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RESEARCH ARTICLE

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Hydrological Modeling of the Effect of the Transition From Flood to Drip Irrigation on Groundwater Recharge Using Multi-Objective Calibration

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Key Points:

- We developed a modeling approach to simulate the impacts of a transition from flood to drip irrigation on basin scale groundwater recharge
- Annual recharge was strongly related to annual rainfall, but to a much smaller extent to irrigation practice
- Sensitivity of daily recharge to single precipitation events was stronger in drip irrigation than in flood irrigation

Supporting Information:

Supporting Information may be found in the online version of this article.

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Abstract

The replacement of flood-irrigation systems by drip-irrigation technology has been widely promoted with the aim of a more sustainable use of freshwater resources in irrigated agriculture. However, evidence for an irrigation efficiency paradox emphasizes the need to improve our understanding of the impacts of irrigation transformations on water resources. Here, we developed a distributed hydrological modeling approach to investigate the spatiotemporal effect of flood and drip irrigation on groundwater recharge. The approach recognizes differences in the water balance resulting from the localized application of water in surface drip-irrigated fields and the more extensive application of water in flood irrigation. The approach was applied to the semi-arid Mediterranean region of Valencia (Spain) and calibrated using a multi-objective framework. Multiple process scales were addressed within the framework by considering the annual evaporative index, monthly groundwater level dynamics, and daily soil moisture dynamics. Daily simulations from 1994 to 2015 suggested that, in our hydroclimatic conditions, (a) annual recharge is strongly related to annual rainfall, which had a four times higher impact on recharge than the type of irrigation practice, (b) flood-irrigated recharge tends to exceed drip-irrigated recharge by 10% at annual time scales, (c) however, recharge response to a particular precipitation event is smaller in flood irrigation than in drip irrigation, and (d) 8–18 rainfall events could generate more than half of the annual recharge in drip and flood irrigation, respectively. Our results highlight the importance of understanding the hydrological dynamics under different irrigation practices for supporting irrigation infrastructure policies.

1. Introduction

Irrigated agriculture is the world's major water user accounting for ∼70% of the global freshwater withdrawals (Grafton et al., 2017; S. Siebert et al., 2010) and contributing to about 40% of the food production worldwide (Grafton et al., 2017). Population growth and climate change are expected to increase irrigation water demand, exerting additional pressure on water resources in the future (Kummu et al., 2016; Vörösmarty et al., 2000). In this context, a wide range of technical and economic measures was proposed to address the challenge of future water constraints (Velasco-Muñoz et al., 2019). One of the predominant measures has been the installation of drip-irrigation systems (Perry et al., 2017) that were promoted in many water scarce regions (Molle & Tanouti, 2017; Ortega-Reig et al., 2017; Scott et al., 2014) with the intention to reduce freshwater use.

Much of the knowledge about potential water savings in drip irrigation has been gained from studies conducted at plot scale (Van der Kooij et al., 2013; Venot et al., 2017). Such local experimental and modeling work allowed a detailed assessment of flow paths at the soil-plant-atmosphere interface. Results thereby indicated that a shift from flood to drip irrigation could result in higher crop transpiration and a reduction of soil evaporation and recharge to the saturated zone (Cavero et al., 2012; Jin et al., 2018; Liu et al., 2012;

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Thorenson et al., 2013; Wang et al., 2018). Also, the increased water use efficiency estimated at plot scale has been a strong argument in favor of drip irrigation (Gleick, 2002; Luquet et al., 2005; Postel et al., 2001).

Meanwhile, a large number of observational studies provided evidence that a large-scale implementation of drip irrigation did not necessarily lower the pressure on regional water resources. Instead, the increased efficiency of drip irrigation was often a motivation to increase the irrigated area, to intensify crop production or to grow more water intensive crops. The observed process of an increase in water use despite increasing efficiencies has been called the "rebound effect" (Contor & Taylor, 2013; Molle & Tanouti, 2017; Pfeiffer & Lin, 2014; Scott et al., 2014; Ward & Pulido-Velazquez, 2008). Water saved in agricultural areas by more efficient irrigation technologies was also observed to be reallocated to alternative water users inhibiting a recovery of the freshwater resources (Grafton et al., 2018; Scott et al., 2014). All together this could lead to a reduction of return flows to aquifers and a spatially and temporally displaced negative effect of apparent local water savings on regional water availability (Perry, 2011; Scott et al., 2014; Van Halsema & Vincent, 2012; Ward & Pulido-Velazquez, 2008). These examples highlight the need of an improved understanding of coupled human-water systems with detailed estimates of water fluxes at basin or regional scale to move towards sustainable water resources management.

Numerical models have been used as a tool to complement the existing experimental and observation-driven findings by insights gained at basin and/or multiple time scales. The chosen models ranged from physically based groundwater models coupled to land surface models (Condon & Maxwell, 2014; Tolley et al., 2019), to distributed agro-hydrological models (Pulido-Velazquez et al., 2015; Ren et al., 2019; Zhang et al., 2016), and single cell bucket-type models linked to crop yield and farmer livelihood (O'Keeffe et al., 2018).

Model simulations across the world indicated that generally irrigation (independent of the technology) can substantially reduce streamflow and groundwater levels (Condon & Maxwell, 2014; O'Keeffe et al., 2018; Zhang et al., 2016), even when adapting irrigation practices or cropping patterns to reduce water abstractions (Van Oort et al., 2016; Xiao et al., 2017; Zhang et al., 2018). However, distributed simulation results have suggested that the effects of sprinkler and flood irrigation on groundwater levels and quality can be highly variable within a basin due to local landscape characteristics and the basin wide connectivity of flow paths (Condon & Maxwell, 2014; Ren et al., 2019). While the variability of groundwater levels was shown to be controlled by irrigation inputs and abstractions, model results from Pulido-Velazquez et al. (2015) and Tolley et al. (2019) suggested that the process of groundwater recharge is rather climate dependent. In an attempt to disentangle the effect of flood irrigation and climate on water resources, O'Keeffe et al. (2018) applied a bottom-up approach to develop a framework for coupling human behavior with agronomic and hydrologic processes. Their simulation outputs pointed towards a potentially greater impact of water use behavior than of climate change on groundwater levels. The modeling examples given here addressed a range of irrigation practices, physical processes and socio-economic effects. However, very few studies so far have investigated the basin-scale impact of a transition from flood to drip irrigation on groundwater resources.

Despite the numerous advantages of models, they are still a simplified and imperfect representation of reality and our perception thereof. Regardless of whether their internal parameters have more empirical or physical characteristics, there is typically a need for some sort of calibration to obtain effective parameters (e.g., Barrios & Francés, 2012; Beven, 1995; Francés et al., 2007; Jhorar et al., 2004; Kabat et al., 1997; Vázquez at al., 2002). Calibration of models for systems under changing conditions is a major challenge in hydrology (Dakhlaoui et al., 2017; Fowler et al., 2016; Siswanto & Francés, 2019; Vaze et al., 2010) due to the non-stationarity of parameter values in case that changes in time are substantial compared to input variability (Ceola et al., 2014; Thirel et al., 2015). It was hypothesized that the applicability of a hydrological model in changing conditions could be improved by its calibration against multiple objectives. In fact, the use of multiple streamflow responses was shown to result in more robust and reliable streamflow simulations through the detection of compromise solutions (Efstratiadis & Koutsoyiannis, 2010). The plausibility of internal catchment behavior could be further improved by extending calibration to information on snow cover and glacier mass balance (Finger et al., 2015), streamflow chemistry (Hartmann et al., 2017), solar radiation and evapotranspiration (Hay et al., 2006), or groundwater level (Kelleher et al., 2017; J. Seibert & McDonnell, 2002), among others. However, impaired data (Condon & Maxwell, 2014), as well as the lack of data (especially in case of a multi variable calibration; O'Keeffe et al., 2018) are often a limiting factor when

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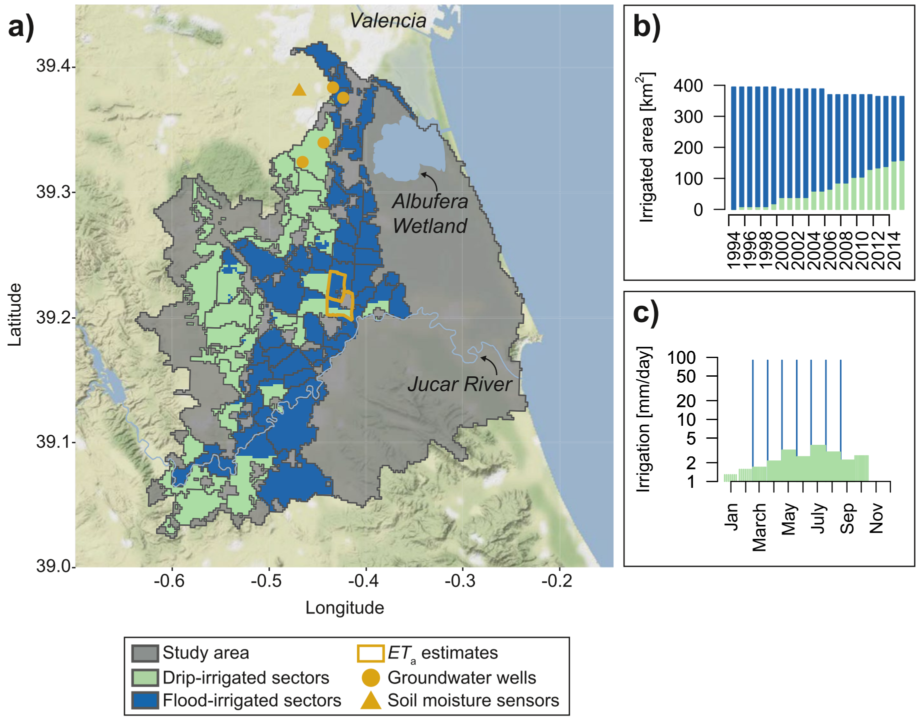

Figure 1. Characterization of the study area. (a) Map with the outline of the modeled study area as well as flood- and drip-irrigated sectors in 2015. The map also indicates the location of field data sites providing information on actual evapotranspiration (ET_a), groundwater level, and soil moisture. The terrain background map was designed by Stamen (2019). (b) Evolution of total, and flood-, and drip-irrigated area during the simulation period from 1994 to 2015. (c) A typical irrigation schedule for flood- and drip-irrigation in the study area.

working with anthropogenically altered basins. Estimating model parameters under changing conditions therefore remains a major challenge to be addressed.

In this study, we investigate how a large scale transformation from flood to drip irrigation, designed to save water, influences the magnitude and timing of groundwater recharge. Using the Valencian Region (Spain) as a case study, we address our research question in three steps: (a) local field observations were used to develop a modeling approach that allowed us to simulate the fundamental differences in water balance between flood and drip irrigation with a spatially distributed hydrological model; (b) the proposed modeling approach was implemented with the hydrological model Tetis (Francés et al., 2007) and model simulations were evaluated in a hierarchical multi-objective calibration framework addressing a range of catchment internal processes; (c) the impact of the gradual irrigation transformation was analyzed at the annual, seasonal, and event scale. Findings of this study can be transferable to other Mediterranean areas as similar climatic conditions, irrigation modernization processes, and environmental challenges are faced in many agricultural areas of the Mediterranean region (Alcolea et al., 2019; Cavero et al., 2012; Molle & Tanouti, 2017; Perry et al., 2017).

2. Study Area

The study area is 913 km^2 in size and covers the aquifer of the Plana de Valencia Sur as well as the adjoining mountain range areas draining into the floodplain of the Jucar River (Figure 1a). The elevation of the study area ranges from sea level to 570 m a.s.l. The subsurface, in particular the shallow part of the aquifer, consists of detrital material with high permeability. The aquifer is an important source of water for the adjacent nationally protected wetland *Albufera*. The study area is characterized by a Mediterranean climate with few and short, but intense rainfall events between September and November and a strong variability in mean annual precipitation (mean of 561 mm, and a range from 306 to 923 mm for the time period 1994–2015). The predominant land use is agricultural fields, though urbanization processes reduced the fraction of agricultural land by 7.5% since 1994. The majority of the agricultural land is cultivated with fruit trees (mainly citrus) and rice fields and a minor area is used to grow a mosaic of crop types.

Here, we focus on the fruit orchards and the adjacent mixed crop areas (382 km^2 in 2015) that are typically located in the flat areas of the former floodplain and that are irrigated by streamflow abstractions from the Jucar River. The area has an almost one thousand year history of irrigated agriculture and has more recently been subject to a gradual modernization of the irrigation system that was publicly subsidized (Sanchis-Ibor et al., 2017). As a result of the irrigation modernization process (Figure 1b), the fraction of surface drip-irrigated fruit orchards gradually increased from 0% in 1994 to 42% in 2015 (information from interviews with irrigation communities; please note that for simplicity, the term drip irrigation will be used throughout this manuscript to refer to surface drip irrigation). The modernization also affected irrigation volumes and frequencies (Figure 1c). In-situ observations from an experimental field site in 2015 (Figure 1a; Ruiz-Rodriguez, 2017) indicate that farmers in the Plana de Valencia Sur irrigate fruit orchards 7 times per year between March and September with 90 mm of water per irrigation shift when using gravity-based irrigation methods (total irrigated depth equaled 630 mm/year). In contrast, the use of drip-irrigation technology requires a more frequent irrigation (every four days to daily) from January to October ranging from 1.3 to 3.8 mm of water per irrigation shift (total irrigated depth equaled 490 mm/year). Farmers in the Plana de Valencia Sur are members of irrigation communities that collectively manage water resources in and between a total of 68 irrigation sectors (Figures 1a and S2). The area of these irrigation sectors ranged from 0.8 to 26 km^2 with a median of 4.5 km^2 in 2015 (CHJ, 2018). The sectors are irrigated by a technician of the irrigation community and farmers have to ask for water before knowing the weather forecast. Hence, irrigation volumes and frequencies do not vary significantly between years. The irrigation schedules observed in 2015, a year with below average rainfall (493 mm), can therefore be considered as representative for the study period 1994–2015.

3. Modeling Approach

3.1. Model Structure and Data Requirement

The daily water balance in the Plana de Valencia Sur was simulated with the hydrological model Tetis. Tetis is a distributed bucket-type model with physically based parameters and a conceptual representation of hydrological processes. Inputs to the model are precipitation and potential evapotranspiration (ET_o) that force fluxes and dynamics in and between a hierarchical sequence of storages. First, precipitation is intercepted until reaching a land cover dependent maximum interception capacity. Excess precipitation then increases soil moisture content from wilting point (θ_{WP}) to field capacity (θ_{FC}). Both the interception storage and the soil moisture storage between θ_{WP} and θ_{FC} are depleted by actual evapotranspiration (ET_a), which is estimated as a function of potential evapotranspiration, available water content, and land cover (single crop coefficient approach according to Allen et al., 1998). Any precipitation exceeding θ_{FC} either runs off as overland flow or infiltrates into deeper soil layers increasing soil water storage between θ_{FC} and saturation (θ_{SAT}). Water in the deeper soil layer becomes subsurface stormflow or percolates (i.e., recharge) into the groundwater storage that sustains the stream with baseflow. Finally, total streamflow is calculated as the sum of overland flow, subsurface stormflow, and baseflow and is routed through the river channel by a geomorphological kinematic wave approach. For the purpose of this study, it is worth noting that the direction of lateral fluxes between pixels is driven by elevation differences. Lateral fluxes due to hydraulic gradients between irrigated and non-irrigated pixels are not modeled. For a more detailed description of the model structure, we refer the reader to Figure S2 and to Francés et al. (2007).

The distributed nature and the physically based parameters of Tetis require a range of spatial data. In this study, the model was run at a spatial scale of 200 m by 200 m and at a daily temporal resolution. Forcing data was extracted from the gridded Spain02 data set (resolution of 10 km by 10 km; Herrera et al., 2012, 2016), whereby potential evapotranspiration was calculated using the Hargreaves-Samani equation (Hargreaves & Samani, 1985) and corrected with local FAO Penman-Monteith estimates from the Valencian Institute of Agricultural Investigations (IVIA, 2019). Land cover data were taken from the CORINE Land Cover data set for the years 1990, 2000, 2006, and 2012 (resolution of 100 m by 100 m; EEA, 2019). Within the CORINE data set, a pixel is defined as a fruit orchard if more than half of its area is cultivated with fruit trees. Soil properties and geological information were retrieved from the European soil database (resolution

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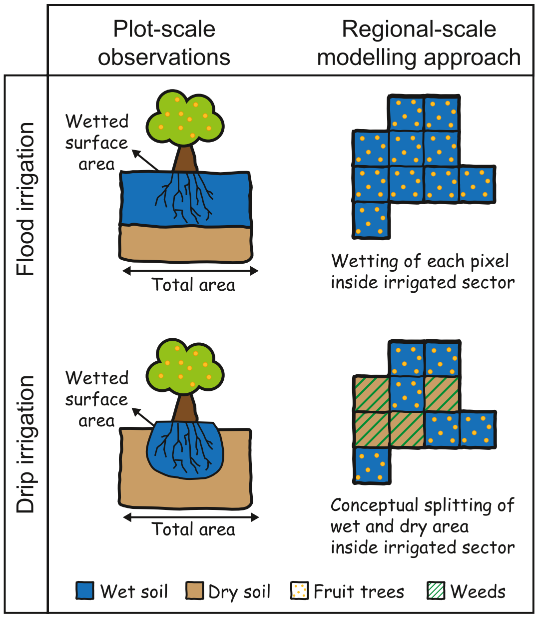

Figure 2. From observations to modeling—representing observed spatial soil wetting patterns in a hydrological model. The left column visualizes the application of water in flood and drip irrigation at the day of irrigation at the individual tree scale. The right column indicates how these field observations were transferred to pixels at the scale of an irrigation sector by pre-processing the distributed model input according to an irrigation practice.

of 500 m by 500 m for physical soil properties and 1 km by 1 km for rooting depth ESDB, 2019), and the Geological Survey of Spain (vector-based data; IGME, 2019), respectively. The ROSETTA Class Average Hydraulic Parameters lookup table (Schaap et al., 2001) was further used to estimate saturated hydraulic conductivity from USDA soil textural classes. Topographic information, such as catchment outlet, river channel location, and the connection of single cells was calculated from a digital elevation model from the Geographical Survey of Spain (resolution of 200 m by 200 m; CNIG, 2019) and a river network shapefile from the Jucar River Basin Authority (CHJ, 2018).

3.2. Modeling Flood and Drip Irrigation in Citrus Orchards

3.2.1. Theoretical Description

To model flood and drip irrigation with a spatially distributed model having pixels larger than the individual tree size, we propose an approach in which model input data in agricultural areas is pre-processed according to the prevailing irrigation technology (Figure 2). The basic entity of the approach is the irrigation sector consisting of n pixels. In flood irrigation, each of these n pixels receives irrigation according to the observed irrigation schedule (see Section 2). ET_a of each pixel is then estimated using the FAO single crop coefficient approach (Equation 1), where ET_o is the potential evapotranspiration (also called reference crop evapotranspiration), K_c is the crop coefficient, and K_s is the water stress coefficient (Allen et al., 1998). Mean ET_a in a flood-irrigated sector is calculated as the mean of all pixels.

$$\mathrm{ET_a} = \mathrm{ET_o} * K_c * K_s \quad (1)$$

In drip irrigation, we propose to conceptually split the n pixels of an irrigation sector into two groups—one group of pixels representing the locally wetted soil surface below citrus trees and another group of pixels representing the dry soil surface, which is typically covered by weeds. Pixels within a drip-irrigation sector are thereby randomly assigned one of the two groups, which creates a homogeneous spatial distribution of wet and dry pixels over the irrigation sector. The total number of pixels for each group was defined according to the fraction of wet soil surface observed in drip-irrigated fields. For each of these pixels, whether it represents the dry or the wet soil surface, ET_a is estimated using Equation 1. Mean ET_a in a drip-irrigated sector is subsequently calculated as the area-weighted mean of wet and dry pixels. It is important to note that ET_a in a drip-irrigation sector is always the combination of both ET_a in dry and wetted soil surface, which is why ET_a has to be interpreted at the scale of an irrigation sector.

The proposed splitting of a drip-irrigated sector into wet and dry pixels introduces a negative bias in mean ET_a (compared to mean ET_a in a flood-irrigated sector) towards ET_a values of dry weed-covered pixels. This bias has to be corrected by adapting the crop coefficients of drip-irrigated citrus and weeds. The adaptation of crop coefficients is based on the assumption that mean ET_a in a flood-irrigated sector equals mean ET_a in a drip-irrigated sector given that identical and optimal environmental conditions (e.g., K_s is one) exist. Based on these assumptions Equation 2 was applied to iteratively determine K_c values of citrus and weeds in drip-irrigated fields. Thereby, n and K_{cf} are the number of pixels and the K_c value of citrus in a flood-irrigated sector, m and K_{cdw} are the number of pixels and the K_c value of citrus in the wet part of a drip-irrigated sector, and p and K_{cdd} are the number of pixels and the K_c value of weeds in the dry part of a drip-irrigated sector.

$$\frac{1}{n}\sum_{i=1}^{n}\mathrm{ET_o}(i) * K_{cf} = \frac{1}{(m+p)}\left(\sum_{i=1}^{m}\mathrm{ET_o}(i) * K_{cdw} + \sum_{i=1}^{p}\mathrm{ET_o}(i) * K_{cdd}\right) \quad (2)$$

It is important to note that the adapted K_c values of citrus and weeds in drip-irrigated fields are not physically real but sensitive to the fraction of wetted soil surface in the drip-irrigated area.

3.2.2. Data for the Practical Implementation

We implemented the proposed approach for modeling flood and drip irrigation using literature values as well as observations and knowledge gained from an experimental field site in the Plana de Valencia Sur (see location with ET_a estimates in Figure 1a). Based on this knowledge, first, the extent of the wet soil bulb in drip-irrigated fields was set to 53% (Ruiz-Rodriguez, 2017). Second, crop coefficients for citrus in flood irrigation were extracted from Allen and Pereira (2009) knowing that the canopy of citrus trees covers about 58% (Ruiz-Rodriguez, 2017) of the soil surface (K_c of 0.8 in the initial development stage; Table S1 for monthly values). Crop coefficients for drip-irrigated citrus (K_c of 1.38 in the initial development stage; Table S1 for monthly values) and weeds (K_c of 0.15 in the initial development stage; Table S1 for monthly values) were adapted, as described in Equation 2, based on the information that the evaporative index (percentage of precipitation and irrigation that evaporates) in flood- and drip-irrigated areas equals 55% and 63%, respectively (Ruiz-Rodriguez, 2017). For simplicity, we assume that weeds are always present although they are occasionally removed. Finally, it was taken into account that the rooting depth of citrus trees varies between flood- and drip-irrigated fruit trees, whereby deeper roots can be expected in flood irrigation than in drip irrigation (100 vs. 70 cm) (Ruiz-Rodriguez, 2017). The rooting depths of weeds was assumed to be 35 cm (e.g., Hu et al., 2018).

3.3. Model Simulations Across Scales

Tetis was used to run spatially distributed simulations from 1994 to 2015 using continuous daily forcing input, typical irrigation schedules, and updated spatial input in years with a change in land use or irrigation technology. The three years prior to the start of the simulation period were used as a warming-up period to ensure suitable initial values of state variables. Monte Carlo runs were performed during the simulation period and served as a basis for the subsequent multi-objective calibration (i.e., the selection of behavioral model parameterizations). The calibration of Tetis is based on the concept of split-parameter structure (Francés et al., 2007), where the effective parameter value at each cell is the product of a point-scale parameter estimate with physical meaning and a global correction factor that is common to all cells. The split-parameter structure acknowledges the spatial variability of parameter values while reducing calibration efforts to the common correction factors. The detailed steps of the model calibration and the subsequent analysis of the results were as follows:

3.3.1. Sampling of Correction Factor Values

One hundred correction factor values were randomly selected within predefined feasible ranges (Francés et al., 2007) for four out of the nine model parameters that are typically calibrated. These four model parameters are the maximum available soil water content from wilting point to field capacity, correction of ET_o, saturated infiltration capacity, and percolation capacity. Each of these four model parameters is associated with vertical fluxes of water in the model. The remaining five model parameters are mainly affecting the shape of the hydrograph, since they allow to calibrate either the lateral fluxes of water or the leakage of groundwater outside the catchment boundary. Given the absence of natural streamflow in the study area, their correction factors were set to default values. Please note that the vertical fluxes are modeled independently of the lateral fluxes and are therefore not affected by the use of default values for the lateral fluxes. Additionally, lateral fluxes in the unsaturated zone are of minor importance due to the flat topography of the study area. Finally, groundwater leakage was neglected, because the aquifer is within the limits of the studied catchment, separated by impermeable materials from the subjacent aquifers, and non-significantly affected by pumping.

3.3.2. Calibration Framework

The model was executed for each of the 100 sets of correction factors and the resulting simulations were evaluated against observed data using a hierarchical calibration framework that considers different process scales. Table 1 provides an overview of the framework with data, metrics and their equations used in calibration.

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Table 1
Model Calibration Framework

	Hydrological aspect	Irrigation aspect	Metric	Abbrev.	Equation	Threshold
Coarse scale	Annual water balance at regional scale	Focus on flood- versus drip-irrigated areas	Evaporative index (%)	R_{ET}	$\frac{\sum_{t=1}^{m} \mathrm{ET}_{\mathrm{a}(t)}}{\sum_{t=1}^{m} P_{(t)} + I_{(t)}} * 100$	Observed R_{ET} +/−10%
Intermediate scale	Monthly groundwater storage dynamics at local scale	Independent of flood and drip irrigation	Spearman rank correlation (−)	$R_{\mathrm{GW\_Corr}}$	$\frac{\sum_{t=1}^{m}\left(R_{\mathrm{obs}(t)} - \bar{R}_{\mathrm{obs}}\right) * \left(R_{\mathrm{sim}(t)} - \bar{R}_{\mathrm{sim}}\right)}{\sqrt{\left(\sum_{t=1}^{m}\left(R_{\mathrm{obs}(t)} - \bar{R}_{\mathrm{obs}}\right)^2\right) * \left(\sum_{t=1}^{m}\left(R_{\mathrm{sim}(t)} - \bar{R}_{\mathrm{sim}}\right)^2\right)}}$	$R_{\mathrm{GW\_Corr}} \geq 0.3$
			Annual amplitude (m.a.s.l.)	$R_{\mathrm{GW\_Amp}}$	$\mathrm{GW}_{\mathrm{max}} - \mathrm{GW}_{\mathrm{min}}$	Observed $R_{\mathrm{GW\_Amp}}$+/−25%
Small scale	Daily soil water storage dynamics at plot scale	Focus on wet and dry parts of drip-irrigated areas	Expert knowledge (−)	R_{SM}	–	Feasibility of simulations: Yes or no

Note. The table lists hydrological and irrigation-related aspects of the calibration as well as the metrics, abbreviations, equations and thresholds used to select behavioral model parameterizations. Abbreviations used in the equations refer to time step t of a time series of length m, observed (obs) and simulated (sim) time series of actual evapotranspiration $\mathrm{ET_a}$, precipitation P, irrigation I and groundwater level GW. R is the rank of time step t within the time series.

The framework starts with an evaluation at the coarsest scale, where the evaporative index (R_{ET}; Table 1) is used to ensure that the regional annual water balance is properly reproduced by the model. For each of the 100 simulations R_{ET} was calculated for each of the 68 irrigation sectors and a mean R_{ET} value was then calculated for flood- and drip-irrigated areas. Estimates of R_{ET} from an experimental site inside the study area in 2015 (Ruiz-Rodriguez, 2017; see location with $\mathrm{ET_a}$ estimates in Figure 1a) were used to evaluate simulated R_{ET} in 2015 for flood and drip irrigated sectors separately. Simulations that resulted in R_{ET} estimates within +/−10% of the expected value, for both flood and drip irrigation, were considered as behavioral and retained for further evaluation at intermediate scale.

At intermediate scale, we used groundwater levels to assess the model's ability for reproducing storage dynamics at the monthly time scale. Two criteria were chosen to describe groundwater dynamics: Spearman rank correlation ($R_{\mathrm{GW\_Corr}}$ [Spearman, 1904]; Table 1) and the annual amplitude in groundwater level ($R_{\mathrm{GW\_Amp}}$ [Heudorfer et al., 2019]; Table 1). Data of four shallow groundwater wells (see location of groundwater wells in Figure 1a; CHJ, 2018) without influence of pumping and monthly observations (from one to five years) were available for model calibration. The observations were compared against an average simulated groundwater level time series from a 5 by 5 matrix around the well location. For the calculation of $R_{\mathrm{GW\_Amp}}$, the water-table fluctuation method was applied (Scanlon et al., 2002), whereby the specific yield of the aquifer was calibrated in a manual iterative process. A mean $R_{\mathrm{GW\_Corr}}$ and $R_{\mathrm{GW\_Amp}}$ score was calculated for each well. The subset of simulations passing the threshold of $R_{\mathrm{GW\_Corr}} \geq 0.3$ (at least moderate correlation; Cohen, 1992) and $R_{\mathrm{GW\_Amp}}$ +/−25% for all wells was subsequently evaluated at the smallest process scale.

The most detailed process scale served to test the realism of daily simulated soil moisture dynamics in wet and dry parts of drip-irrigated fields. Expert knowledge (R_{SM}; Table 1) gained in earlier field research was used to judge the feasibility of the model simulations. This is in strong contrast to the previous steps of the calibration framework, where measurable criteria were used for calibration. However, "soft information" has been shown to be highly valuable when local measurements inside the study area are missing (J. Seibert & McDonnell, 2002). The expert knowledge used here comes from a nearby experimental plot just outside the study area (see location with soil moisture sensors in Figure 1a), where meteorological conditions, soil type, and canopy cover of the citrus trees are comparable with the study area (Ruiz-Rodriguez, 2017). The experimental plot was equipped with soil moisture sensors at 10, 30, 50, and 70 cm depth measuring at a temporal resolution of five minutes (Ruiz-Rodriguez, 2017). To compare these field observations with our model simulations, we calculated daily average soil moisture values over the entire soil profile.

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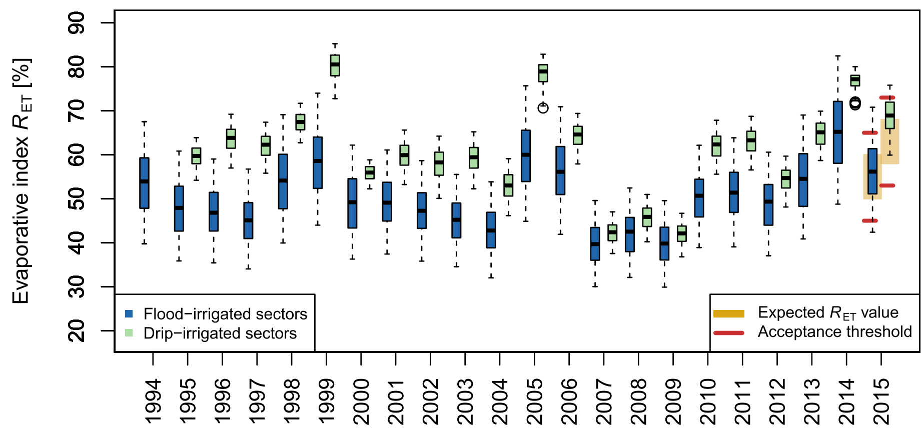

Figure 3. Model calibration at coarse scale using the evaporative index R_{ET}. R_{ET} was calculated for the entire simulation period from 1994 to 2015, but simulations were only evaluated for the year 2015 for which field estimates (expected R_{ET} value) were available. Each boxplot consists of the 100 values from the Monte Carlo simulations, whereby a median R_{ET} of all irrigation sectors was calculated per simulation run.

3.3.3. Recharge Analysis for Evaluating Irrigation Practice Performance

All model parameterizations that resulted in behavioral simulations were used to analyze the simulated recharge magnitudes and variations during the simulation period. The analysis consisted of two steps focusing (a) on recharge trends and their controlling factor in the entire irrigated area, and (b) recharge differences between flood and drip irrigation. In step one, a multiple linear regression was used to estimate the influence of irrigation modernization and annual precipitation on recharge. Equation 2 shows the regression model, which predicts annual recharge y for year i using annual precipitation x_1 and drip-irrigated area x_2 as predictors. The y-intercept β_0 and the regression coefficient β_1 and β_2 were estimated based on the ordinary least squares method resulting in a model error ε (Harrell, 2015):

$$y_i = \beta_0 + \beta_1 * x_{i1} + \beta_2 * x_{i2} + \varepsilon_i \quad (3)$$

The second part of the analysis focused on the difference in groundwater recharge between flood and drip irrigation. As a consequence of the conceptual splitting of wet and dry areas in drip-irrigated sectors, simulations from all pixels inside an irrigation sector had to be averaged, which resulted in a single recharge time series per irrigation sector and accepted simulation. Results were then aggregated for analysis by calculating the mean recharge of all irrigation sectors for each accepted simulation. The aggregation across irrigation sectors allowed to condense information while still acknowledging uncertainties from the model parameterization.

4. Results

4.1. Model Calibration Across Scales

The 100 Monte Carlo simulations were first evaluated at the coarsest process scale using R_{ET} (Figure 3). Simulations of R_{ET} from 1994 to 2015 indicated consistently higher actual evapotranspiration in drip irrigation than in flood irrigation with an average annual difference of 11.2% (for the yearly median). For both irrigation technologies R_{ET} had a high inter-annual variability, whereby the yearly median values tended to fluctuate more for drip irrigation (values from 42.1% to 80.5%) than for flood irrigation (values from 39.7% to 65.2%). Overall, results suggested that the inter-annual variability in R_{ET} was higher than the differences in R_{ET} due to an irrigation technology. Of the initially 100 simulations, there were 75 that resulted in R_{ET} estimates within the acceptance threshold (+/−10% of the reference R_{ET} values) used for selecting behavioral model parameterizations.

The 75 parameterizations that all reproduced the annual water balance to an acceptable degree resulted in surprisingly different simulations of groundwater dynamics (Figure 4a). Taking R_{GW_Corr} as a metric to evaluate modeled groundwater dynamics revealed that only 25 of these parameterizations reproduce the

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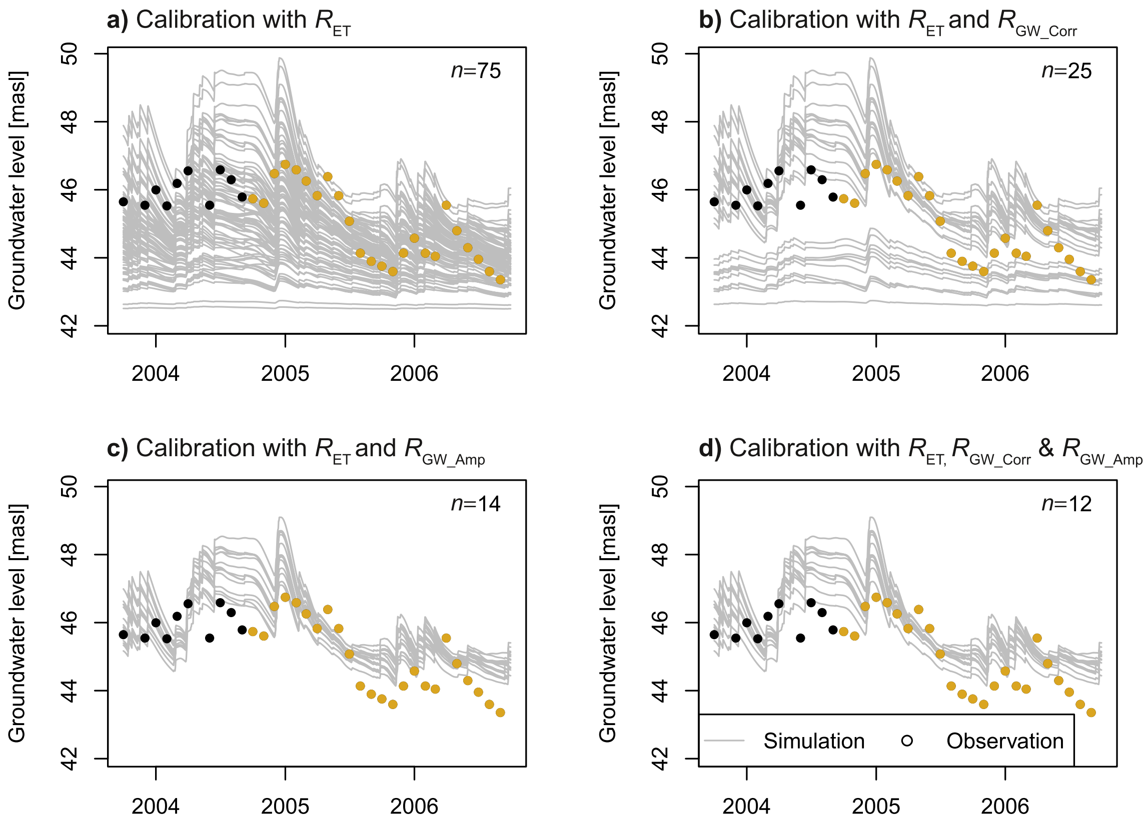

Figure 4. Model calibration at intermediate scale using groundwater level data. The gray lines are simulations that were accepted after applying (a) R_{ET}, (b) R_{ET} and R_{GW_Corr}, (c) R_{ET} and R_{GW_Amp}, and (d) R_{ET}, R_{GW_Corr}, and R_{GW_Amp} (n is the number of accepted simulations). Circles indicate observed groundwater levels, whereby data represented with orange circles were used for calibration.

dynamics to an acceptable degree (Figure 4b). There was a marked difference in the simulated amplitude of groundwater levels within the R_{GW_Corr} subset, which indicates that correlation alone did not necessarily constrain the amplitude aspect of groundwater dynamics. Realistic estimates of the annual amplitude of groundwater levels were fostered by using the calibration criteria R_{GW_Amp} (Figure 4c). Applying only R_{GW_Amp} to the subset of the 75 initial parameterizations reduced their number to 14. Finally, the use of the two groundwater calibration metrics R_{GW_Corr} and R_{GW_Amp} simultaneously led to a selection of 12 acceptable parameterizations (Figure 4d). The selected parameterizations also resulted in reasonable groundwater level simulations for observations not included in calibration (see black points in Figure 4).

In a last step, these 12 simulations were evaluated at small scale in terms of daily soil water dynamics. The lack of local data that could be used for an evaluation with "hard" criteria required a visual inspection of the simulations at the level of a pixel. Although many pixels in the dry and wet area of drip irrigation were reviewed during the analysis, we only present results for two pixels representative for the typical simulated soil water dynamics. Figure 5a points to a marked difference in storage variability between wet and dry parts of drip-irrigated fields. As expected, soil moisture in dry parts was tightly linked to rainfall with an increase in storage at the onset of a rain event and a prolonged storage decrease after the event. Instead, wet parts exhibited a constant change in soil moisture at the frequency of the irrigation schedule, which is especially evident in periods with irregular irrigation events (e.g., spring months). The simulation results are in agreement with soil moisture observations in an experimental irrigation plot outside the study area that indicate that frequent irrigation increases the temporal variability in soil moisture compared to purely rain fed areas (Figure 5b). The generally higher soil water storage observed in the dry parts of drip irrigation that is covered by shallow-rooting weeds was also captured by the model simulations. We therefore concluded that all 12 model parameterizations passed the final reality-check and could therefore be used in the further analysis.

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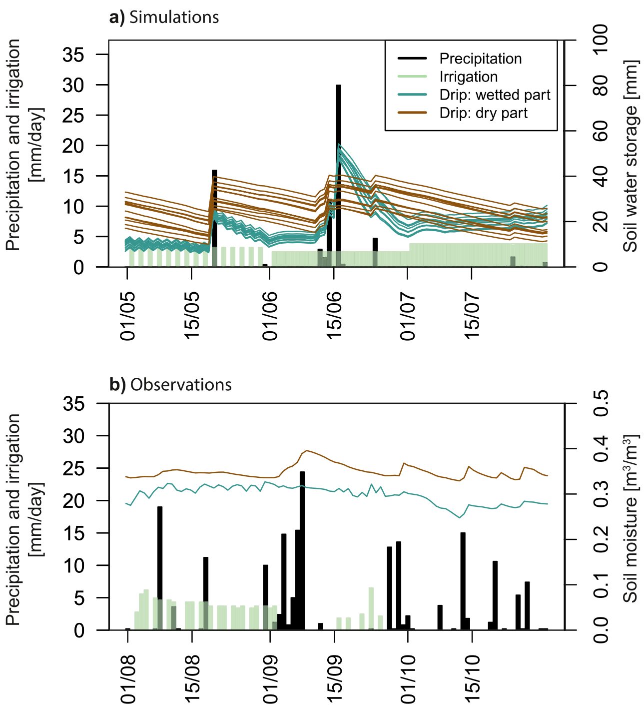

Figure 5. Model calibration at small scale using soil water dynamics (total soil water storage between θ_{WP} and θ_{SAT}). (a) Simulated soil water storage (mm) as a function of precipitation and irrigation for a wet and a dry pixel within a drip-irrigated sector. (b) Observed soil moisture (m^3/m^3) as a function of precipitation and irrigation in an experimental field site close to the study area (see Figure 1a). Simulated and observed time series are shown for the year 2015, however, the time periods do not overlap, because they were chosen to have similar conditions for the comparison of the typical soil water dynamics in drip irrigation. Note that irrigation was only applied to the wet pixel.

4.2. Effect of Flood and Drip Irrigation on Groundwater Recharge

Simulations from the 12 accepted parameterizations were first used to analyze recharge in the Plana de Valencia Sur without distinguishing between flood- and drip-irrigated areas. The median of the 12 simulations indicated a strong variability in annual recharge with values ranging between 112 up to 337 mm and a long-term mean value of 227 mm. Most of this simulated variation (88% according to the multiple linear regression; Table 2) around the mean could be explained by yearly changes in the annual sum of precipitation and the fraction of drip-irrigated area. While both of these predictors significantly contributed in explaining annual recharge variations, it is important to note that precipitation had an almost four times higher impact on annual recharge during the simulation period than irrigation modernization.

Analyzing the annual recharge response for flood- and drip-irrigated areas separately revealed considerable differences between the two irrigation technologies (Figure 6). While annual recharge was highly variable for both irrigation technologies, fluctuations in recharge were much more pronounced for drip irrigation (84–343 mm) than for flood irrigation (132–338 mm). Calculating the mean annual recharge for the entire simulation period suggested that annual recharge for flood irrigation (231 mm) exceeded the one from drip irrigation (210 mm) by about 21 mm, which corresponds to a 10% difference in annual recharge. The cumulative difference in recharge from the first to the last year of the irrigation transformation was 449 mm corresponding to ∼2 years of recharge. This difference in recharge between flood and drip irrigation could be attributed to the fact that recharge within a single year was in 16 out of 20 years higher for flood irrigation than for drip irrigation.

Given that recharge in flood irrigation was not always higher than in drip irrigation raises the question "when can one expect more recharge in drip irrigation than in flood irrigation?" Figure 7a shows that there is a strong correlation between the difference in annual recharge and the total annual precipitation (Spearman rank correlation of −0.83 significant at a 99% level). In years with below-average precipitation, clearly more recharge occurred in flood-irrigated areas than in drip-irrigated areas. With increasing wetness of a year the chance increased that recharge in drip irrigation exceeded the one in flood irrigation. Additionally, independent of the wetness of a year, there was a persistent pattern of seasonality in monthly recharge differences (Figure 7b). During the flood-irrigation season from March to September, clearly more recharge was produced in flood-irrigated areas than in drip-irrigated areas (cumulative difference of 68 mm from March to September). The reverse recharge pattern could be observed in late autumn and throughout the winter months when only drip irrigation was active or when both flood and drip irrigation were entirely ceased (cumulative difference of 27 mm from October to February).

Table 2
Results From the Multiple Linear Regression, Where Annual Recharge was Estimated Using Precipitation and Drip-Irrigated Area

Variable	β-coefficient
Intercept	68.168*** (15.243)
Precipitation	0.317*** (0.025)
Drip-irrigated area	−0.287** (0.084)
Adjusted R-square	0.883
No. of observations	22

Note. The unit for recharge is mm/year, precipitation is mm/year (with a range from 306 to 923 mm), and drip-irrigated area is km^2 (with a range from 0 to 158 km^2).
** and *** indicate the significance levels at 1% and 0%, respectively.
Standard errors are reported in parenthesis.

Finally, recharge behavior was evaluated at daily time scale to gain more detailed insights into the timing and magnitude of recharge. The year 1996, with close to average annual precipitation, was selected to illustrate two typical recharge characteristics that could be noted from the evolution of daily recharge along a year (Figure 8). The first observation is that the timing of recharge production was tightly linked to the timing of rainfall events in case of drip irrigation, which was in stark contrast to flood irrigation, where recharge also occurred during non-rainy days. The second characteristic is that recharge response to a rainfall event tended

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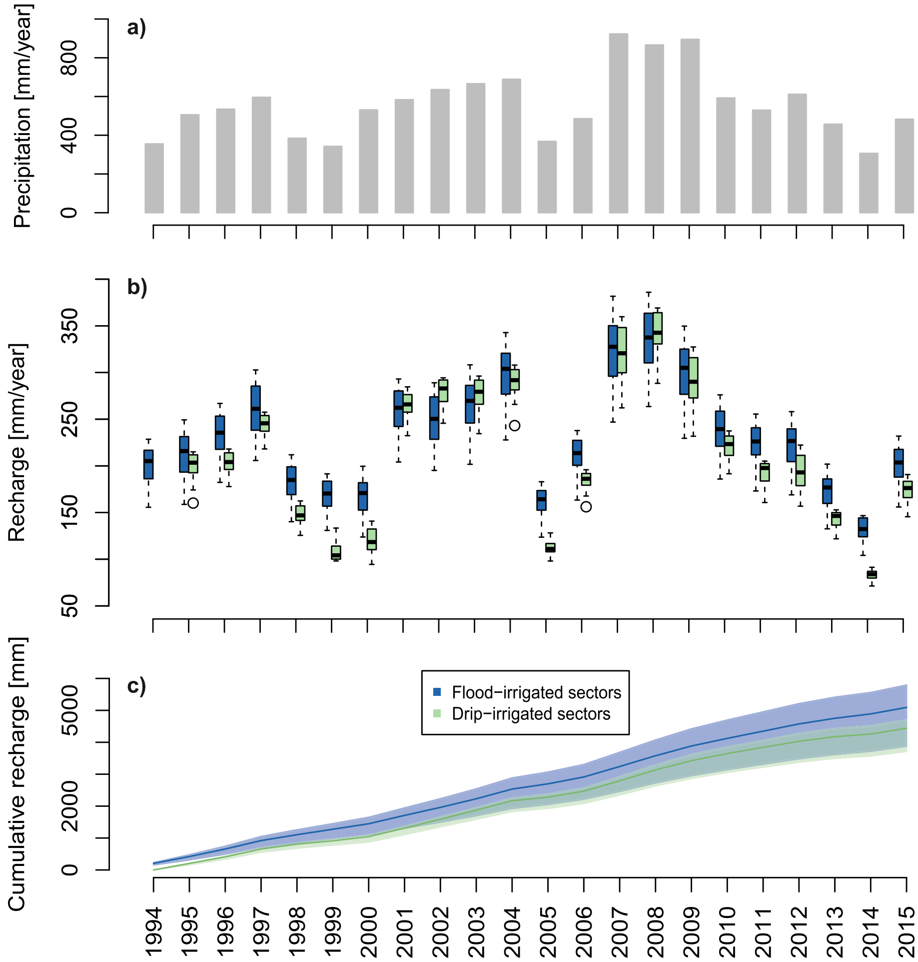

Figure 6. (a) Annual precipitation, (b) annual recharge, and (c) cumulative recharge in flood and drip irrigation. Each boxplot consists of 12 values, whereby each value is the mean of the annual recharge sums of all flood or drip-irrigated sectors calculated from an accepted model parameterization. Similarly, the line and the shaded area of the cumulative plot represent the median, the minimum, and the maximum value of all 12 accepted model parameterizations.

to be stronger in drip-irrigated areas than in flood-irrigated areas, because flood-irrigated areas could accommodate on average 35% more precipitation at the day of rainfall than drip-irrigated areas. These findings were confirmed by the analysis of recharge across all simulation years (Figure 9). Results from all simulation years further indicated that much of the annual recharge (in flood and drip irrigation) could be produced within a few days. The strong dependency of annual recharge on a small number of heavy rainfall events was especially pronounced in drip irrigation, where half of the annual recharge (105 mm) occurred on average within 8 days of a year (Figure 9a). In case of flood irrigation, 18 days were needed on average to generate half of the annual recharge (116 mm; Figure 9a). Moreover, the fact that recharge magnitudes could vary considerably for a given precipitation event size (difference for a given event could range from 4 to 13 mm in flood irrigation and from 5 to 17 mm in drip irrigation) and the observation of a recharge plateau after an initial increase in recharge with increasing precipitation event size points towards a non-linear recharge response in the study area (Figure 9b).

5. Discussion

5.1. Effect of Flood and Drip Irrigation on Groundwater Recharge

Simulation results for the Plana de Valencia Sur indicated a highly variable recharge process with different dynamics and drivers at different time scales. Mean annual recharge of the entire study area varied by

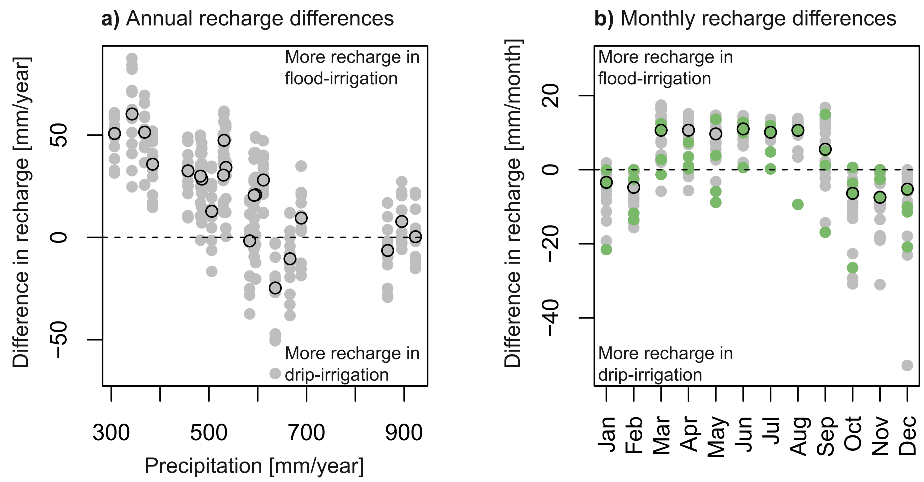

Figure 7. (a) Annual recharge differences in flood and drip irrigation. Differences were calculated between the mean of the annual recharge sums of all flood- or drip-irrigated sectors. Each point represents the difference for one of the 12 accepted model parameterizations in each simulation year. Black circles represent the median of the 12 accepted model parameterizations. (b) Monthly recharge differences in flood and drip irrigation. Differences were calculated between the mean of the monthly recharge sums of all flood- or drip-irrigated sectors. Each point represents the difference for the median of the 12 accepted model parameterizations in each simulation year. Black circles represent the median of the 22 simulation years. Green colored circles indicate the years in which recharge was higher in drip irrigation than in flood irrigation.

almost a factor of 3 between years. Such a variability is a common observation for both irrigated and natural basins located in the Mediterranean region or in semi-arid areas (Cheng et al., 2017; Hornero et al., 2016; Scanlon et al., 2006). The statistical analyses conducted in this study suggested a significant correlation between annual recharge and precipitation, whereas the fraction of drip-irrigated area was of minor importance for explaining annual recharge variability. These findings are in agreement with the conclusions of the studies of Mohan et al. (2018) and Keese et al. (2005) that were conducted with a global data set and a hydrologically diverse data set from the state of Texas (USA). Both studies revealed precipitation as the dominant controlling factor for recharge and suggested that other variables such as soil characteristics or vegetation type were less important than originally expected. In the case of Texas, precipitation alone could explain up to 80% of the inter-annual recharge variability (Keese et al., 2005), which is comparable to our results. A reason for the surprisingly small effect of the irrigation modernization on annual recharge in our

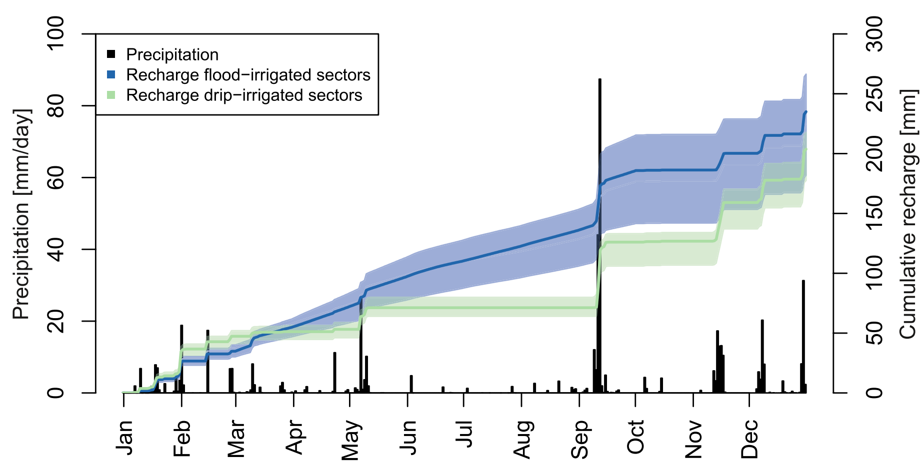

Figure 8. Daily precipitation and cumulative daily recharge in flood and drip irrigation for an example year. The colored lines represent the median value of the 12 accepted model parameterizations, whereas the colored areas represent the minimum and maximum values of the 12 accepted model parameterizations. Data is shown for the year 1996 and corresponds to the mean of the daily recharge of all flood or drip-irrigated sectors.

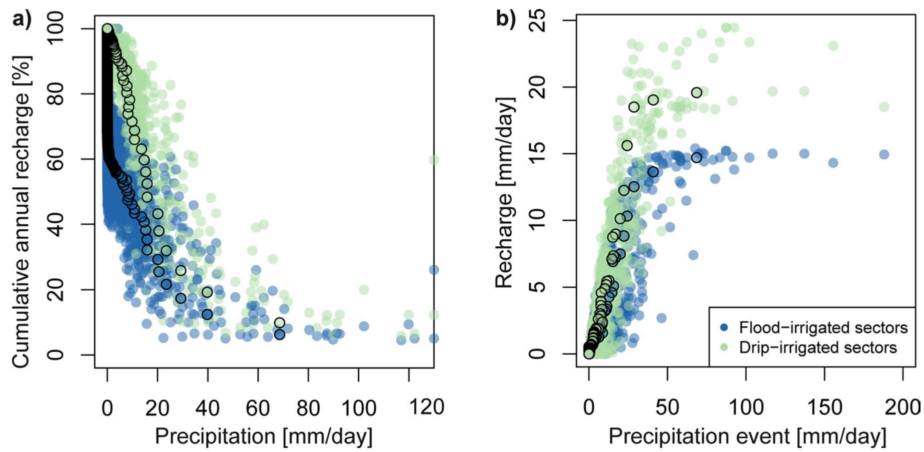

Figure 9. Daily precipitation and daily recharge in flood and drip irrigation for all simulation years. (a) Cumulative annual recharge as a function of daily precipitation. For example, a precipitation event of 68 mm generated 6% of annual recharge in flood-irrigated areas and 10% of annual recharge in drip-irrigated areas. (b) Daily recharge as a function of the precipitation event size. Each point in (a) and (b) represents the mean of the daily value of all flood- or drip irrigated sectors. Daily means were calculated for all years from the median of the 12 accepted model parameterizations. Black circles represent the median of the 22 simulation years. In (a), precipitation events larger than 125 mm were plotted on the *y*-axis at the right side.

study region could be the fact that the fraction of irrigated area using drip irrigation has "only" increased up to 40% along the 22 years of modernization. Given the high precipitation variability, the effect of modernization might become more prominent once the drip-irrigated area is extending towards a 100%. It is, however, important to keep in mind that drip-irrigated area significantly contributed to explaining recharge variability once the effect of precipitation on recharge was filtered out (see previous results of the multiple linear regression analysis in Section 4.2).

The Mediterranean climate is characterized by few intense rainfall events concentrated in fall and winter. The occurrence or non-occurrence of these events in a given year is of high importance for aquifer recharge as much of it can be generated by a few single rainfall events (Cheng et al., 2017; Poch-Massegú et al., 2014; Vallet-Coulomb et al., 2017). Our results confirmed this observation and additionally provided evidence that the sensitivity of annual recharge to single events was stronger in drip irrigation than in flood irrigation. In particular, recharge rates for a given rainfall intensity tended to be higher in drip-irrigated fields than in flood-irrigated fields. One possible explanation for these differences could be differences in soil properties, such as the soil textural class and the saturated hydraulic conductivity. The predominant soil textural classes encountered in our study area are clay-loam and loam (Figure S3) and their close characteristics and similar distribution in flood- and drip-irrigated sectors should not significantly influence our results. While saturated hydraulic conductivity varies greatly across the study region (0.0416–4,166 mm/day), there are no marked differences in the distribution of these values between flood- and drip-irrigated fields. Instead, the generally lower storage potential of soils under drip irrigation during rainy days could provide an explanation for the higher recharge rates in drip irrigation than in flood irrigation during an identical rainfall event. This finding is in line with observations and plot-scale simulations from experimental field sites in Spain, which indicated that the permanently high soil moisture content in drip-irrigated fields could enhance recharge response to rainfall (Jiménez-Martínez et al., 2010; Poch-Massegú et al., 2014). Marked differences in soil moisture content resulting from a particular irrigation schedule could therefore provide an explanation for the difference of our simulated recharge rates in flood and drip irrigation during an identical rainfall event.

The effect of soil moisture on recharge probably also manifested itself at the annual time scale. For example, increasing annual precipitation—usually linked to a higher number of intense rainfall events—could increase annual recharge in drip irrigation to the point where it exceeded the one in flood irrigation.

The different irrigation schedule in flood and drip irrigation not only affected the temporal evolution of soil moisture, but also its spatial distribution. In flood irrigation, it is common to cover the water demand of single fields at different days. Therefore, at a given day with rainfall, only a fraction of the fields will be watered, which further reduces the potential of recharge in flood-irrigated sectors compared to drip-irrigated sectors. At first sight, our findings might be contradictory with the prevailing concept of the high efficiency of drip irrigation. However, we would argue that they rather highlight the complex and spatiotemporally dynamic nature of the groundwater recharge process in irrigated areas.

5.2. Model Development

In this study, we presented an approach to model the water balance for flood- and drip-irrigated fields at regional scale. It was developed in a bottom-up approach, informed by field knowledge about flood and drip irrigation in a citrus orchard in the Plana de Valencia Sur. These field observations indicated that the localized application of water in drip irrigation substantially reduces the wetted soil volume compared to flood irrigation (Ruiz-Rodriguez, 2017), which affects the relative contribution of soil evaporation and plant transpiration to actual evapotranspiration (Allen et al., 1998). The fraction of wetted soil volume is therefore a crucial element when modeling the daily water balance in drip-irrigated fields.

Hydrological models commonly applied for basin-scale irrigation studies (Ren et al., 2019) typically don't consider the fractional wetting of soils as a function of irrigation practice in the model structure. While this is unproblematic when modeling flood and sprinkler irrigation, it can bias hydrologic simulations in case of drip-irrigation. Our proposed modeling approach therefore closes a research gap by providing a simple way to pre-process the spatially distributed input information according to an irrigation practice. The approach has some advantages that facilitate its transferability to other places: it doesn't require additional input data, except for the fraction of wetted area in drip irrigation for a given crop type; technically it can be applied at various spatial scales; and it is relatively independent of the chosen hydrological model structure.

However, the conceptual splitting of a drip-irrigated sector into dry and wet pixels limits the scale of interpretation to the area of an irrigation sector. We further acknowledge that the translation of the spatial wetting pattern observed at plot-scale to the scale of model pixels, which in our case have a resolution of 200 m by 200 m, is a strong simplification of reality. Also, knowing the high temporal dynamics of Mediterranean catchments (Merheb et al., 2016) and the importance of soil moisture processes for recharge generation, simulations at an hourly time step could have provided additional insights into the recharge process at sub-event scale.

As stated by Paola and Leeder (2011), essentially improving our understanding through modeling requires simplification and the willingness to be wrong. With this, we fully acknowledge that our modeling approach is a simplification of reality and recognize the uncertainties inherently related to that. Yet, the proposed modeling approach allowed us to gain novel insights into the spatiotemporal dynamics of recharge in flood and drip irrigation.

5.3. Model Calibration Under Changing Land Use Conditions

The options for estimating the parameter values for the model itself were largely influenced by the quantity and quality of hydrological information available at regional scale. The availability of information on the evaporative index, groundwater level and soil moisture allowed us to conduct a multi-variable calibration approach in which model internal fluxes and state variables were evaluated at different time scales. Results not presented here demonstrated that the evaporative index and groundwater level provided information to constrain different regions of the parameter space. The use of multiple variables thereby greatly decreased the initially 100 parameter sets to a final set of 12 acceptable parameterizations. Similar findings were reported by Kelleher et al. (2017) and indicate the significant value of multi-variable calibration for parameter estimation. Even though such a multi-variable calibration seems to be a promising tool towards more robust model calibrations (Efstratiadis & Koutsoyiannis, 2010; Hartmann et al., 2017; Kelleher et al., 2017), it remains uncertain how robust parameter estimates are in catchments with changing conditions when estimated from short discontinuous time series.

Indeed, the lack of unimpaired continuous long-term time series for the Plana de Valencia Sur put considerable constraints on the choice of calibration metrics. Furthermore, the fact that the soil moisture data used in this study was not measured inside the modeled area limited its use for constraining parameter values. On the other hand, using the soil moisture data in a “soft” way still provided valuable information for a rough reality-check of simulated soil water dynamics in wet and dry soil areas of drip-irrigated fields. As demonstrated in previous studies, soft data (J. Seibert & McDonnell, 2002) or short discontinuous time series (Perrin et al., 2007; Pool et al., 2017; Singh & Bárdossy, 2012) could provide surprisingly valuable information for model calibration. Making the most out of data is most likely better than neglecting information and it forces a modeler to move beyond blindly matching simulations against observations.

The challenging data situation in the Plana de Valencia Sur is not uncommon for anthropogenically altered basins. Data in agricultural basins was reported to be a major constraint for model evaluation in O'Keeffe et al. (2018) and even prevented any calibration of model parameters in Condon and Maxwell (2014). Here, one of the major limitations due to the absence of long time series was that we could not conduct a classical split-sample test needed to test the model's performance in situations different from the calibration period (Klemeš, 1986). This is certainly increasing the uncertainty of the reported absolute recharge values. However, the relative recharge values, that is, recharge difference between flood and drip irrigation, are likely less affected by the lack of a validation period.

5.4. Relevance of our Findings in the Context of Water Management in Mediterranean Regions

The effectiveness of drip irrigation as a tool to improve the state of freshwater resources in agricultural regions is highly debated. With this study, we contributed to this ongoing debate by evaluating the effect of flood and drip irrigation from the perspective of regional groundwater recharge. Results provided evidence that the introduction of drip irrigation in the Plana de Valencia Sur is so far less decisive for the annual groundwater balance than the extreme variability in annual precipitation between years. In contrast, the change in irrigation practice was considerably modifying the seasonal recharge fluxes independent of the wetness of a year. While drip irrigation increased recharge during the rainy fall and winter months, flood irrigation sustained groundwater recharge during the dry summer period, when coastal wetlands rely most on sufficient discharge from the aquifer.

Reliable predictions of groundwater recharge are highly important for water management, especially in semi-arid areas, where water supply during dry periods often depends on groundwater resources. Our results indicated that the sensitivity of recharge in drip-irrigated fields to the occurrence of (a few) rain events make annual recharge predictions in drip-irrigated areas highly uncertain. In contrast, excess irrigation in flood irrigation could lead to slightly more constant recharge in flood-irrigated areas. The important role of flood irrigation for maintaining groundwater levels, especially in regions characterized by large precipitation variability, was also highlighted in Scanlon et al. (2006) and Vallet-Coulomb et al. (2017). Therefore, the planned increase in drip-irrigated area in the Plana de Valencia Sur could further increase the region's vulnerability in terms of groundwater recharge.

The level of detail at which information about irrigation practices and their change over time was used in this study is uncommon for agricultural areas. This certainly enhances the relevance of the results for the management of water resources in the Plana de Valencia Sur. Yet, the situation of the Plana de Valencia Sur is representative for many agricultural areas in the circum-Mediterranean region. Findings presented here could therefore be a common characteristic of regions with similar hydroclimatic conditions.

The study was a first step towards evaluating the effects of the irrigation modernization on regional groundwater recharge dynamics in the Plana de Valencia Sur. Further research could address the quality of recharged groundwater, which is an essential criterion for its environmental value. It is generally well known that extensive irrigation can lead to widespread groundwater quality degradation through the mobilization and flushing of naturally accumulated salts in the unsaturated zone (Scanlon et al., 2006) or the leakage of fertilizers (Poch-Massegú et al., 2014). Yet, results are still inconsistent when evaluating the effect of irrigation practice on water quality (García-Garizábal & Causapé, 2010; Poch-Massegú et al., 2014).

An improved understanding of the relationship between modernization, hydrological processes and the health of groundwater dependent coastal wetlands is critical in view of the future modernization plans for the Plana de Valencia Sur. While the current study evaluated the effect of the modernization in the past, the planned future increase in drip-irrigated area will be embedded in a different climatic and socio-economic context. Water management will become even more challenging under these changing conditions and an improved understanding of future recharge dynamics could substantially contribute to decrease uncertainties in decision-making.

6. Concluding Remarks

This study assessed the effect of a transition from flood to surface drip irrigation on the dynamics of regional groundwater recharge in agricultural areas. The assessment was based on a distributed modeling approach, informed by local field knowledge and developed to explicitly account for peculiarities in the water balance of different irrigation practices. The proposed approach makes use of information about the spatial distribution of irrigation practices to pre-process model input information accordingly. We believe that the simplicity of the approach along with the low demand for additional input data and the applicability to other distributed hydrological models facilitate its transferability to other places.

We applied the proposed approach to the region of the Plana de Valencia Sur (Spain), which has a long history of irrigated agriculture. As it is common in agricultural basins, the absence of (unimpaired) continuous long-term time series of hydrological variables created a challenging context for estimating model parameters. Our findings indicated that information of multiple variables can be highly valuable for evaluating model internal fluxes and state variables even if the information is considered as suboptimal in terms of the length of the time series. While these findings are encouraging, it remains uncertain how robust parameter estimates are in basins with changing conditions when estimated from short discontinuous time series.

Our work suggested that groundwater recharge in agricultural areas is a complex process resulting from the temporally dynamic interplay between irrigation practice, soil moisture and precipitation. As a consequence, the influence of flood and drip irrigation on groundwater recharge is highly variable at different time scales. Our results therefore highlight the importance of carefully assessing the effects of irrigation modernization on groundwater recharge at multiple temporal scales. Although our findings are limited to the Mediterranean region and remain to be confirmed for other agricultural areas, we recommend to explicitly integrate irrigation practice in hydrological models to ultimately better inform water management. This is especially important in view of the uncertainties and risks related to future changes in the precipitation regime and the socio-economic context.

Data Availability Statement

The authors further thank AEMET and UC for the data provided for this work (Spain02 v5 data set, available at http://www.meteo.unican.es/datasets/spain02).

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