes, suggesting that sustainable conditions can be achieved under favorable hydroclimatic circumstances. This variability highlights the need for adaptive management strategies capable of responding dynamically to interannual changes in climate and water availability.

5.2. Comparison with Other Aquifer Systems

In the Kansas HPA, Butler et al. [7] found that pumping reductions of less than 22% would have stabilized water levels across much of the aquifer from 1996 to 2013. The Eastern Mancha System requires a much smaller reduction (1.6%) to achieve stability, suggesting that it is in better condition relative to its sustainable yield than many portions of the Kansas HPA.

The linear relationship observed in both systems demonstrates that the fundamental water balance principles underlying the method are robust across different hydrogeological settings. This consistency supports the broader applicability of the approach to other aquifer systems worldwide.

5.3. Implications for Data-Sparse Environments

One of the most significant contributions of this study is the demonstration that the Water Balance Approach can provide reliable results in data-sparse environments. The Eastern Mancha System analysis was conducted with approximately 35 monitoring points across 7,260 km^2 (one point per 200 km^2) compared to over 1,400 monitoring points across the Kansas HPA (one point per 40 km^2). Despite this five-fold difference in monitoring density, the method produced robust results with clear management implications.

In particular, this finding has important implications for groundwater management in developing countries and other regions where extensive monitoring networks may not be feasible due to resource constraints. The study demonstrates that meaningful quantitative assessments of the sustainability of the aquifer can be conducted with relatively sparse data, provided that appropriate quality control procedures are followed.

5.4. Management Implications and Recommendations

The results provide several important insights for groundwater management:

Achievable Sustainability: The finding that only modest pumping reductions are required for sustainability suggests that the goal of achieving good quantitative status for the aquifer is realistic and achievable over the near-term.

Recovery Potential: The analysis demonstrates that more ambitious reductions could lead to significant aquifer recovery. The Júcar Water Authority's target of 275 Mm^3/year would result in average water level increases of 0.97 m per year in the more conservative analisis.

Adaptive Management: The year-to-year variability in water level changes highlights the importance of adaptive management approaches that can respond to changing conditions.

Method Transferability: The WBA could be applied to other Mediterranean aquifers experiencing similar challenges of intensive agricultural groundwater use and limited data availability. Potential candidates include the Western Mancha, Llanos de Albacete, Los Arenales, and several aquifers in the Segura and Tajo basins, which share comparable hydrogeological and operational conditions.

However, successful transfer of the methodology requires a careful preliminary evaluation of data quality and availability, as well as consideration of groundwater depth and dominant water uses. The WBA is not suitable for coastal aquifers affected by seawater intrusion or for shallow unconfined systems where evapotranspiration and rapid recharge responses introduce nonlinear behaviors. In such cases, more detailed modelling approaches that explicitly represent these processes would be required.

5.5. Limitations and Future Research Needs

While this study demonstrates the successful application of the Water Balance Appro to a data-sparse Mediterranean environment, several limitations must be acknowledged. First, by design, the method operates at a regional scale: it provides basin-wide management targets, such as the 1.6% pumping reduction identified for the Eastern Mancha System, yet cannot prescribe where, spatially, such reductions should occur. This is particularly relevant in Spain, where large groundwater bodies often aggregate multiple hydrogeologically independent aquifers; in many areas, including parts of the Eastern Mancha System, geological compartmentalization produces hydraulically disconnected units whose behavior may diverge from regional trends. Translating regional WBA findings into actionable local strategies, therefore, requires complementary tools such as detailed hydrogeological characterization, spatially distributed piezometric monitoring, or numerical groundwater flow models capable of representing local heterogeneity and compartmentalization. Second, the reliance on indirect water-use estimates introduces uncertainty that could be reduced through improved monitoring of actual pumping volumes. As illustrated by the 2011 and 2023 outliers, remote-sensing irrigation estimates can exhibit systematic biases during climatic extremes: in 2011, delayed hydrological effects from the exceptionally humid 2010 decoupled satellite-detected irrigation activity from aquifer response, whereas in 2023, an exceptionally dry year, lower-than-expected water-use estimates likely reflect limitations of NDVI-based crop classification when drought-stressed vegetation reduces reflectance. These complexities underscore the challenges of applying remote sensing in Mediterranean settings where non-linear climate-agriculture-hydrology interactions emerge under extreme conditions. Third, the assumption of constant net inflow will not hold indefinitely, because the aquifer will eventually adjust to pumping reductions via changes in natural discharge and recharge rates [5, 6]; interactions with surface-water bodies such as the Jcar River may further complicate the water balance, particularly in wet periods when river-aquifer exchanges can partially offset pumping-induced declines.

Looking forward, progress will likely come from extending the temporal coverage to capture longer-term trends and additional extremes; exploring local-scale applications of the method, and integrating the Water Balance Approach with other assessment methods, including numerical modeling and remote sensing techniques.

6. Conclusions

This study demonstrates that the Water Balance Approach can be successfully applied to data-sparse Mediterranean environments, expanding its applicability beyond the original Kansas High Plains context. Three key contributions emerge from this work.

First, the method produces reliable results with significantly reduced data requirements. Despite using five times fewer monitoring points than the Kansas application, the Eastern Mancha analysis yielded a strong linear relationship and actionable management guidance. The successful validation of indirect water use estimates through precipitation-based regression provides a pathway for applying the method where direct pumping measurements are unavailable.

Second, the quantitative results offer encouraging prospects for aquifer sustainability. The calculated Q-stable value of 305 Mm^3/year indicates that only a 1.6% reduction in current pumping would stabilize water levels, while the Jucar Water Authority's target of 275 Mm^3/year would support active recovery at 0.97 m per year. These modest requirements contrast sharply with the severe reductions often needed in heavily depleted aquifer systems.

Third, the approach provides a practical complement to complex numerical models for initial assessments and stakeholder communication. Its transparency and simplicity make it particularly valuable for evidence-based policy development and adaptive management frameworks that can respond to changing conditions. However, users must recognize that the WBA provides regional-scale sustainability targets and cannot resolve local-scale variations or hydraulic compartmentalization. Implementation of system-wide pumping reductions requires complementary local assessments, particularly in heterogeneous systems where groundwater bodies aggregate hydrogeologically independent aquifers.

The successful application to the Eastern Mancha System validates the broader utility of simple, theoretically sound approaches in groundwater management and provides a model for similar applications in data-limited environments worldwide, provided that adequate monitoring networks and reliable pumping estimates are available.

Conflict of Interest Statement

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

CRediT authorship contribution statement

Vanessa A. Godoy: Methodology, Software, Validation, Formal analysis, Investigation, Writing - Original Draft, Visualization. **James J. Butler Jr.:** Methodology, Conceptualization, Formal analysis, Investigation, Writing - Review & Editing, Supervision. **J. Jaime Gómez-Hernández:** Methodology, Validation, Formal analysis, Investigation, Writing - Review & Editing, Visualization, Supervision, Funding acquisition.

Funding

The authors acknowledge project OurMED, which is part of the PRIMA Programme supported by the European Union's Horizon 2020 Research and Innovation Programme under Grant Agreement No 2222.

Data Availability Statement

The datasets and code used in this analysis are available under reasonable request from the corresponding author. Water level data are maintained by the Confederación Hidrográfica del Júcar and are available through their public data portal. Precipitation data were obtained from the Spanish Meteorological Agency (AEMET).

[1] Alley, W. M. and Alley, R. (2017). *High and dry: Meeting the challenges of the world's growing dependence on groundwater*. Yale University Press.

[2] Babbitt, C. H., Gibson, K. E., Sellers, S., Brozovic, N., Saracino, A., Hayden, A., Hall, M., and Zellmer, S. (2018). The future of groundwater in california: Lessons in sustainable management from across the west.

[3] Bohling, G., Butler Jr, J., Whittemore, D., and Wilson, B. (2021). Evaluation of data needs for assessments of aquifers supporting irrigated agriculture. *Water Resources Research*, 57(4):e2020WR028320.

[4] Butler, James J., J., Whittemore, D. O., Wilson, B. B., and Bohling, G. C. (2018). Sustainability of aquifers supporting irrigated agriculture: a case study of the high plains aquifer in kansas. *Water International*, 43(6):815–828.

[5] Butler Jr, J., Bohling, G., Perkins, S., Whittemore, D., Liu, G., and Wilson, B. (2023). Net inflow: An important target on the path to aquifer sustainability. *Groundwater*, 61(1):56–65.

[6] Butler Jr, J., Bohling, G., Whittemore, D., and Wilson, B. (2020). Charting pathways toward sustainability for aquifers supporting irrigated agriculture. *Water Resources Research*, 56(10):e2020WR027961.

[7] Butler Jr, J. J., Whittemore, D. O., Wilson, B. B., and Bohling, G. C. (2016). A new approach for assessing the future of aquifers supporting irrigated agriculture. *Geophysical Research Letters*, 43(5):2004–2010.

[8] Castaño, S., Sanz, D., and Gómez-Alday, J. J. (2010). Methodology for quantifying groundwater abstractions for agriculture via remote sensing and gis. *Water resources management*, 24:795–814.

[9] Confederación Hidrográfica del Júcar (CHJ) (2019). Hydrological plan of the Júcar hydrographic demarcation. hydrological planning cycle 2022-2027. Accessed: 2019.

[10] Doherty, J. and Moore, C. (2020). Decision support modeling: Data assimilation, uncertainty quantification, and strategic abstraction. *Groundwater*, 58(3):327–337.

[11] European Environment Agency (2018). Corine land cover 2018.

[12] Konikow, L. F. (2014). Long-term groundwater depletion in the united states. *Groundwater*, 53(1):2–9.

[13] Lohman, S. W. (1972). *Ground-Water Hydraulics*. Number 708 in U.S. Geological Survey Professional Paper. U.S. Government Printing Office, Washington, D.C.

[14] Miller, R. D., Buchanan, R., and Brosius, L. (1999). *Measuring water levels in Kansas*. Kansas Geological Survey Lawrence.

[15] Pulido-Velazquez, M., Peña-Haro, S., García-Prats, A., Mocholi-Almudever, A. F., Henríquez-Dole, L., Macian-Sorribes, H., and Lopez-Nicolas, A. (2015). Integrated assessment of the impact of climate and land use changes on groundwater quantity and quality in the mancha oriental system (spain). *Hydrology and Earth System Sciences*, 19(4):1677–1693.

[16] Sanz, D., Castaño, S., Cassiraga, E., Sahuquillo, A., Gómez-Alday, J. J., Peña, S., and Calera, A. (2011). Modeling aquifer-river interactions under the influence of groundwater abstraction in the mancha oriental system (se spain). *Hydrogeology Journal*, 19(2):475.

[17] Sanz, D., Gómez-Alday, J. J., Castaño, S., Moratalla, A., De las Heras, J., and Martínez-Alfaro, P. E. (2009). Hydrostratigraphic framework and hydrogeological behaviour of the mancha oriental system (SE Spain). *Hydrogeology Journal*, 17(6):1375.

[18] Sanz, D., Vos, J., Rambags, F., Hoogesteger, J., Cassiraga, E., and Gómez-Alday, J. J. (2019). The social construction and consequences of groundwater modelling: insight from

the mancha oriental aquifer, spain. *International Journal of Water Resources Development*, 35(5):808–829.

[19] Sanz Martínez, D. (2005). *Contribución a la caracterización geométrica de las unidades hidrogeológicas que integran el sistema de acuíferos de la Mancha Oriental*. Tesis doctoral, Universidad Complutense de Madrid, Madrid, España.

[20] Singh, A., Prasad, R., Singh, R., and Kumar, M. (2018). Detection and classification of groundwater over-exploitation using remote sensing and machine learning techniques. *Journal of Hydrology*, 563:1025–1038.

[21] van Buuren, S. and Groothuis-Oudshoorn, K. (2011). mice: Multivariate imputation by chained equations in r. *Journal of Statistical Software*, 45(3):1–67.

[22] Whittemore, D. O., Butler Jr, J. J., and Wilson, B. B. (2016). Assessing the major drivers of water-level declines: New insights into the future of heavily stressed aquifers. *Hydrological Sciences Journal*, 61(1):134–145.