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Impact of a transformation from flood to drip irrigation on groundwater recharge and nitrogen leaching under variable climatic conditions

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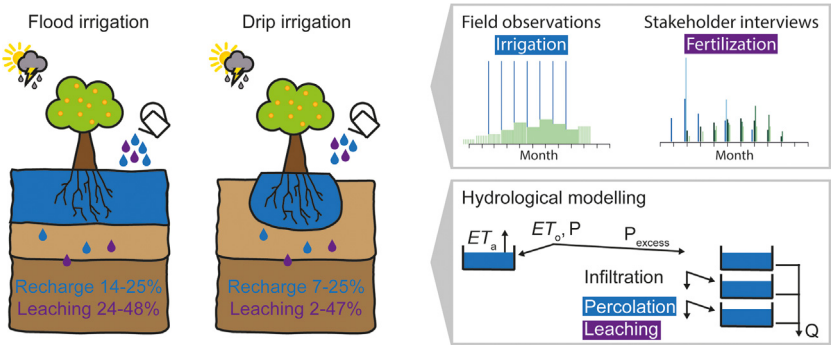
HIGHLIGHTS

- Performance of irrigation-fertilizer practices in Mediterranean climate is modelled.
- Lower long-term recharge and nitrogen leaching in drip than in flood irrigation
- High fluctuations in recharge and leaching controlled by annual precipitation
- Similar recharge and leaching in flood and drip irrigation in wet years
- Pronounced year-to-year soil nitrogen memory especially in drip irrigation

GRAPHICAL ABSTRACT



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ABSTRACT

The sustainability of agriculture in the Mediterranean climate is challenged by high irrigation water demands and nitrogen fertilizer losses to the environment, causing significant pressure on groundwater resources and groundwater-dependent ecosystems. Advanced irrigation technologies and improved fertilizer management have been promoted as key solutions to reduce the agricultural impact on aquatic systems. However, it remains unclear how different irrigation-fertilizer practices perform on the long-term under a highly variable climate, such as the Mediterranean one. Here, we conduct hydrological simulations over a fifty-year period to quantify the magnitude and dynamics of groundwater recharge and nitrogen leaching under five real-case irrigation-fertilizer practices observed in Valencia (eastern Spain). The Valencian Region is the largest citrus-producing region of Europe and current irrigation-fertilizer practices reflect the ongoing transformation of irrigation systems from flood to drip irrigation. Our simulations highlight three major implications of the irrigation transformation for groundwater resources. First, the transformation from flood to drip irrigation reduces the recharge fraction (19% vs. 16%) and especially the nitrogen leaching fraction (33% vs. 18%) on the long term. Second, the long-term performance of the two irrigation practices is subject to substantial inter-annual differences controlled by precipitation variability. The sensitivity of recharge and nitrogen leaching to annual meteorological conditions is stronger in drip irrigation, which eventually leads to a similar

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performance of flood and drip irrigation in wet years if fertilizer inputs are similar. Third, we identify a pronounced year-to-year nitrogen memory in the soil, whereby an enhanced (decreased) nitrogen leaching is observed after anomalously dry (wet) years, affecting the performance of irrigation-fertilizer practices. Overall, the study demonstrates the highly variable nature of the performance of irrigation-fertilizer practices, and the major findings can guide future efforts in designing sustainable water management strategies for agricultural areas with a Mediterranean climate.

1. Introduction

Agriculture uses 70% of the total freshwater withdrawals (Grafton et al., 2017; Siebert et al., 2010) and strongly relies on the use of nitrogen fertilizers to secure food production (Lassaletta et al., 2016; Sutton et al., 2013; Zhang et al., 2015). More than half of the nitrogen added to agricultural land is lost to the environment (Bijay-Singh and Craswell, 2021; Lassaletta et al., 2014; Liu et al., 2018), where it remains for many decades (Martin et al., 2021; McMahon et al., 2006; Sebilo et al., 2013) and causes contaminated aquifers, impure drinking water, and nutrient enrichment in connected surface waters (Sabo et al., 2019; Sutton et al., 2013). Intensively managed agricultural land is considered as one of the main stressors for the quality and quantity of groundwater resources and groundwater-dependent ecosystems (Kløve et al., 2011; Kristensen et al., 2018; Leduc et al., 2017; Sabo et al., 2019). Developing sustainable water management strategies for agricultural areas requires a solid understanding of the amount and dynamics of groundwater recharge and nitrogen leaching, their interaction, as well as their controlling factors and memory (i.e., time lags due to the retention and subsequent release in soils; Peña-Haro et al., 2010, 2011; Roy et al., 2021).

The introduction of drip irrigation techniques has been widely promoted as a prominent measure to save water in agriculture (Grafton et al., 2018; Perry et al., 2017). The promotion has been largely based on findings at the field scale, which proved that drip irrigation could increase crop evapotranspiration while reducing unwarranted water losses through soil evaporation and percolation below the root zone (Cavero et al., 2012; Jin et al., 2018; Liu et al., 2012; Thoreson et al., 2013; Wang et al., 2018). Advanced irrigation techniques are also frequently listed among potential nitrogen leaching mitigation strategies (Causapé et al., 2006; Cavero et al., 2012; Liu et al., 2014; Mack et al., 2005; Sharma and Bali, 2017; Sutton et al., 2013). In fact, a meta-analysis on strategies to control nitrogen leaching (Quemada et al., 2013) revealed that an improved water management is the most effective way to reduce leaching, followed by an improved fertilizer management, the use of cover crops, and an improved fertilizer technology (e.g., controlled release or nitrification inhibitors). Despite the high importance of water management for reducing nitrogen losses to the groundwater, studies on the relevant issues are rare (Quan et al., 2021; Quemada et al., 2013; Sharma and Bali, 2017) and direct comparisons of different irrigation techniques under similar fertilizer applications are uncommon.

The effectiveness of water and nitrogen management strategies can greatly depend on precipitation characteristics. An increase in annual precipitation reduces travel times in soils (Kumar et al., 2020) and therefore increases groundwater recharge (Keese et al., 2005; Mohan et al., 2018) as well as nitrogen leaching (Ballard et al., 2019; Eagle et al., 2017; Scaini et al., 2020). Both processes can occur throughout the entire year in humid regions with frequent rainfall; however, they are typically limited to a few months or even a few years in drier regions (Kumar et al., 2020). In semi-arid and arid climatic conditions, a disproportionally high fraction of the annual recharge and leaching is produced by heavy precipitation events (de Paz and Ramos, 2004; Jiménez-Martínez et al., 2010; Vallet-Coulomb et al., 2017; Yahdjian and Sala, 2010; Zhou et al., 2016). Surprisingly, experimental work showed that the occurrence of such intense rainfall events can also lead to considerable recharge and leaching under advanced irrigation techniques, making their efficiencies comparable to the one of traditional irrigation practices (Poch-Massegú et al., 2014). While advanced irrigation techniques have been widely promoted in many water scarce regions all over the world (Molle and Tanouti, 2017; Ortega-Reig et al., 2017; Scott et al., 2014), there is still a limited understanding of their long-term performance under high inter-annual precipitation variability.

The purpose of this study is to investigate how sensitive the performance of irrigation-fertilizer practices is to changes in inter-annual meteorological conditions. We aim to contribute new insights into this question by applying a modeling approach which allows to systematically compare real-case practices at regional scale and using long-term time series. Our focus is on the Mediterranean region of the Valencia province (Spain), which is the largest citrus producing area in Europe (European Commission, 2018; MAPA, 2019). The intensive agriculture deteriorates groundwater quality with negative implications for the aquifer of the Plana de Valencia Sur (Escrivá Benito, 2020; Ramos et al., 2002; Sanchis-Ibor et al., 2019). It also frequently challenges water allocation during drought periods (Rubio-Martin et al., 2020). To increase the resilience and sustainability of the agricultural production, irrigation systems are transformed from flood to drip irrigation (Sanchis-Ibor et al., 2017) and regulations for good nitrogen management were published by the regional government (Generalitat Valenciana, 2018). In this study, we identify five typical irrigation and fertilizer schedules from local field experiments and stakeholders interviews. We combine this information with fifty years of meteorological data to simulate daily groundwater recharge and nitrogen leaching under the five irrigation-fertilizer practices with a distributed hydrological model. Three modeling experiments are conducted to quantify (i) the long-term response, (ii) the annual sensitivity, and (iii) the memory of groundwater recharge and nitrogen leaching under the different irrigation and fertilizer practices. While these modeling experiments are conducted in the Valencian Region, the resulting conclusions have implications beyond the study region as irrigation transformations are ongoing globally in many arid and semi-arid regions (Cavero et al., 2012; Harmanny and Malek, 2019; Molle and Tanouti, 2017; Pfeiffer and Lin, 2014; Scott et al., 2014).

2. Study site

The study area (913 km^2) is the agricultural region south of the city of Valencia in eastern Spain (Fig. 1a). The area includes the catchments draining into the flood plain of the Jucar River, as well as the aquifer of the Plana de Valencia Sur. The area is characterized by a typical semi-arid Mediterranean climate with heavy rainfall events in fall (mean intensity of the ten largest annual events was 30 mm d^{-1} between 1966 and 2015), a large inter-annual variability in precipitation (mean of 529 mm $year^{-1}$ and a range from 230 mm $year^{-1}$ to 1193 mm $year^{-1}$ between 1966 and 2015), and frequent multi-year droughts (Marcos-Garcia et al., 2017). In eastern Spain, climate change is expected to increase the regional water scarcity (Chirivella Osma et al., 2015; Ferrer et al., 2012; Marcos-Garcia et al., 2017) while individual rainfall events may become more extreme (Alpert, 2002; Moutahir et al., 2017; Pulido-Velazquez et al., 2015).

Citrus orchards are the predominant agricultural land use in the study area. The orchards are irrigated with streamflow from the Jucar River and occasionally with small amounts of groundwater. Irrigation frequencies and depths for flood and drip irrigation (Fig. 1b and Table S1) were obtained from local field experiments conducted by Ruiz Rodríguez (2017) in two commercial citrus orchards. Daily irrigation depths in the flood-irrigated orchard were estimated using discharge measurements in the channel transporting the water to the orchard. Daily irrigation depths in the drip-irrigated orchard were measured with a flow meter installed in the hydrant from which water is supplied to the pipe system. The observed

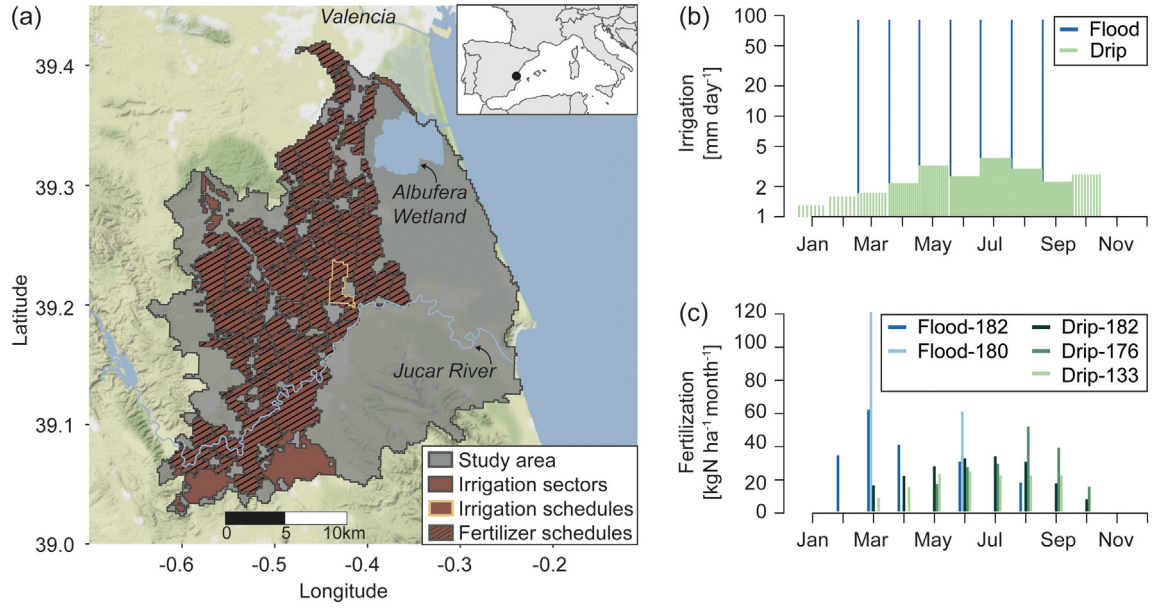

Fig. 1. Characteristics of the study area. a) Extent of the study area and location of the citrus orchards, which are divided in 68 irrigation sectors for irrigation and fertilizer management. Irrigation sectors used to define typical irrigation schedules from field experiments are outlined in orange. Irrigation sectors used to define typical fertilizer schedules from interviews with technicians are marked with hatched areas. The terrain background map was designed by Stamen (2021). b) Typical daily irrigation schedules for flood and drip irrigation. c) Typical monthly fertilizer applications in flood and drip irrigation. Fertilizer application is in the form of NO_3^-.

annual irrigation depths are 630 mm in flood irrigation and 492 mm in drip irrigation. To define typical fertilizer schedules for flood and drip irrigation (Fig. 1c and Table S1), we conducted interviews with the three technicians of the major Valencian irrigation communities and one technician from the main cooperative of citrus producers in the study area (accounting for 90% of the irrigated area). Each technician provided its estimate of monthly fertilizer inputs (NO_3^-) for flood and/or drip irrigation in 2020. These estimates were complemented with fertilization schedules for 2020 that two local irrigation communities yearly publish on their websites (Benimodo, 2021; Los Tollos, 2021), which finally resulted in five combinations of irrigation-fertilizer practices. The five practices include flood irrigation with 182 kgN ha^{-1} $year^{-1}$ (*Flood-182*), flood irrigation with 180 kgN ha^{-1} $year^{-1}$ (*Flood-180*), drip irrigation with 182 kgN ha^{-1} $year^{-1}$ (*Drip-182*), drip irrigation with 176 kgN ha^{-1} $year^{-1}$ (*Drip-176*), and drip irrigation with 133 kgN ha^{-1} $year^{-1}$ (*Drip-133*). The interviews further revealed that irrigation schedules are comparable across years as they are usually not adapted to meteorological forecasts. Hence, the irrigation schedules observed in 2016 are considered as representative for the entire study period (1966 to 2015). Instead, the fertilizer schedules have been prone to some changes in the past and were explicitly chosen to represent current practices.

3. Recharge and nitrogen leaching modeling experiments

3.1. Hydrological model

We used the spatially distributed, process-based hydrological model TETIS (Francés et al., 2007; Puertes et al., 2021) to perform simulations of groundwater recharge and nitrogen leaching for the study region. The water balance of the model was forced with precipitation (Herrera et al., 2012, 2016), irrigation (Fig. 1b and Table S1), as well as potential evapotranspiration calculated with the Hargreaves-Samani equation (Hargreaves and Samani, 1985) and corrected using local FAO Penman-Monteith estimates (IVIA, 2019). The driving variables for the nitrogen cycle were fertilization (NO_3^-; Fig. 1c and Table S1) and atmospheric deposition (NO_3^- and NH_4^+; García-Gómez et al., 2014). Model parameter values were estimated from CORINE land use maps (EEA, 2019) and the corresponding FAO crop coefficients (Allen et al., 1998), soil maps from the European soil database (ESDB, 2019) and pedotransfer functions (Puertes et al., 2021; Schaap et al., 2001), geological maps from the Geological Survey of Spain (IGME, 2019), and a digital elevation model from the Geographical Survey of Spain (CNIG, 2019).

The measured model parameter values were adjusted through a hierarchical multi-process calibration, which started with the estimation of water balance parameters, followed by the adaptation of the nitrogen cycle parameters. The water balance parameters were previously calibrated for the study region by Pool et al. (2021a, 2021b) using the annual evaporative index, monthly groundwater storage and dynamics, and daily soil water dynamics. In case of the nitrogen cycle, we largely used parameter values suggested by Puertes et al. (2021) for a semi-arid, irrigated, agricultural catchment south of our study region. We further adjusted the values of three nitrogen parameters, namely the mineralization rate constant, the nitrification rate constant, and the partition coefficient for sorption using nitrogen leaching fractions reported for irrigated citrus orchards (Alva et al., 2006; Castel et al., 1995; Lidón, 1994; Martínez-Alcántara et al., 2012; Paramasivam et al., 2002; Phogat et al., 2014; Ramos et al., 2002; Syvertsen and Sax, 1999). The Monte Carlo approach used for model calibration resulted in twelve behavioral model parameterizations, which allowed to account for model parameter uncertainty and equifinality (Beven and Freer, 2001). A more detailed description of the model and its calibration is provided in the supporting information (Figs. S1 and S2).

3.2. Three modeling experiments

Model simulations were performed at a 200 m by 200 m spatial resolution and on a daily time scale for the fifty-year period from 1966 to 2015. Following a scenario-based approach, separate simulations were run for each of the five observed irrigation-fertilizer practices assuming identical practices for all citrus orchards within the study region. To investigate the impact of these practices on recharge and nitrogen leaching (sum of NO_3^- and NH_4^+) under varying meteorological conditions, we conducted three modeling experiments.

The first modeling experiment aimed at quantifying the monthly long-term recharge and nitrogen leaching regimes. Therefore, simulations were run for the continuous fifty years and the resulting monthly sums of recharge and nitrogen leaching were averaged over all simulation years.

The year 2010, was used to define the boundary conditions, i.e., initial water and nitrogen storages and concentrations, before starting the simulations. The year 2010 has close to average annual precipitation ($\overline{P}$) and its use avoids the introduction of biases in the boundary conditions.

With the second modeling experiment, we evaluated the sensitivity of annual recharge and nitrogen leaching to annual meteorological conditions. Each year was simulated separately starting from the same initial boundary conditions (again related to 2010) to remove the dependency from the meteorological conditions of previous years. The resulting annual sum of recharge (mm) and nitrogen leaching (kgN ha^{-1}) of each year was further used to calculate the recharge fraction (−), defined as the ratio between recharge and the sum of precipitation and irrigation, as well as the nitrogen leaching fraction (−), defined as the ratio between nitrogen leaching and the sum of fertilizer input and atmospheric deposition.

The third modeling experiment was used to analyze the memory of annual recharge and nitrogen leaching. The methodology is based on the idea of stress testing where the overarching question is "what would have happened if the previous year was different?" (Stoelzle et al., 2020). We therefore systematically modified the antecedent conditions of each year by replacing its original preceding year with a dry (0.5 $\overline{P}$; 310 mm $year^{-1}$), average ($\overline{P}$; 583 mm $year^{-1}$), and wet (1.5 $\overline{P}$; 872 mm $year^{-1}$) year. Simulations for each of these modified two-year combinations were started from the same initial boundary conditions (again related to 2010). The memory, defined as the persistence of a meteorological anomaly beyond a year (following definitions given in D'Odorico et al., 2003; Seneviratne et al., 2006; Vero et al., 2018), was then quantified as the ratio between annual recharge (or nitrogen leaching) in a wet or dry year and the annual recharge (or nitrogen leaching) in an average year. Please note that while simulations were run for the entire hydrological system, results are only reported for the area containing irrigated citrus orchards (Fig. 1a).

4. Results

4.1. Long-term monthly recharge and nitrogen leaching

The irrigation transformation significantly modified the magnitude and timing of recharge and nitrogen leaching (Fig. 2). On the long-term, annual recharge in flood-irrigated orchards (230 mm $year^{-1}$) was 1.3 times higher than the annual recharge in drip-irrigated orchards (174 mm $year^{-1}$). Similarly, nitrogen leaching was 1.7 times higher in flood irrigation (69 kgN ha^{-1} $year^{-1}$ for both fertilizer practices) than in drip irrigation (mean of all fertilizer practices was 39 kgN ha^{-1} $year^{-1}$ and values ranged from 31 to 46 kgN ha^{-1} $year^{-1}$). However, the performance of drip-irrigated systems was typically lower than the one of flood-irrigated systems during the fall and winter months (September to February) due to dissimilarities in process seasonality (see also Fig. S3). More specifically, most of the annual recharge and nitrogen leaching in drip irrigation was generated during large rainfall events, which occur in fall and partly in winter. Recharge in flood irrigation peaked in spring and fall and was sustained by excess irrigation in spring and summer, whereas the largest losses of nitrogen to the groundwater happened after fertilizer applications in spring.

4.2. Sensitivity of recharge and nitrogen leaching to meteorological conditions

The meteorological conditions from 1966 to 2015 led to a wide range of recharge and nitrogen leaching responses (Fig. 3). With increasing annual precipitation, significantly more recharge and nitrogen leaching occurred (Fig. 3a and c) reducing the performance (recharge and nitrogen leaching fractions) of all irrigation and fertilizer practices (Fig. 3b and d). The generally higher sensitivity of drip irrigation to meteorological conditions (see also Fig. S4) eventually led to a comparable performance of flood and drip irrigation practices in relatively wet years if the total fertilizer input was similar. This is reflected by the performance values for recharge and

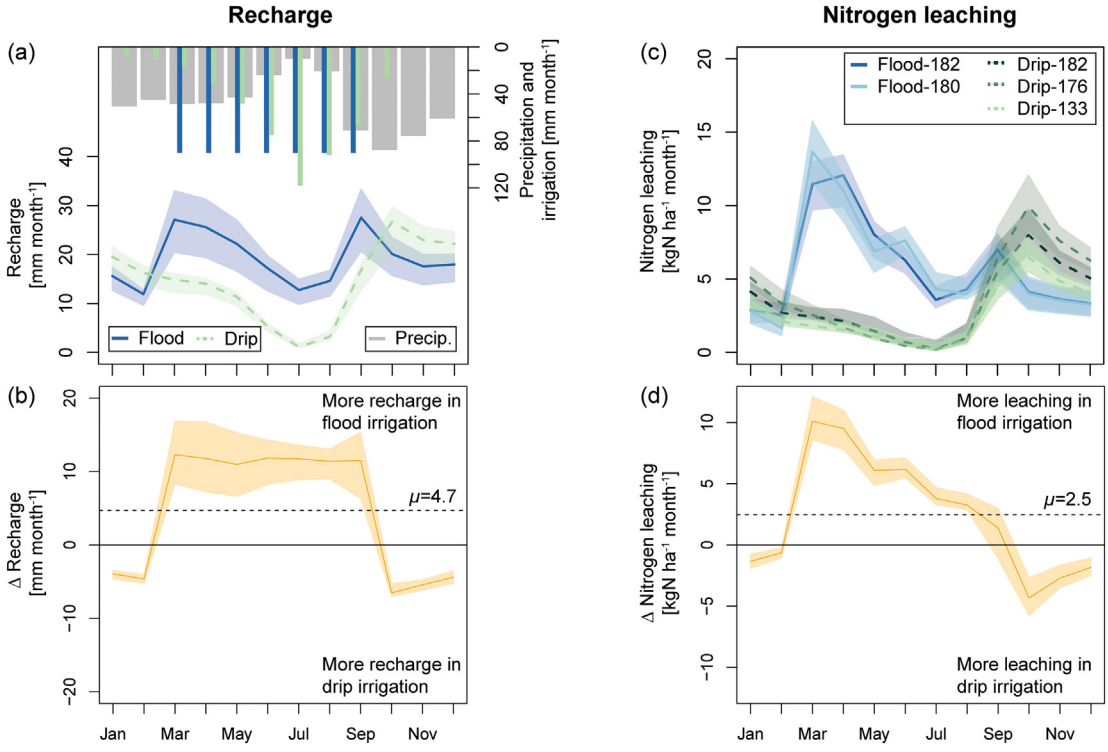

Fig. 2. Recharge (a and b) and nitrogen leaching (c and d) regimes. Regime curves are the mean monthly response of all fifty years from 1966 to 2015. The regime curves were used to calculate the monthly difference (Δ) between flood and drip irrigation (μ is the mean monthly difference). For nitrogen leaching, monthly differences were calculated from the mean of all fertilizer practices for a given irrigation practice. Annual differences between flood and drip irrigation were compared with the nonparametric Wilcoxon signed rank test and are statistically significant at $p < 0.05$. The colored lines and the corresponding shaded bands represent the median and the range of the twelve hydrological model parameterizations, respectively.

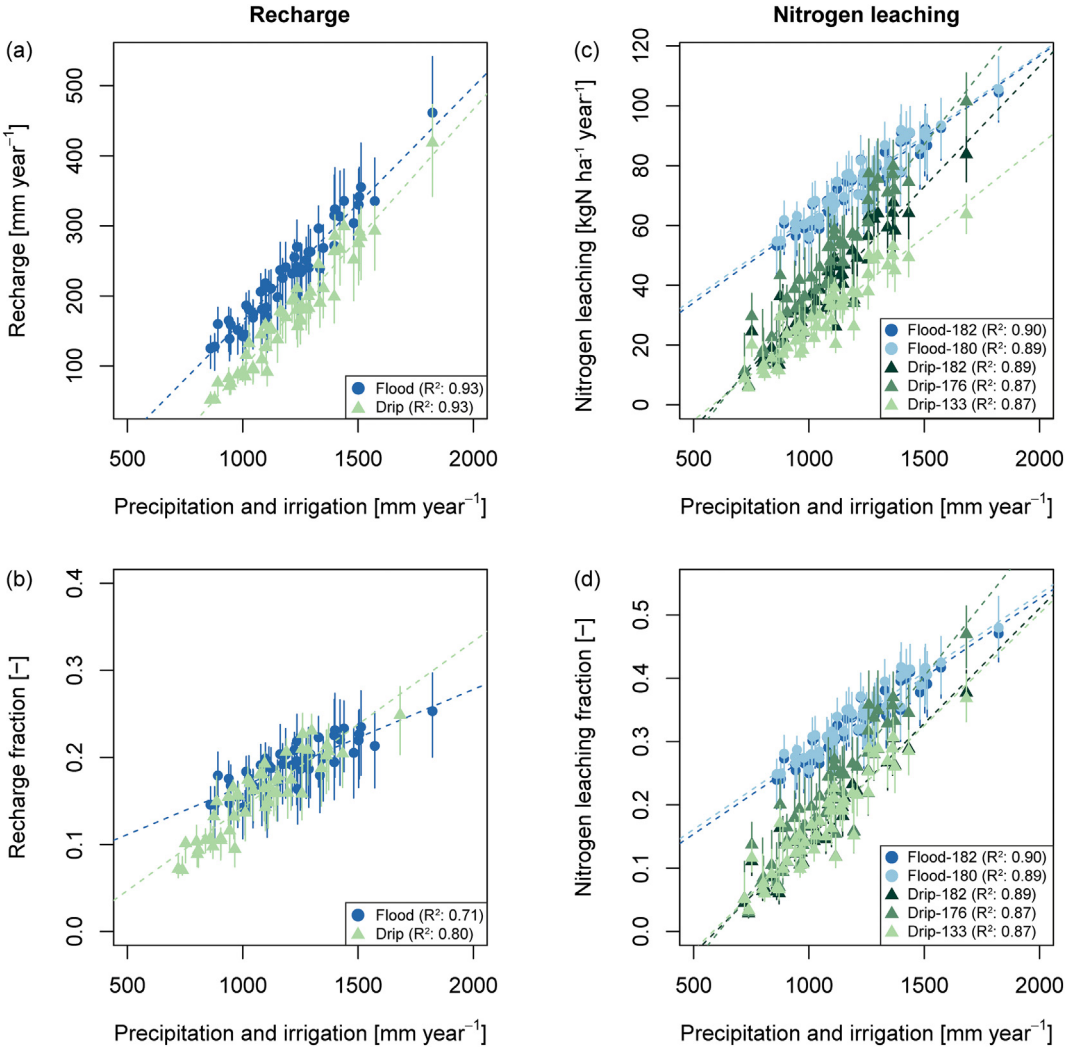

Fig. 3. Sensitivity of recharge and recharge fraction (a and b), and nitrogen leaching fraction (c and d) to annual meteorological conditions in the fifty years from 1966 to 2015. The recharge fraction is the ratio of recharge to the sum of precipitation and irrigation. The nitrogen leaching fraction is the ratio of nitrogen leaching to the sum of fertilizer input and atmospheric deposition. The points and the bars represent the median and the range of the twelve hydrological model parameterizations for each year, respectively. The dashed lines are the linear least squares regression lines fitted to the median values of each irrigation and irrigation-fertilizer practice. The regressions are statistically significant at $p < 0.05$.

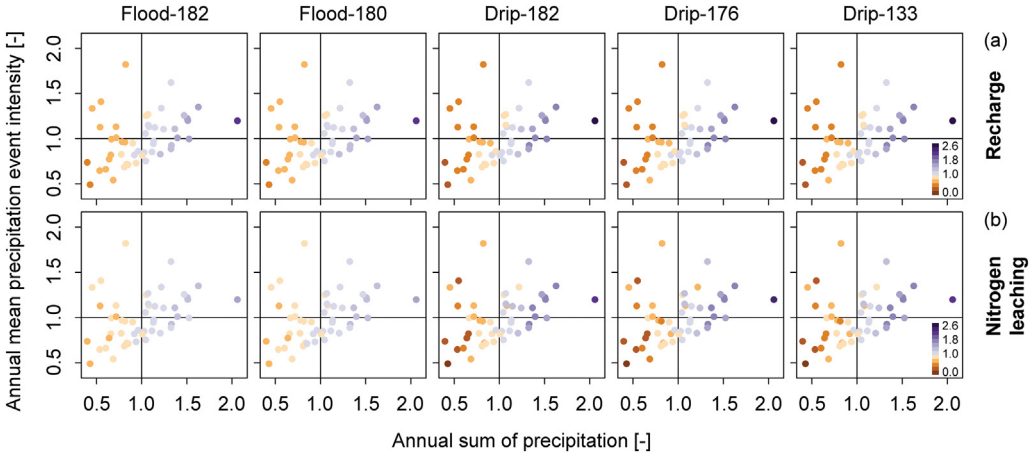

Fig. 4. Sensitivity of recharge (a) and nitrogen leaching (b) to the annual sum of precipitation and the annual mean precipitation event intensity in the fifty years from 1966 to 2015. Precipitation event intensity is defined as the mean precipitation of events critical for recharge generation (i.e., events larger than 16 mm day^{-1}; see e.g., Moutahir et al., 2017; Pool et al., 2021a, 2021b; Touhami et al., 2015). Each variable is normalized by its mean of all years. The points represent the median recharge and nitrogen leaching of the twelve hydrological model parameterizations for each year. Purple (brown) colors indicate above (below) average recharge and nitrogen leaching.

nitrogen leaching, which varied between the years from 14 to 25% (mean 19%) and 24–48% (mean 33%) in flood irrigation, but had much larger ranges from 7 to 25% (mean 16%) and 2–47% (mean 18%) in drip irrigation. The meteorological conditions further changed the importance of nitrogen management, in particular for drip irrigation. While lower fertilizer applications tended to reduce total nitrogen losses to the groundwater, the timing of fertilizer application became more critical than the total nitrogen input for the performance of drip irrigation with increasing annual wetness.

The large variability of meteorological conditions, in particular the range in annual precipitation, observed between 1966 and 2015 was partly a result of the occurrence of heavy rainfall events (Fig. 4; Spearman rank correlation of 0.44). However, the analysis of the relative role of annual precipitation and event intensity for recharge and nitrogen leaching suggests that both processes are strongly controlled by annual precipitation (Spearman ran correlation of 0.96 for flood irrigation and 0.93 for drip irrigation), whereas their sensitivity to event intensity is surprisingly low (Spearman ran correlation of 0.28 for flood irrigation and 0.36 for drip irrigation). Indeed, for a given event intensity, recharge and nitrogen leaching could be either above or below their long-term average value.

4.3. Memory of recharge and nitrogen leaching under variable climatic conditions

The effect of different antecedent annual meteorological conditions varied greatly between recharge and nitrogen leaching (Fig. 5). For recharge, the wetness of a previous year was of limited importance for both irrigation practices. Yet, there was a clear tendency towards an average increase in recharge of 1% (range from 0% to 4%) if the previous year was relatively wet, and an average decrease in recharge of −4% (range from −12% to 0%) if the previous year was relatively dry for both irrigation practices. For nitrogen leaching, annual sums of fertilizer losses could be strongly influenced by the conditions in the preceding year with larger impacts in drip than in flood irrigation. In contrast to recharge, a preceding dry year enhanced nitrogen leaching on average by 2% (range from −2% to 4%) in flood irrigation and 8% (range from −10% to 24%) in drip irrigation, and wetter antecedent conditions reduced nitrogen leaching on average by −12% (range from −14% to −10%) in flood irrigation and −22% (range from −48% to −10%) in drip irrigation. Although antecedent conditions had a larger impact on nitrogen leaching than on recharge, both processes differed significantly the year after a dry and a wet year for all irrigation and fertilizer practices.

5. Discussion

5.1. Meteorological controls on recharge and nitrogen leaching

5.1.1. Long-term recharge and nitrogen leaching regimes

Drip irrigation is typically associated with smaller irrigation depths and a more frequent application of water than flood irrigation, reducing groundwater recharge and nitrogen leaching to the aquifer (Cavero et al., 2012; Jin et al., 2018; Liu et al., 2014; Sharma et al., 2012; Thoreson et al., 2013). Our simulations confirm the lower recharge and nitrogen leaching fractions after an irrigation transformation, and predict similar mean long-term performances as previously reported from experimental field work or plot-scale modeling in citrus orchards (e.g., Alva et al., 2006; de Paz and Ramos, 2004; Lidón et al., 2013; Phogat et al., 2014; Ramos et al., 2002).

5.1.2. Sensitivity of recharge and nitrogen leaching to annual meteorological conditions

Our results show a strong variability in the performance of irrigation-fertilizer practices between years and suggest that these inter-annual differences are largely controlled by precipitation. Similar to our findings, recharge (Keese et al., 2005; Mohan et al., 2018; Xu et al., 2020) and nitrogen (Ballard et al., 2019; Eagle et al., 2017; Scaini et al., 2020) studies across hydroclimatic regions found that wetness conditions are a key factor to explain temporal and spatial differences in groundwater recharge and nitrogen leaching. By comparing the performance of flood and drip irrigation for the same region, we are able to highlight that recharge and nitrogen leaching in drip irrigation are more sensitive to precipitation variability than in flood irrigation. In drip irrigation, constantly moist soils from frequent irrigation in fall and the continued application of fertilizer until the onset of the first rainfalls cause a high potential for recharge and nitrogen leaching. Thus, the typical but highly variable rainfall events in fall have a decisive impact on the performance of drip irrigation (Jiménez-

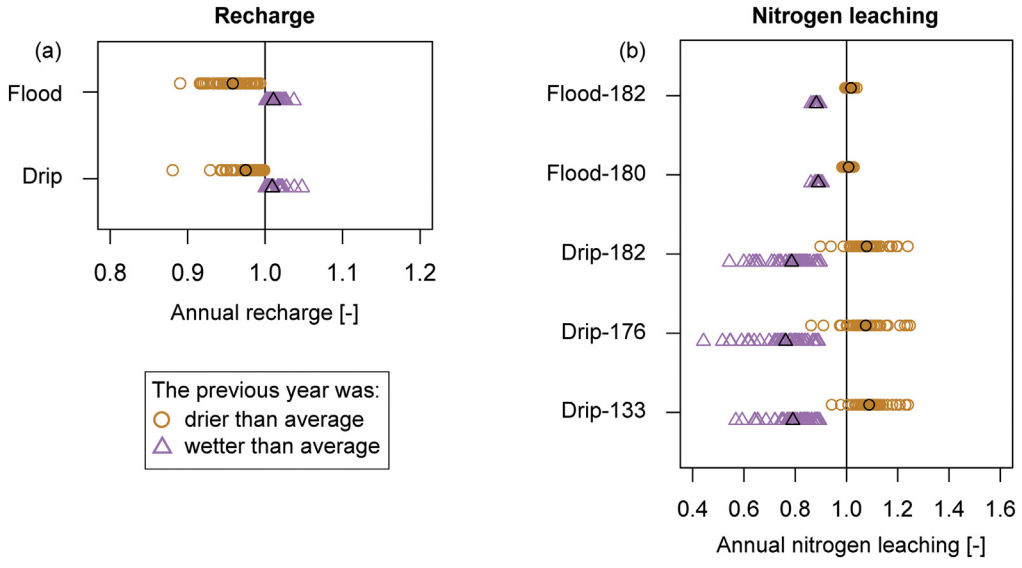

Fig. 5. Memory of recharge (a) and nitrogen leaching (b) in the fifty years from 1966 to 2015. The memory is an indicator for the impact of meteorological conditions of a previous year on this year's recharge and nitrogen leaching. The purple triangles show the impact of a wet year relative to the impact of an average year. The brown circles show the impact of a dry year relative to the impact of an average year. The values represent the median of the twelve hydrological model parameterizations for each year. The mean of all years is marked with a black triangle or circle. Differences in the mean values for each irrigation and fertilizer practice were compared with the nonparametric Wilcoxon signed rank test and are statistically significant at $p < 0.05$.

Martínez et al., 2010; Poch-Massegú et al., 2014; Pool et al., 2021a). In contrast to drip irrigation, the more sporadic irrigation events and the restriction of fertilizer application to spring and summer in flood irrigation reduce the sensitivity of recharge and nitrogen leaching to precipitation. The different sensitivity of the two irrigation practices has three interesting consequences. First, recharge and nitrogen leaching are seasonally (September to February) higher in drip irrigation than in flood irrigation. Second, annual recharge and nitrogen leaching in both irrigation practices become similar for a given fertilizer input in relatively wet years. Third, the application of considerable amounts of fertilizer in fall can lead to enhanced nitrogen leaching in drip irrigation despite lower total fertilizer inputs.

Besides annual precipitation sums, heavy precipitation events are also important recharge and leaching drivers (de Paz and Ramos, 2004; Jiménez-Martínez et al., 2010; Vallet-Coulomb et al., 2017; Yahdjian and Sala, 2010; Zhou et al., 2016). It was therefore hypothesized that increased precipitation event intensity associated with climate change will enhance recharge and nitrogen losses to the groundwater all over the world (Bijay-Singh and Craswell, 2021; Xu et al., 2020; Zhou et al., 2016). Within the Mediterranean Region, climate models project increased event intensities together with a reduction of annual precipitation (Alpert, 2002; Moutahir et al., 2017; Rajczak et al., 2013; Seager et al., 2019). Based on fifty-year simulations, our results suggest that the annual sum of precipitation exerts a stronger control on recharge and nitrogen leaching than the mean event intensity, potentially leading to reduced future recharge and nitrogen leaching despite higher event intensities. Our results with data from the past are thereby in line with future recharge projections in our study area that are based on climate models (Pool et al., 2021b). Based on our results, there are mainly two reasons for the higher importance of annual precipitation than event intensity. First, soils tend to have a larger storage potential at the day of an intense precipitation event in dry years than in wet years and therefore have a larger buffer potential in dry years (Fig. S5). Second, intense precipitation events typically occur in fall, whereas the annual sum of precipitation is distributed over a much longer time span ranging from fall to spring continuously contributing to annual recharge and nitrogen leaching in both flood and drip irrigation (Fig. S3).

5.1.3. Memory of recharge and nitrogen leaching

The recharge and nitrogen leaching patterns observed under different annual wetness conditions are further reinforced by the sum of precipitation fallen in the preceding year. If the preceding year was dry instead of wet, nitrogen leaching rates were relatively small leading to an accumulation of nitrogen in the soil due to overfertilization (Fig. S5). The additionally stored nitrogen contributes to leaching in the following year resulting in an enhanced nitrogen leaching after a dry preceding year. The described memory effect is strongest for drip irrigation and wet antecedent conditions due to the high sensitivity of drip irrigation to annual precipitation. While it is well-known that the memory effect (also called legacy effect) of nitrogen within entire ecosystems holds for decades (Martin et al., 2021; McMahon et al., 2006; Sebilo et al., 2013), our results indicate that this long-term memory is subject to remarkable year-to-year dynamics in the unsaturated zone. Our results thereby support the importance of considering the transient nature of nitrogen transport processes in modeling studies (Ascott et al., 2021; Kumar et al., 2020; Vero et al., 2018). In contrast to nitrogen, the simulated recharge was not much affected by the wetness conditions of the previous year due to the typically daily to seasonal memory of soil moisture (McColl et al., 2019; Seneviratne et al., 2006; Zhao et al., 2019).

5.2. Implications for irrigation and fertilizer management in a Mediterranean climate

The adaptation of water and fertilizer management will be key to increase the sustainability of agriculture in the coming decades (Dobermann, 2016; Harmanny and Malek, 2019; Iglesias et al., 2012; Sutton et al., 2021). In a Mediterranean climate, such adaptation strategies are implemented in the context of large precipitation variability, a general water scarcity, selected crop varieties and rotations, and a long tradition of irrigated agriculture. Explicitly considering the specific agro-environmental context of the Mediterranean region when designing adaptation strategies is therefore essential (Iglesias et al., 2012; Lassaletta et al., 2021). With the focus on farmer irrigation-fertilizer practices observed in citrus orchards of our study region (inside the Valencian Region), we contribute to an improved understanding of their performance in a representative Mediterranean area. Our findings have three main implications for water management.

First, the choice of an irrigation technique has a considerable impact on groundwater resources, whereby a transformation from flood to drip irrigation reduces both recharge and nitrogen leaching. While it is common in research and practice to assign a fix performance value to an irrigation practice (Bijay-Singh and Craswell, 2021; de Paz and Ramos, 2004; Lassaletta et al., 2021), we encourage the use of a range of values to account for the uncertainty arising from the substantial inter-annual performance differences caused by precipitation variability. Second, our analysis confirms that water management practices have a stronger control on nitrogen leaching than differences in currently used fertilizer schedules (Cavero et al., 2012; Quemada et al., 2013). However, the timing of fertilizer application, such as avoiding inputs before the onset of the rainy months, is key for further reducing the nitrogen leaching risk. Third, recent research highlighted the need to integrate the decade-long legacy of nitrogen application into the design of best management practices (Ascott et al., 2021; Martin et al., 2021; Vero et al., 2018). Our research shows that additionally considering the year-to-year memory of nitrogen storage, e.g., through the inter-annual adaption of fertilizer inputs, could substantially contribute to a more sustainable agriculture and increased groundwater protection.

5.3. Relevance beyond the Valencian Region

This study was conducted at the regional scale, which is the traditional working scale of water authorities. The regional scale allowed us to work with five locally observed irrigation-fertilizer practices representing an average farmer behavior in the study region and providing a frame for further discussion and analysis. With its climatic and agricultural challenges, and the ongoing region-wide irrigation transformation, the Valencian case is paradigmatic for many agricultural areas in the Mediterranean region (Cavero et al., 2012; Cramer et al., 2018; Lassaletta et al., 2021; Perry et al., 2017) and insights gained from this study are likely transferrable to other places with a similar context. However, we acknowledge that differences in farmer's practices regarding irrigation schedules and fertilizer application, and also fertilizer technology and cover crop management can affect recharge and nitrogen leaching (Quan et al., 2021; Quemada et al., 2013; Sharma and Bali, 2017). Given the importance of the timing of irrigation and fertilization in our study area, a systematic testing of different application dates and rates, as extensively done at plot scale (e.g., Alva et al., 2006; Gheysari et al., 2009; Liu et al., 2014; Xu et al., 2020; Yahdjian and Sala, 2010), would be particularly valuable for regional decision-making in Valencia but also any other agricultural area of interest. Furthermore, changes in irrigation and fertilizer management can affect water and nutrient uptake by plants as well as crop yield (Alva et al., 2006; Martínez-Alcántara et al., 2012; Zhang et al., 2018), which are two important factors for the implementation of adaptation strategies (Roy et al., 2021; Sutton et al., 2021) that were not evaluated in this study. In arid and semi-arid regions, irrigation and fertilization can considerably affect crop yield indirectly through secondary salinization resulting from an imbalance between fertilizer application and fertilizer uptake or leaching. A recent global review (Cuevas et al., 2019) of measures to cope with soil salinization revealed an ambivalent relationship between advanced irrigation practices and soil salinization. While drip irrigation enables a more precise timing of fertilizer magnitudes, it can also aggravate soil salinization in arid and semi-arid regions due to reduced leaching rates. In the Valencian Region, soil salinization has so far not become a significant challenge in drip-irrigated orchards due to the good quality of irrigation water, the

common practice of occasional salt flushing (Ortega-Reig et al., 2017), and the intense rainfalls events occurring in fall.

The fifty-year time series of daily meteorological data used in this study covers a much wider range of annual and event precipitation characteristics than typically encountered in observation-based evaluations of agricultural management practices (for recent studies in different continents see e.g., Chilundo et al., 2018; García-Garizábal et al., 2017; Huang et al., 2017; Pfeiffer and Lin, 2014; Sharma et al., 2012). The exceptionally long time span of this study, thereby, enables robust estimates of recharge and nitrogen leaching for the tested irrigation and fertilizer practices. Assuming that future climatic conditions are represented in the historical data, our simulations can be used for rough estimates of future trends in recharge and nitrogen leaching (Stoelzle et al., 2020) to avoid the large uncertainties commonly associated with future projections in semi-arid regions (Blanke et al., 2017; Niraula et al., 2017). While precipitation exerted a strong control on recharge and nitrogen leaching in the past, temperature could be an important factor in the future by influencing crop water demand (Fader et al., 2016; Rodríguez Díaz et al., 2007; Tanasijevic et al., 2014) and nitrogen transformation processes (Doltra et al., 2014; He et al., 2018; Teixeira et al., 2021). The impact of precipitation and temperature on hydrological processes and crop yield is expected to be even larger if their combined effect is evaluated (Cramer et al., 2018; Marcos-Garcia et al., 2017; Zscheischler et al., 2017). In view of the projected future decrease in precipitation and increase in temperature for Mediterranean areas (Ceglar et al., 2019; Cramer et al., 2018; Tuel and Eltahir, 2020), an evaluation of the combined temperature-precipitation effect on the performance of irrigation-fertilizer practices would certainly provide further valuable information for water management.

6. Conclusions

The loss of irrigation water and fertilizer to the groundwater is a common indicator for the performance and sustainability of irrigation and fertilizer practices. In this study, we assessed how sensitive the performance of irrigation-fertilizer practices is to meteorological conditions. We addressed this question using three modeling experiments that quantify the long-term response, the annual sensitivity, and the memory of groundwater recharge and nitrogen leaching under different irrigation-fertilizer practices. The study was conducted in the Valencian Region (eastern Spain), which is one of the major citrus producers in Europe and is in the ongoing process of a transformation from flood to drip irrigation. Our model simulations with fifty years of meteorological data reveal that the long-term performance of irrigation-fertilizer practices is prone to substantial seasonal and year-to-year fluctuations related to precipitation variability. Considering this precipitation variability when developing and evaluating water management strategies can be beneficial in several ways. First, using a range of annual performance values for flood and drip irrigation allows quantifying climate-related uncertainty, which improves the robustness of impact assessments. Second, knowledge on the year-to-year memory of soil nitrogen storage and its dependence on annual precipitation can be used to implement a simple adaptive inter-annual fertilizer management and to reduce nitrogen losses from potential overfertilization in the previous year. Third, long-term observations on the seasonality of precipitation provide important information to refine existing best management practices, in particular the timing of irrigation and fertilizer applications, and thereby provide a simple but effective tool to considerably reduce environmental impacts of intense agriculture.

CRediT authorship contribution statement

Sandra Pool: Conceptualization, Methodology, Software, Formal analysis, Writing - Original Draft, Visualization; **Félix Francés:** Conceptualization, Validation, Writing - Review & Editing; **Alberto Garcia-Prats:** Validation, Writing - Review & Editing, Funding acquisition; **Cristina Puertes:** Conceptualization, Software, Validation, Writing - Review & Editing; **Manuel Pulido-Velazquez:** Conceptualization, Validation, Writing - Review & Editing, Funding acquisition; **Carles Sanchis-Ibor:** Validation, Data Curation, Writing - Review & Editing, Funding acquisition; **Mario Schirmer:** Validation, Writing - Review & Editing, Funding acquisition; **Hong Yang:** Validation, Writing - Review & Editing, Funding acquisition; **Joaquín Jiménez-Martínez:** Conceptualization, Validation, Writing - Review & Editing, Supervision, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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The hydrological modeling software TETIS used to run simulations is available at the Universitat Politècnica de València – Research Group of Hydrological and Environmental Modelling via http://lluvia.dihma.upv.es/EN/software/software.html (Francés et al., 2007; Puertes et al., 2021). The irrigation and fertilizer schedules used as model input are presented in Table S1. Atmospheric deposition of NO_3^- and NH_4^+ used as model input were extracted from the publication of García-Gómez et al. (2014): Fig. 4. Precipitation and temperature data used as model input are available at the University of Cantabria - Santander Meteorology Group: Spain02 v5 via http://www.meteo.unican.es/datasets/spain02 (Herrera et al., 2012, 2016). FAO Penman-Monteith evapotranspiration data used as model input are available at the Instituto Valenciano de Investigaciones Agrarias via http://riegos.ivia.es/datos-meteorologicos (link only available in Spanish; IVIA, 2019). Land use maps used to estimate vegetation related model parameter values are available at the European Environment Agency: CORINE Land Cover Dataset CLC 2012 via https://land.copernicus.eu/pan-european/corine-land-cover (EEA, 2019). Crop coefficients used to estimate vegetation related model parameter values were extracted from the FAO Irrigation and Drainage Paper No 56 (Allen et al., 1998): Tables 11 and 12. Data on soil type and soil properties used to estimate soil related model parameter values are available from the European Soil Database: Topsoil physical properties for Europe, maps of soil chemical properties at European scale, and European soil database derived data via https://esdac.jrc.ec.europa.eu/resource-type/european-soil-database-soil-properties (ESDB, 2019). Geological maps used to estimate aquifer related model parameter values were used from the Instituto Geológico y Minero de España: Maps – Permeability map via http://info.igme.es/cartografiadigital/datos/tematicos/pdfs/Mapa_Permeabilidad_200.pdf and are available upon request (IGME, 2019). The digital elevation model used to estimate topography related model parameter values is available at the Centro Nacional de Información Geográfica: Digital Elevation Models – Digital Terrain Model – DTM200 via http://centrodedescargas.cnig.es/CentroDescargas/locale?request_locale=en (CNIG, 2019).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2022.153805.

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