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From Flood to Drip Irrigation Under Climate Change: Impacts on Evapotranspiration and Groundwater Recharge in the Mediterranean Region of Valencia (Spain)

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Key Points:

- In the Mediterranean region of Valencia, climate change is expected to significantly reduce groundwater recharge in irrigated agriculture
- Actual evapotranspiration could increase in flood irrigation but decrease in drip irrigation under *business as usual* irrigation volumes
- The ongoing irrigation transition in Mediterranean areas may have a greater impact on evapotranspiration and recharge than climate change

Supporting Information:

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

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Abstract Agricultural irrigation is the major water consumer in the Mediterranean region. In response to the growing pressure on freshwater resources, more efficient irrigation technologies have been widely promoted. In this study, we assess the impact of the ongoing transition from flood to drip irrigation on future hydroclimatic regimes under various climate change scenarios, with a particular focus on actual evapotranspiration and groundwater recharge in the Mediterranean region of Valencia, Spain. Hydroclimatic predictions for the near-term future (2020–2049) and the mid-term future (2045–2074) were made under two emission scenarios (RCP 4.5 and RCP 8.5) using a hydrological model that was forced with data from five GCM-RCM combinations and field-based irrigation volume and frequency observations. Our findings suggest that climate change could lead to statistically significant changes in the regional hydroclimatic regime despite projection uncertainties. Major changes include a statistically significant decrease in mean groundwater recharge of up to −6.6% under flood irrigation and −9.3% under drip irrigation and contrasting changes in mean actual evapotranspiration for flood and drip irrigation in the order of +1% and −2.1%, respectively. Since sustainably available water resources in the Valencia region are entirely allocated, the expected changes and associated uncertainties create a challenging context for future water management. Our simulations further indicate that, rather than climate change, the choice of irrigation technique may have a greater impact on actual evapotranspiration and groundwater recharge. Our findings therefore highlight the importance of considering both climate change and irrigation technique when assessing future water resources in irrigated Mediterranean agriculture.

Plain Language Summary Agricultural irrigation is the major water consumer in the Mediterranean region. Climate change is expected to add additional pressure on water resources as precipitation might decrease and the occurrence of droughts might increase. To improve the resilience to water scarcity, governments in many regions are promoting a transformation from flood to drip irrigation. In this study, we assess the relative role of irrigation techniques and climate change for the availability of future water resources in Valencia (Spain). We thereby combine multiple future climate projections with a hydrological model, and with field-based irrigation volume and frequency observations. Our findings suggest that climate change could lead to significant changes in actual evapotranspiration and groundwater recharge. However, the choice of an irrigation technique may have a greater impact on actual evapotranspiration and groundwater recharge than climate change itself. We therefore highly recommend to consider both climate change and irrigation technique when assessing future water resources in irrigated Mediterranean agriculture.

1. Introduction

Irrigated agriculture contributes to approximately 40% of the global food production and is the world's major water consumer, accounting for about 70% of the total freshwater withdrawals (Grafton et al., 2017; Siebert et al., 2010). The demand for irrigation water is expected to increase in the future due to the combined effect of continued population growth and climate change (Fischer et al., 2007; Schlosser et al., 2014; Vörösmarty et al., 2000). Increased frequency and intensity of climate extremes (in particular droughts) will likely heighten the importance of groundwater as a reliable source for water supply (Taylor et al., 2013). Therefore, understanding both future climatic regimes (Konapala et al., 2020) as well as the temporal distribution of groundwater recharge (Green et al., 2011; Smerdon, 2017) is crucial for long-term water resources management.

Climate change may affect groundwater recharge in two ways. First, directly through natural replenishment from precipitation or leakage from surface waters, and second, indirectly through changes related to vegetation responses or land use changes (Holman et al., 2012; Taylor et al., 2013). Many large-scale studies reported a decreasing trend in recharge over large areas as a direct consequence of climate change (Crosbie et al., 2013; Döll, 2009; Meixner et al., 2016; Niraula et al., 2017). However, the expected recharge response to climate change varies spatially with pronounced reductions in semi-arid areas and increases in humid regions (Döll, 2009; Green et al., 2011; Kurylyk & MacQuarrie, 2013; Meixner et al., 2016; M. Pulido-Velazquez et al., 2015). Locally, these estimates of future recharge often disagree in the magnitude and the sign of change due to uncertainties in projected precipitation (Crosbie et al., 2011; Kurylyk & MacQuarrie, 2013; Ng et al., 2010; Niraula et al., 2017).

Indirect effects of climate change on recharge in agricultural areas are further complicated by uncertainties related to future irrigation water demands (Cramer et al., 2018; Fader et al., 2016; Falloon & Betts, 2010) and irrigation application. Consequently, climate change impacts can range from a reduction in recharge due to reduced precipitation or higher actual evapotranspiration rates (Lauffenburger et al., 2018; M. Pulido-Velazquez et al., 2015) to an increase in recharge as a result of raising irrigation volumes (Hanson et al., 2012; Meixner et al., 2016). Future recharge may additionally be affected by a transformation toward more efficient irrigation technologies. Findings from experimental field sites and small-scale modeling typically suggest that recharge is reduced when changing from flood to drip irrigation (Cavero et al., 2012; Jin et al., 2018; Liu et al., 2012; Thorenson et al., 2013; Wang et al., 2018). However, basin-scale studies provided evidence for an irrigation efficiency paradox indicating that local water savings do not necessarily improve water availability at larger scales (Contor & Taylor, 2013; Grafton et al., 2018; Molle & Tanouti, 2017; Pfeiffer & Lin, 2014; Scott et al., 2014; Ward & Pulido-Velazquez, 2008). The diverging findings of these studies highlight the need for a deeper understanding of the controls of irrigation techniques and climate on recharge.

Future sustainable water management will become particularly challenging in the Mediterranean area as existing environmental problems are intensified by the high rates of climate change (Ceglar et al., 2019; Cramer et al., 2018). Within the Mediterranean area, the Jucar River Basin in Eastern Spain (about 22,000 km^2) is among the most water scarce watersheds (Cramer et al., 2018). The majority of the surface water and groundwater resources of the Jucar River Basin available for a sustainable use are fully allocated. Irrigated agriculture is the main water user and receives 87% of the total freshwater withdrawals, whereas the domestic and industrial sectors only account for about 10% and 3% of the total water use. The source of water varies regionally within the basin (CHJ, 2014). The availability of these freshwater resources will likely be affected by future climate change. Higher annual mean temperatures combined with a decrease in annual precipitation are expected to reduce streamflow by 2%–20% in the near future and up to 50% on long term (Chirivella Osma et al., 2015; Ferrer et al., 2012; Marcos-Garcia & Pulido-Velázquez, 2017). The pronounced reduction of summer precipitation along with increased actual evapotranspiration rates could additionally result in longer and more intense meteorological and hydrological droughts (Marcos-Garcia et al., 2017). The Valencia region is located at the floodplain of the Jucar River and is one of the major citrus producing regions in Europe (European Commission, 2018; MAPA, 2019). In response to the growing pressure on water resources, the regional government of Valencia approved a plan for the modernization of irrigation systems in 1995 (Sanchis-Ibor et al., 2017). The still ongoing change from flood to surface drip irrigation had a temporally variable effect on recharge that resulted from the interplay between irrigation technique, soil moisture, and precipitation (Pool et al., 2020). Predictions of future water availability under flood and

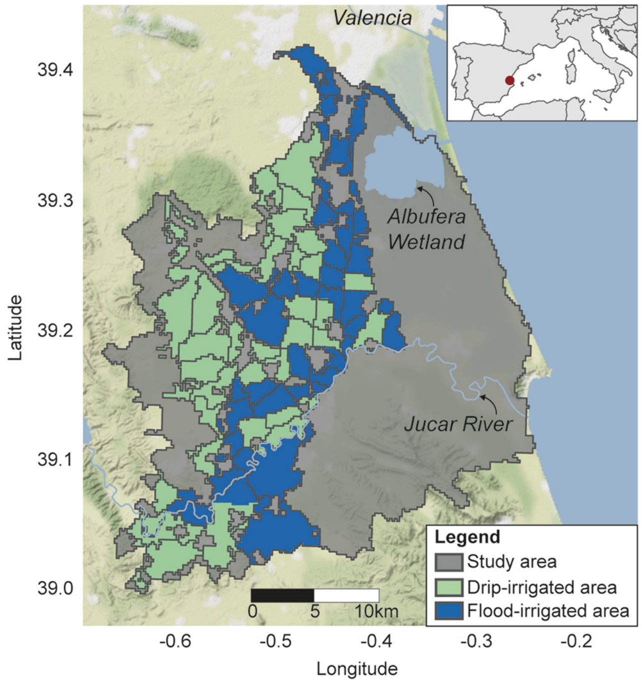

Figure 1. Location and characteristics of the study area. The map shows the geographical outline of the study area and the 68 irrigation sectors. The spatial distribution of drip- and flood-irrigated area (mostly citrus orchards) corresponds to the situation in 2020. The inset map indicates the location of the study area (red point) within the western Mediterranean region. The terrain background map was designed by Stamen (2019).

drip irrigation will be highly valuable for informing future modernization plans in the Valencia region.

The present study aims to contribute to an improved understanding of future hydroclimatic regimes in flood and drip irrigated agriculture. The study is conducted in the Mediterranean region of Valencia, where water scarcity, intense agriculture, and a region-wide transformation of irrigation systems provide an excellent context to address the following research questions:

(a) What is the effect of climate change on future hydroclimatic regimes in irrigated Mediterranean agriculture?
(b) What are the consequences of irrigation technique transformation (i.e., transformation from flood to surface drip irrigation) on future hydroclimatic regimes?
(c) How is the future regional hydroclimate affected by the modernization plans of Valencia for the next 10 yr?

While these research questions will be investigated with a focus on the Valencia Region, similar climatic and agricultural conditions can be found in many regions around the world. In fact, advanced and more efficient irrigation technologies have been promoted globally (Grafton et al., 2018) and implemented in many arid and semi-arid regions (Cavero et al., 2012; Harmanny & Malek, 2019; Molle & Tanouti, 2017; Pfeiffer & Lin, 2014; Scott et al., 2014). While results for the third research question will be particularly relevant for the region of Valencia, findings for the first two research questions will likely be transferrable to other agricultural areas with comparable climate.

2. Study Area

The study area is located in the agricultural region south of the city of Valencia in Eastern Spain (Figure 1). The area has a size of 913 km^2 and is characterized by a gentle topography with elevations ranging from sea level to 570 m a.s.l. The region encompasses the mountainous subcatchments draining into the flood plain of the Jucar River as well as the aquifer of the Plana de Valencia Sur, which are hydrologically connected to the protected Albufera coastal wetland. Soils within the agricultural area are classified as loam or clay-loam, whereby the lack of tillage in citrus orchards reduces the presence of macropores to the top few centimeters minimizing the potential for fast preferential flow paths. The natural availability of water resources is dominated by the prevailing semi-arid Mediterranean climate with a concentration of a few, but intense rainfall events in September and November, and a lack of notable precipitation during the summer months. The high variability in mean annual precipitation (mean of 568 mm and a range from 375 to 750 mm for the period 1971–2000) results in the frequent occurrence of dry spells (Marcos-Garcia et al., 2017).

To improve the resilience to water scarcity, both the national and the regional governments have promoted the modernization of the irrigation system in the fruit orchards (mostly citrus) of the Plana de Valencia Sur (Ortega-Reig et al., 2017; Sanchis-Ibor et al., 2017). The modernization process, which prioritized irrigation pressurization, has been largely led by water user associations that collectively manage irrigation infrastructure and water resources in 68 irrigation sectors (total area equals 419 km^2). The process of replacing flood irrigation by surface drip irrigation started in the beginning of the 1990s decade, and since then the fraction of drip-irrigated area has gradually increased to 52% in 2020. Future modernization plans include the expansion of drip irrigation systems to 85% of this area by 2030 (Servicio de Regadíos, 2020). In contrast to flood and drip irrigation, sprinkler irrigation was not practiced in the past and is not part of the future modernization plans because 90% of the study area is cultivated with citrus orchards.

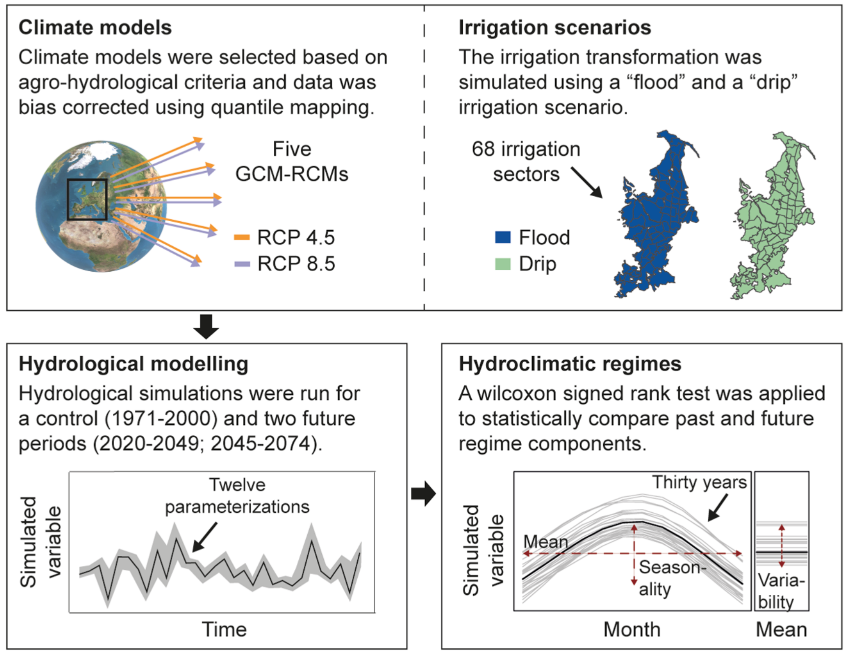

Figure 2. Overview of the study framework. Future changes in hydroclimatic regimes (defined by their mean, seasonality, and variability) in drip- and flood-irrigated agriculture were assessed using 5 climate models (GRCM-RCMs), 2 greenhouse gas emission scenarios (RCP 4.5 and RCP 8.5), 1 bias correction method, and 12 parameterizations of a hydrological model.

As a consequence of the changing irrigation techniques, annual irrigation volumes for citrus orchards could be reduced from approximately 630 mm/yr in flood-irrigated sectors to approximately 490 mm/yr in drip-irrigated sectors (Ruiz-Rodríguez, 2017). The main source of water for irrigation are streamflow withdrawals from the Jucar River, whereas groundwater contributions to annual irrigation volumes usually do not exceed 2%.The importance of groundwater increases during severe droughts when up to 16% of the annual irrigation water is extracted from the regional aquifer. The intense agriculture and the use of fertilizer led to high levels of nitrate concentrations in the groundwater (Lidón et al., 2013). The regional groundwater is therefore only marginally used to supply the domestic and industrial sector. However, the aquifer is of high environmental importance because of its direct connection with the Albufera coastal wetland. While agriculture has clearly impaired groundwater quality, soil salinization has not become a significant challenge due to the intense rainfalls occurring in fall.

3. Data and Methods

Future changes in the hydroclimatic regimes of the irrigated agricultural area were projected by a chain of models that included 2 greenhouse gas emission scenarios (RCPs; Representative Concentration Pathways), 5 GCM-RCM combinations (Global Circulation Models—Regional Climate Models), 1 bias correction method, 1 hydrological model with 12 parameterizations, and 2 irrigation scenarios. The subsequent sections provide a detailed description of the different elements of the modeling chain and how the output of the modeling chain was analyzed (see also Figure 2).

3.1. Climate Models

3.1.1. GCM-RCM Forcing Data

Past and future GCM-RCM time series were retrieved from the Coordinated Regional Downscaling Experiment for Europe (EURO-CORDEX; https://www.euro-cordex.net/). The GCM-RCM data used in this study include daily precipitation, and daily minimum and maximum temperature simulated at a spatial resolution of 0.11° during a control period (1971–2000), the near-term future (2020–2049), and the mid-term future (2045–2074). Future projections used in this study correspond to RCP 4.5 and RCP 8.5, which represent a stabilization of CO_2 emissions by 2040 and a continued CO_2 emission throughout the 21st century, respectively (Meinshausen et al., 2011). Past and future (bias-corrected) temperature data were additionally used to create potential evapotranspiration time series. Potential evapotranspiration was estimated with the Hargreaves–Samani equation (Hargreaves & Samani, 1985) and corrected using local Penman-Monteith estimates (IVIA, 2019).

3.1.2. GCM-RCM Selection

The number of GCM-RMCs used in this study had to be restricted due to computational constraints related to the distributed nature of the hydrological model (see Section 3.2). From the initial set of 19 GCM-RMCs available from the EURO-CORDEX project, we selected five climate models (ICHEC-EC-EARTH—CCLM4-8-17, ICHEC-EC-EARTH—HIRHAM5, MPI-M-MPI-ESM-LR—CCLM4-8-17, CNRM-CM5—CCLM4-8-17, and CNRM-CM5—ALADIN63). Hakala et al. (2018) suggested that climate model selection for hydrological impact studies should ideally be informed by errors in hydrological metrics relevant to end users. Thus, the selection of climate models for this study was based on a range of climatic indicators that are known to control actual evapotranspiration (ET_a) and recharge (R) in flood and drip irrigation (Pool et al., 2020). The list of performance indicators included the annual sum of precipitation, monthly sum of precipitation, sum of the eight most intensive precipitation events, monthly mean of daily mean temperature, and monthly mean of daily temperature range. The selection was done during the control period (1971–2000) by comparing the raw climate model time series against the observed time series from the Spain02 data set (Herrera et al. 2012, 2016) using the relative error as performance metric. The climate models with the best average rank across all five performance indicators were retained for further analysis.

3.1.3. Bias Correction

The temperature and precipitation time series of the five selected climate models were corrected for their biases relative to the observed climate data (Spain02 data set). Bias adjustment was based on the nonparametric statistical transformation of empirical quantiles (Gudmundsson et al., 2012) and was implemented for each season separately (December–February, March–May, June–August, and September–November). The bias correction procedure applied in this study also considered the adaptation of the wet-day frequency and the dry-day frequency as proposed by Themeβl et al. (2012). The bias correction functions established in the control period were applied to future climate projections assuming stationary biases.

3.2. Hydrological Modeling

3.2.1. The Hydrological Model Tetis

The Tetis model (Francés et al., 2007) is a distributed bucket-type model with physically based parameters that constrain the fluxes of water between a hierarchical sequence of storages. The first storage element of the model represents the land cover-dependent interception of precipitation. Precipitation exceeding the interception capacity infiltrates into the upper soil water storage until field capacity is reached. Both of these first two storage elements are solely depleted by ET_a. ET_a is thereby calculated using the single crop coefficient approach of Allen et al. (1998) and is a function of potential evapotranspiration (i.e., crop reference evapotranspiration), soil water storage, and land cover. Any time soil moisture reaches field capacity, additional precipitation either runs off as overland flow or infiltrates into the lower soil water storage. The outflows of this lower soil water storage are hillslope interflow and groundwater recharge R. Groundwater is the final storage element and sustains the river baseflow.

The basic model structure of Tetis can be extended with an irrigation module. The module allows the specification of irrigation volumes and frequencies, as well as the type of irrigation for each irrigation sector. In case of flood and drip irrigation, irrigation water is directly applied to the soil surface avoiding interception of irrigation water by vegetation. As irrigation is a handled as a model input, it is always applied to the entire pixel designated as an irrigated land surface. Thus, small-scale differences, such as the fractional wetting of the soil surface in surface drip irrigation, cannot be explicitly modeled. In this study, we accounted for the localized application of water in drip irrigation by adopting the approach developed in Pool et al. (2020). The approach simulates the fraction of the wet soil surface at the scale of an irrigation sector rather than

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at pixel scale. For each irrigation sector, pixels are grouped into two classes representing the dry and the wet soil surface. The fraction of pixels classified as dry or wet can be chosen according to the expected wetting fraction. Here, we used local field observations that indicate that the fraction of wetted soil surface in surface drip-irrigated citrus orchards is approximately 53% (Ruiz-Rodríguez, 2017). As a consequence of classifying pixels inside an irrigation sector into wet and dry areas, model simulations need to be aggregated and interpreted at the scale of an irrigation sector.

3.2.2. Spatial Model Input Data

The Tetis model was run at a spatial resolution of 200 m by 200 m using spatial input data from various sources. Data on land cover and vegetation were retrieved from the CORINE Land Cover inventory (EEA, 2019), whereby the corresponding monthly crop coefficients were chosen according to the FAO Irrigation and Drainage Paper (Allen et al., 1998). Soil specific information such as soil water capacity and soil textural class were extracted from the European soil database (ESDB, 2019). Soil textural classes were then used to estimate saturated hydraulic conductivity using the Rosetta Class Average Hydraulic Parameters lookup table (Schaap et al., 2001). The European soil database and the CORINE Land Cover inventory were further used to estimate rooting depths. In case of citrus orchards, rooting depths were adjusted to 100 cm in flood-irrigated fields and 70 cm in drip-irrigated fields based on local field observations from Ruiz-Rodríguez (2017). The parametrization of the subsurface was based on geological maps from the Geological Survey of Spain (IGME, 2019). The spatial delineation of the catchment and the hydrological connectivity between individual model pixels was defined from a digital elevation model of the Geographical Survey of Spain (CNIG, 2019) and a river network shapefile from the Jucar River Basin Authority (CHJ, 2018).

3.2.3. Model Calibration and Simulations

The calibration of Tetis is based on the split-parameter concept in which the effective parameter value in each pixel is composed of a local measurable physical characteristic and a global correction factor (Francés et al., 2007). We used a Monte Carlo approach to generate 100 random correction factors within physically realistic parameter boundaries. Subsequently, model simulations with these 100 parameter values were evaluated in a multi-objective evaluation framework that addresses multiple hydrological process scales. Model simulations were thereby considered as behavioral if they passed the acceptance thresholds for the annual evaporative index in flood and drip irrigation at basin scale (bias $\leq \pm 10\%$), monthly groundwater dynamics in four groundwater wells (Spearman rank correlation ≥ 0.3 and amplitude bias $\leq \pm 25\%$), and daily soil water dynamics in the wet and dry parts of drip irrigation at plot scale (soft evaluation of simulation feasibility). The described calibration approach was applied to simulations forced with daily Spain02 observations from 1994 to 2015. The evaluation against observed ET_a (Ruiz-Rodríguez, 2017), groundwater (CHJ, 2018), and soil moisture (Ruiz-Rodríguez, 2017) resulted in 12 acceptable model parameterizations. For further details on the calibration, see Pool et al. (2020).

Finally, the calibrated hydrological model was forced with bias-corrected daily data of the five GCM-RCMs for the control period (1971–2000) and the future (2020–2074). Climate model data from the year preceding the control period and the future period were used for model warming up to ensure realistic initial storage conditions.

3.3. Irrigation Scenarios

Hydrological simulations were run for two extreme irrigation scenarios: a situation in which traditional flood irrigation is practiced in all irrigation sectors, and a hypothetical situation in which the entire irrigated area completed the transformation to drip technology. To analyze the impact of the planned gradual change in irrigation systems from the currently 52% toward 85% drip-irrigated area by 2030, area-weighted mean values were calculated from the simulations of the two main scenarios. The details on the timing and location of the irrigation transformation were provided by the regional water authority and water user associations (Servicio de Regadíos, 2020). While we accounted for the spatial changes in irrigation technique, we assumed *business as usual* irrigation schedules in the future (for details on monthly volumes see Figure 4). This assumption was made due to the large uncertainties regarding future irrigation water access and future irrigation water demand (Fader et al., 2016; Rodríguez Díaz et al., 2007; Tanasijevic et al., 2014).

3.4. Analysis of Hydroclimatic Regimes

The use of the described modeling chain resulted in 240 hydrological simulations for the control period (1971–2000), the near-term future (2020–2049), and the mid-term future (2045–2074). Each of these simulations was used to compute a hydroclimatic regime curve for the three simulation periods. The regime curve represents the typical monthly variation of a hydroclimatic variable throughout the course of a year (Figure 2; for some early work on regime curves see, e.g., Haines et al., 1988). The regime curve is the mean of multiple yearly curves and is here described by three components: (i) the mean monthly value, (ii) the seasonality within a year, which is the difference between the highest and lowest monthly value, and (iii) the variability between years, which is the difference between the highest and lowest mean monthly value of each year during a particular time period.

To thoroughly asses the region's hydrological vulnerability, we extend the analysis from purely climatological variables to hydrological aspects by examining the regime curves of precipitation, ET_a, and R. Streamflow was not considered in this study because it is highly altered by abstractions for irrigation, terraced surface, and by retentions in multiple upstream reservoirs.

To evaluate the impact of an irrigation technique on future hydroclimatic changes (mean, seasonality, and inter-annual variability) under RCP 4.5 and RCP 8.5, changes in the three regime components were calculated for the flood and drip-irrigation scenario separately. The significance of these changes was tested using the nonparametric Wilcoxon signed rank test for paired observations. Future median values of each regime component were assumed to be significantly different from the past when p-values were <0.05 (95% confidence level). The significance test was not calculated for precipitation and temperature as their predictions only included the five values from the selected climate models. Finally, linear least squares regression was used to quantify trends in ET_a and R during the completion of the irrigation transformation (2020–2030).

4. Results

4.1. Temporal Evolution of Hydroclimatic Variables

Projections of the possible future evolution of the major water balance components are presented in Figure 3 for the control period (1971–2000), the near-term future (2020–2049) and the mid-term future (2045–2074). Climate models generally predict a steady increase in mean daily temperature throughout the control period and the near- and mid-term future. As by definition, the increase in temperature will be higher in the mid-term future for RCP 8.5 than for RCP 4.5. For annual precipitation, ET_a, and R temporal trends and differences between the two emission scenarios are less evident due to model uncertainties and considerable inter-annual variability. Nevertheless, the simulations suggest marked differences in ET_a and R between drip and flood irrigation. ET_a in drip irrigation is clearly lower than in flood irrigation throughout the entire modeling period. ET_a in drip irrigation is further subject to higher inter-annual variability and model uncertainty. Similarly, simulations predict less R with slightly higher uncertainty for drip irrigation than for flood irrigation. Generally, ET_a and R in drip irrigation tend to decrease by the mid-term future, whereas simulated ET_a in flood irrigation reveals a weak increasing trend. More detailed information about the projected changes in temperature, precipitation, actual evapotranspiration, and recharge can be found in Tables S1–S4.

4.2. Hydroclimatic Regime Curves

The regime curves for precipitation, ET_a, and R indicate a typical Mediterranean climate, which is generally similar in the control period and the future (Figure 4 and Tables S1–S4). The precipitation regime is characterized by a distinct peak during the fall months, a plateau with relatively high values during winter, and a dry summer. Irrigation provides additional water during the major crop growing stages and is most intense during the driest period. As expected, ET_a has a strong seasonal regime, whereby monthly rates are consistently higher in flood irrigation than in drip irrigation. The annual peak ET_a in drip irrigation occurs one month later than in flood irrigation (July vs. June) and coincides with the application of the largest irrigation volumes. The combination of precipitation, irrigation, and ET_a results for most cases in a bimodal R regime (an exception is drip irrigation during the control period). In drip irrigation, annual peak R occurs

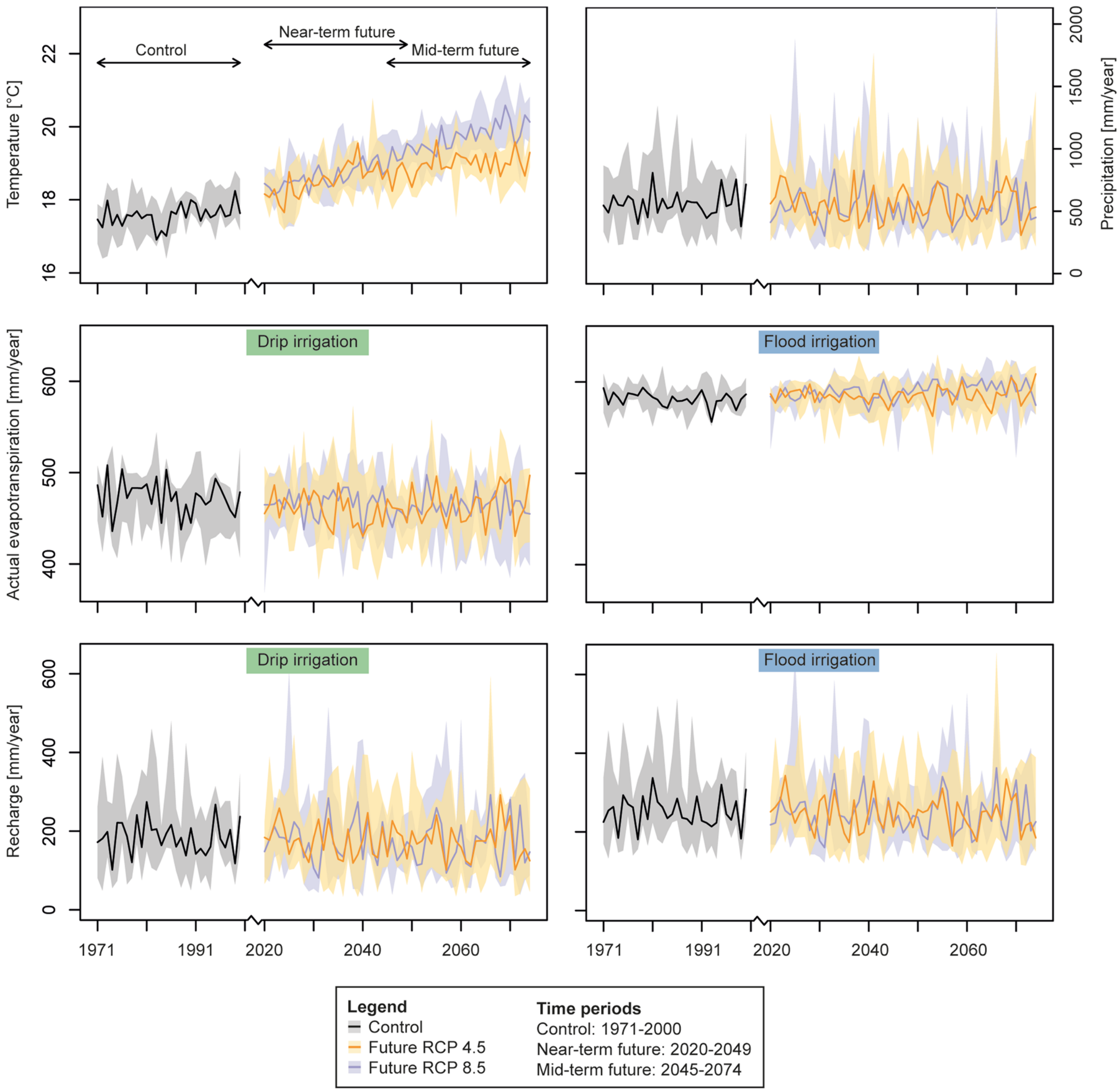

Figure 3. Temporal evolution of annual hydroclimatic variables in drip and flood irrigation. Solid lines show the median of the five climate models, and shaded bands show the range of the five climate models. Values for each climate model represent the mean of the 12 corresponding hydrological simulations. Note that there is a break in the *x*-axis between 2000 and 2020.

when precipitation is highest, and *R* is clearly lowest during the dry and warm summer months. Peak *R* in flood irrigation is slightly shifted with a later winter/spring peak at the start of the flood-irrigation season and an earlier peak in fall when precipitation starts to increase and a last irrigation turn is applied. Low *R* rates in flood irrigation occur both in summer and winter. Seasonal differences in *R* response finally lead to higher *R* in flood irrigation between March and September (which is the flood irrigation season), and greater *R* rates in drip irrigation during the remaining months. The described differences in ET_a and *R* between drip and flood irrigation are clearly pronounced despite the considerable uncertainties in the precipitation and *R* predictions.

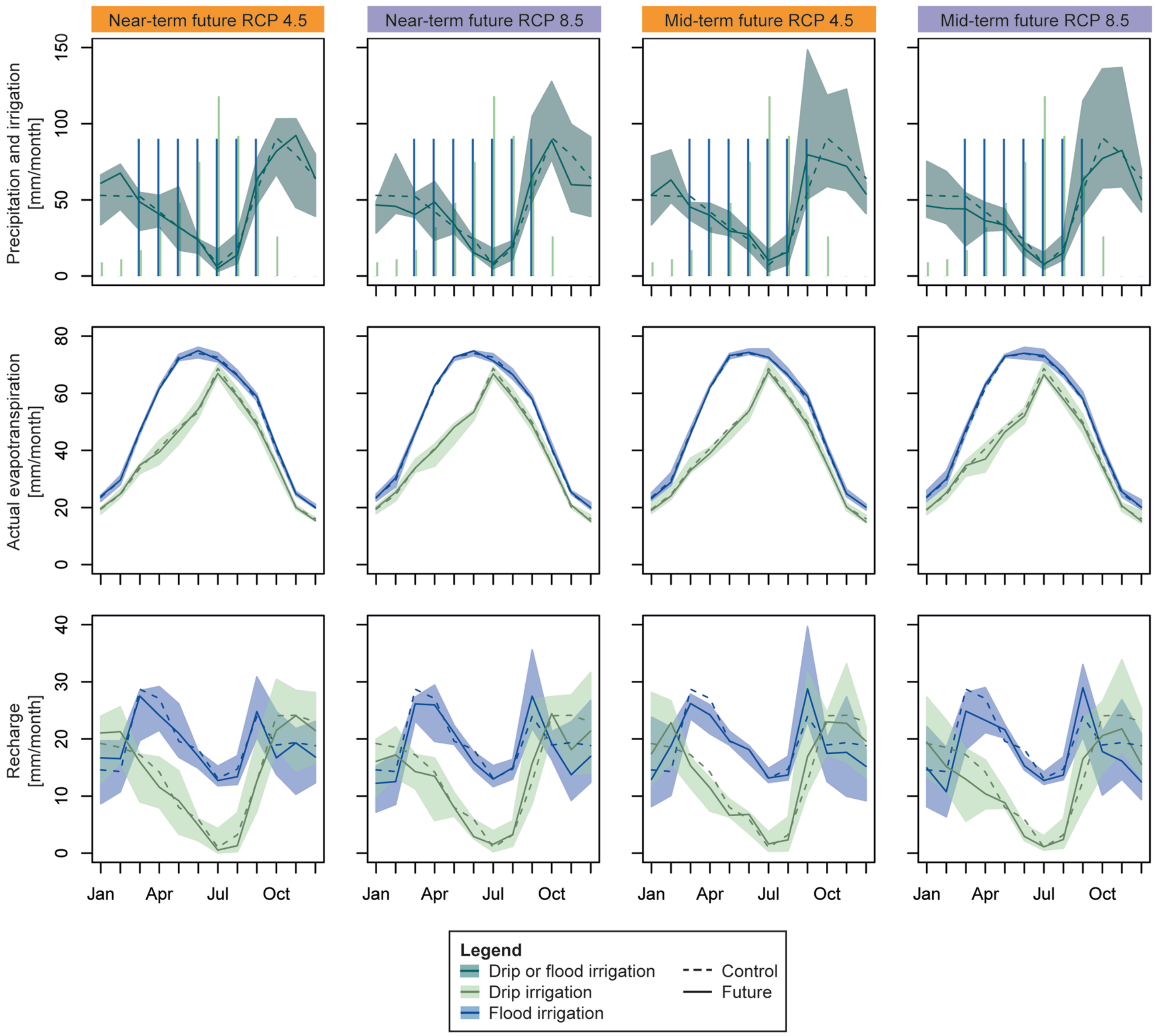

Figure 4. Hydroclimatic regime curves in drip and flood irrigation. Solid lines show the median of the five climate models, and shaded bands show the range of the five climate models. Values for each climate model represent the mean of the 12 corresponding hydrological simulations. The monthly regime values are presented for the control period (1971–2000), the near-term future (2020–2049), and the mid-term future (2045–2074). For an improved readability, only the median of the five climate models is shown for the control period. In the top row, the lines represent precipitation, whereas the bars show the irrigation volumes applied in drip and flood irrigation.

4.3. Changes in the Hydroclimatic Regime Components

4.3.1. Climate Change Impact in Drip and Flood Irrigation

Predictions of future changes in the mean, seasonality, and inter-annual variability of precipitation, ET_a, and R are in many cases associated with considerable uncertainties regarding the magnitude and the sign of change (Figures 5–7). These uncertainties are reflected in the statistical significance of future changes: expected changes in future mean values are in many cases statistically significant as opposed to often insignificant changes in seasonality and variability. The subsequent description of expected changes will thus mostly focus on the statistically significant median changes.

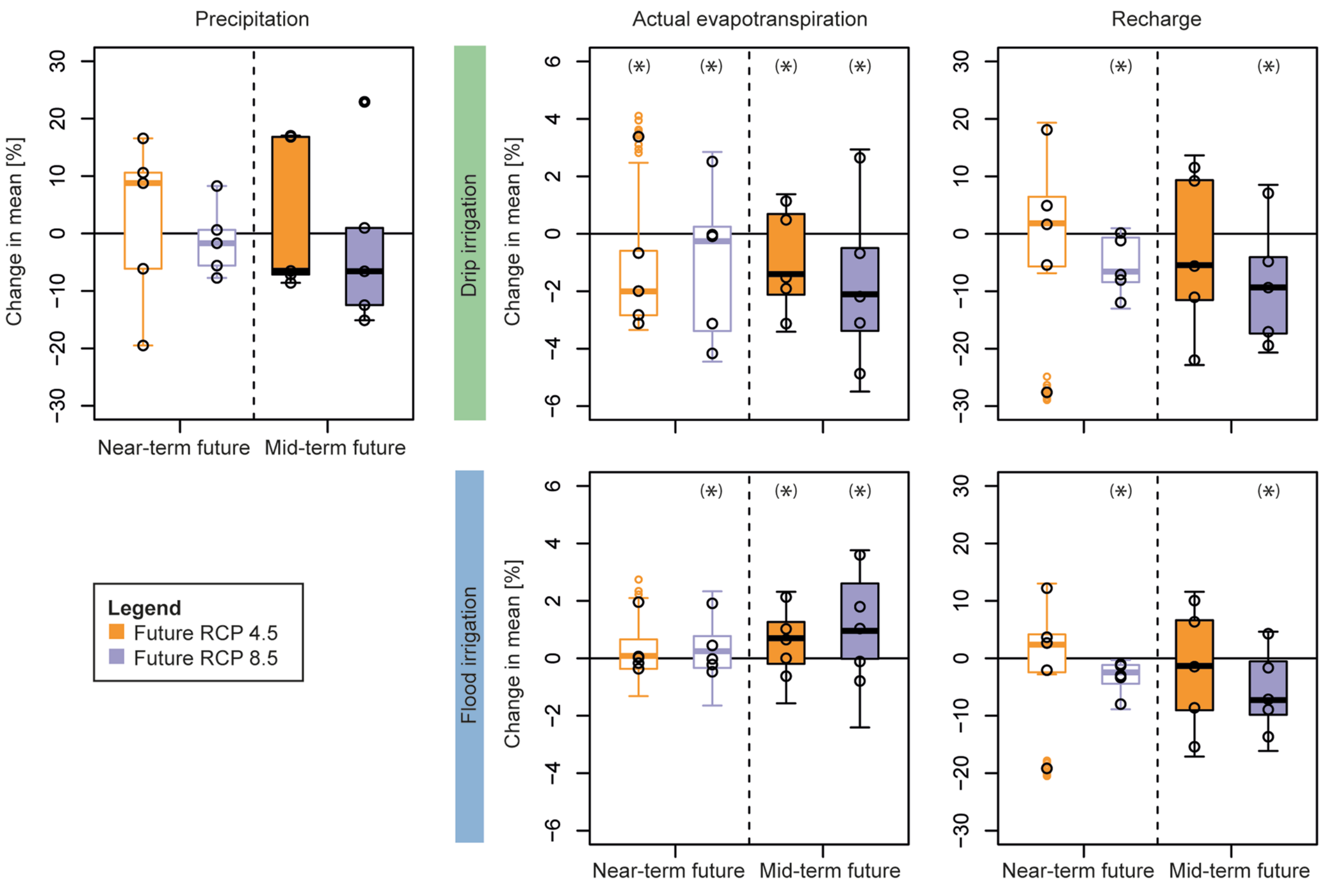

Figure 5. Percent changes in the *mean* of the hydroclimatic regime curves in drip and flood irrigation. Changes in the mean are presented for the near-term future (2020–2049) and the mid-term future (2045–2074). Changes are relative to the control period (1971–2000). Circles indicate the values of the climate models. The value of each climate model represents the mean of the 12 corresponding hydrological simulations. In case of precipitation, each boxplot consists of five values (i.e., five climate models). In case of actual evapotranspiration and recharge, each boxplot consists of 60 values (i.e., 12 hydrological simulations times 5 climate models). *The stars indicate statistically significant changes at the 95% confidence level for actual evapotranspiration and recharge.

4.3.1.1. Mean Component

Mean precipitation is generally expected to decrease with increasing climate change (Figure 5). Except for an initial increase of +8.8% for RCP 4.5, precipitation will decrease by −1.7% for RCP 8.5 in the near-term future and by −6.5% and −6.6% in the mid-term future for RCP 4.5 and RCP 8.5, respectively. While mean precipitation tends to decrease, there will be an increase in January, February, July, and September (Figure 4).

In case of mean ET_a, contrasting changes are predicted in drip and flood irrigation. Reduced ET_a rates are expected in drip irrigation that are in the order of −2.0% and −0.3% in the near-term future and of −1.4% and −2.1% the mid-term future for RCP 4.5 and 8.5, respectively (Figure 5). Most of this decrease will happen in summer, whereas higher ET_a might occur in February, October, and November (Figure 4). Future ET_a in flood irrigation will consistently increase by +0.2% in the near future for RCP 8.5, and by +0.7% and +1.0% in the mid-term future for RCP 4.5 and RCP 8.5, respectively (Figure 5). The described increase for flood irrigation is most pronounced during the rainy months (Figure 4).

Trends in mean *R* are similar to the ones in precipitation (Figure 5). Significant negative changes are only predicted for RCP 8.5, whereby changes are more pronounced in drip irrigation than in flood irrigation. *R* reductions thereby range from −2.4% and −6.6% in the near-term future to −7.3% and −9.3% in the mid-term future. As previously described for precipitation, *R* can increase in some months (mostly January, February, and September; Figure 4) despite the general downward trend.

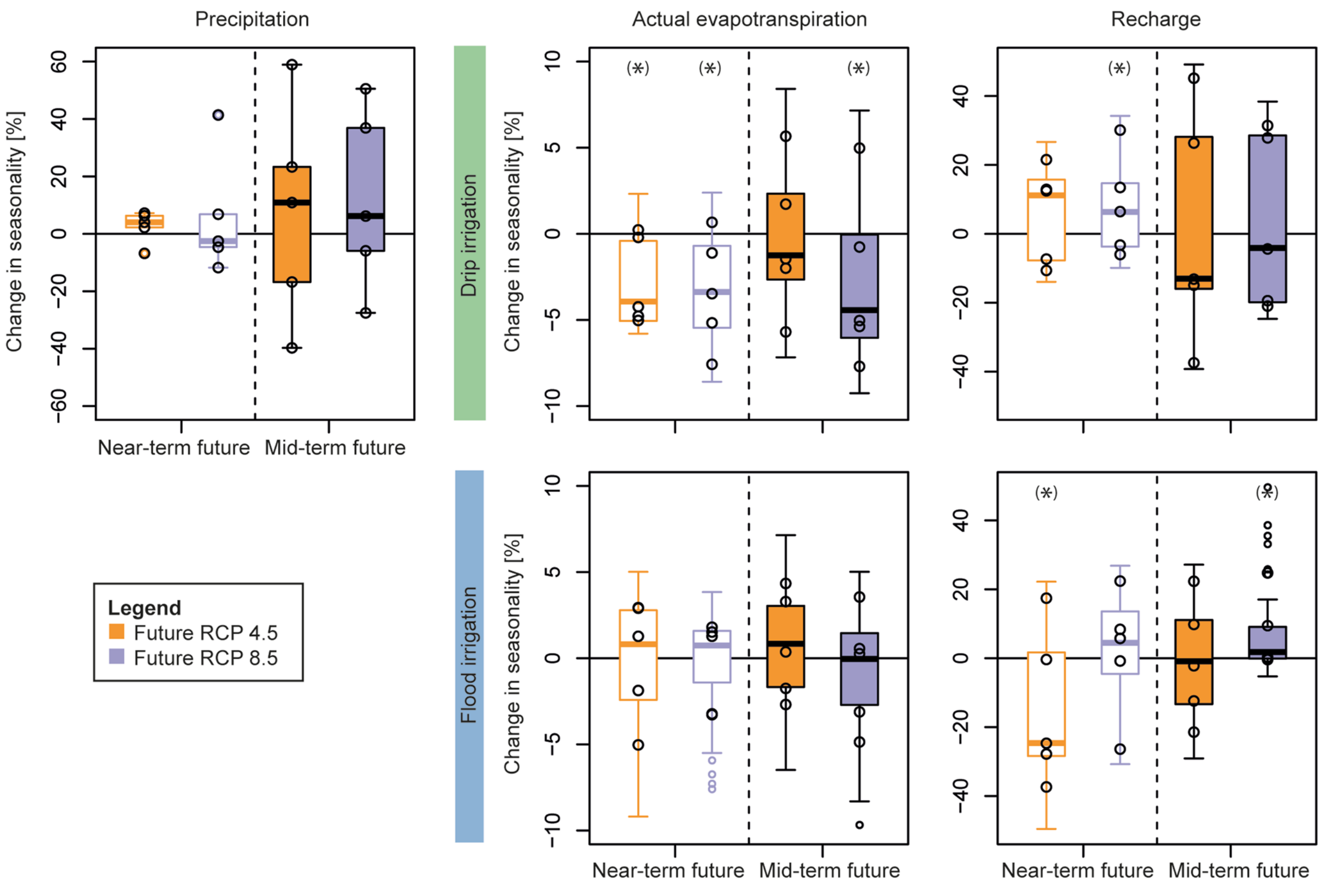

Figure 6. Percent changes in the *seasonality* of the hydroclimatic regime curves in drip and flood irrigation. Changes in the mean are presented for the near-term future (2020–2049) and the mid-term future (2045–2074). Changes are relative to the control period (1971–2000). Circles indicate the values of the climate models. The value of each climate model represents the mean of the 12 corresponding hydrological simulations. In case of precipitation, each boxplot consists of five values (i.e., five climate models). In case of actual evapotranspiration and recharge, each boxplot consists of 60 values (i.e., 12 hydrological simulations times 5 climate models). *The stars indicate statistically significant changes at the 95% confidence level for actual evapotranspiration and recharge.

4.3.1.2. Seasonality Component

Precipitation seasonality is generally predicted to increase and will become stronger in time (Figure 6). With the exception of a decrease of −2.5% in the near-term future for RCP 8.5, an increase of +4.0% is expected for the RCP 4.5 near-term future, and increases of 10.1% and 6.2% are predicted in the mid-term future for RCP 4.5 and RCP 8.5, respectively.

Simulations of ET_a seasonality point toward an opposite sign of change in flood and drip irrigation, whereby changes are only significant for the latter (Figure 6). ET_a seasonality in drip irrigation will be −4.0% lower in the near-term future for RCP 4.5, and decrease in the mid-term future by −1.3% and −4.4% for RCP 4.5 and RCP 8.5, respectively.

The pattern in future R seasonality is rather inconsistent and without clear trends (Figure 6). For drip irrigation, R seasonality might be significantly higher in the near-term future under RCP 8.5 (+6.4%). R seasonality in flood irrigation will decrease by −24.6% in the RCP 4.5 near-term future, but increase by 1.8% in the RCP 8.5 mid-term future.

4.3.1.3. Variability Component

Climate simulations suggest that the inter-annual variability in precipitation will strongly increase in the near-term future (+28.2% for RCP 4.5 and + 43.0% for RCP 8.5), but only slightly change on mid-term (+4.5% for RCP 4.5 and no change for RCP 8.5; Figure 7).

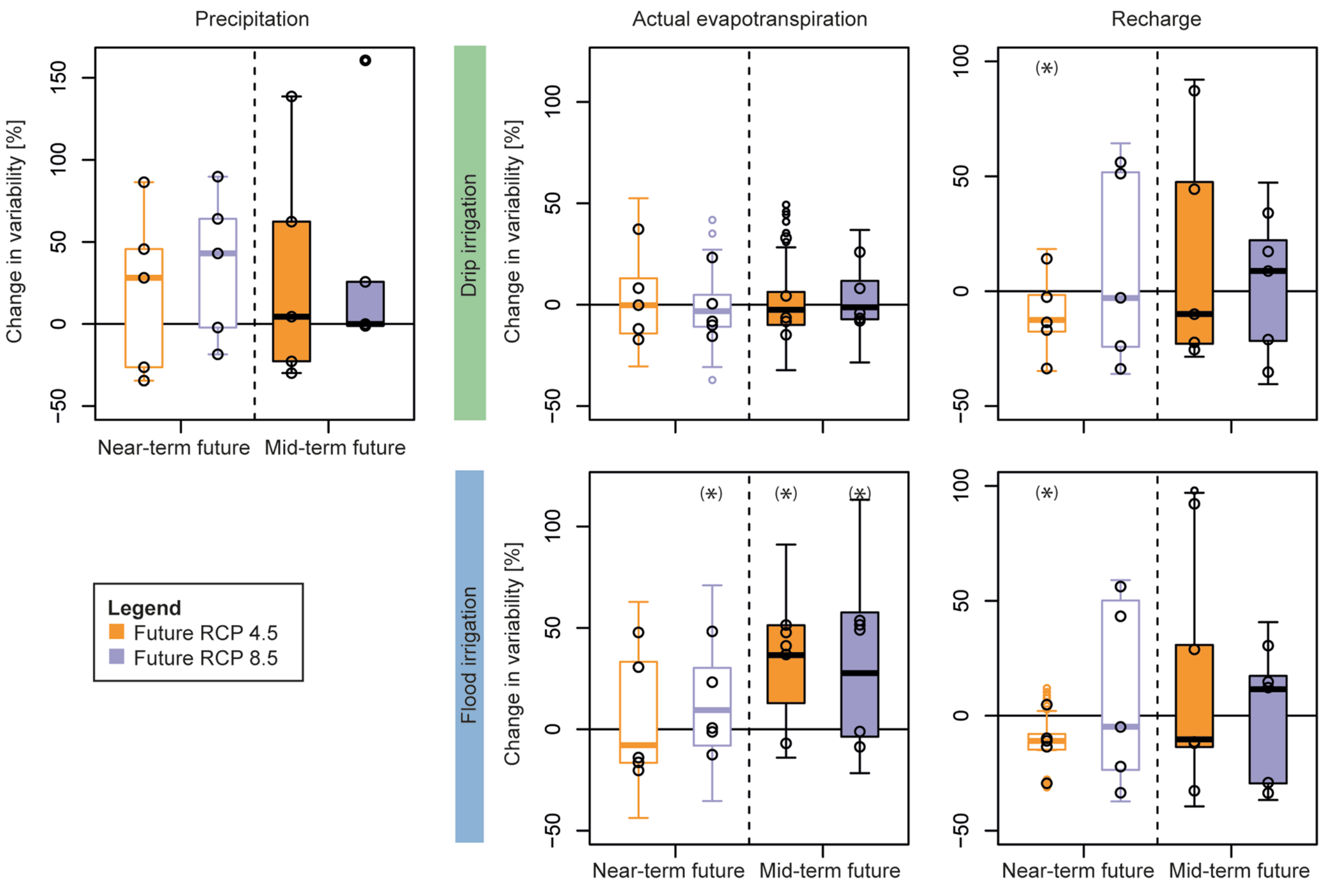

Figure 7. Percent changes in the *variability* of the hydroclimatic regime curves in drip and flood irrigation. Changes in the mean are presented for the near-term future (2020–2049) and the mid-term future (2045–2074). Changes are relative to the control period (1971–2000). Circles indicate the values of the climate models. The value of each climate model represents the mean of the 12 corresponding hydrological simulations. In case of precipitation, each boxplot consists of five values (i.e., five climate models). In case of actual evapotranspiration and recharge, each boxplot consists of 60 values (i.e., 12 hydrological simulations times 5 climate models). *The stars indicate statistically significant changes at the 95% confidence level for actual evapotranspiration and recharge.

While future changes in the variability of ET_a will be negligible in drip irrigation, they could be significant in flood irrigation. Variability will thereby increase by +9.4% in the near-term future under RCP 8.5, and by 36.6% and 27.7% in the mid-term future for RCP 4.5 and RCP 8.5, respectively (Figure 7).

Future changes for R variability are only significant for the RCP 4.5 near-term future, whereby the variability will be −12.5% lower in drip irrigation and −11.0% lower in flood irrigation (Figure 7).

4.3.2. Relative Importance of Climate Change and Irrigation Techniques

Linking the predicted future changes in ET_a and R to their absolute values allows analyzing the relative impact of climate change and irrigation technique on hydroclimate (Figure 8). Simulation results thereby suggest that changes induced by the transformation from flood to drip irrigation might often be more substantial than (statistically significant) changes caused by climate change.

More specifically, simulated mean monthly ET_a in the control period is 39.4 mm in drip irrigation and 50.2 mm in flood irrigation. Although significant, changes caused by climate change are at most 0.8 mm/month, which is clearly less than the difference between the two irrigation types. Similarly, mean monthly R in the control period is 14.3 and 19.1 mm in drip and flood irrigation, respectively, whereby climate change is predicted to significantly reduce these values by about 1.4 mm/month.

Past seasonality in ET_a is 53.0 and 56.3 mm in drip and flood irrigation, respectively. Predicted changes are only significant in drip irrigation and will increase the difference between irrigation techniques by up to 2.4 mm. In case of R, seasonality in the control period is higher in drip irrigation (24.5 mm) than in flood

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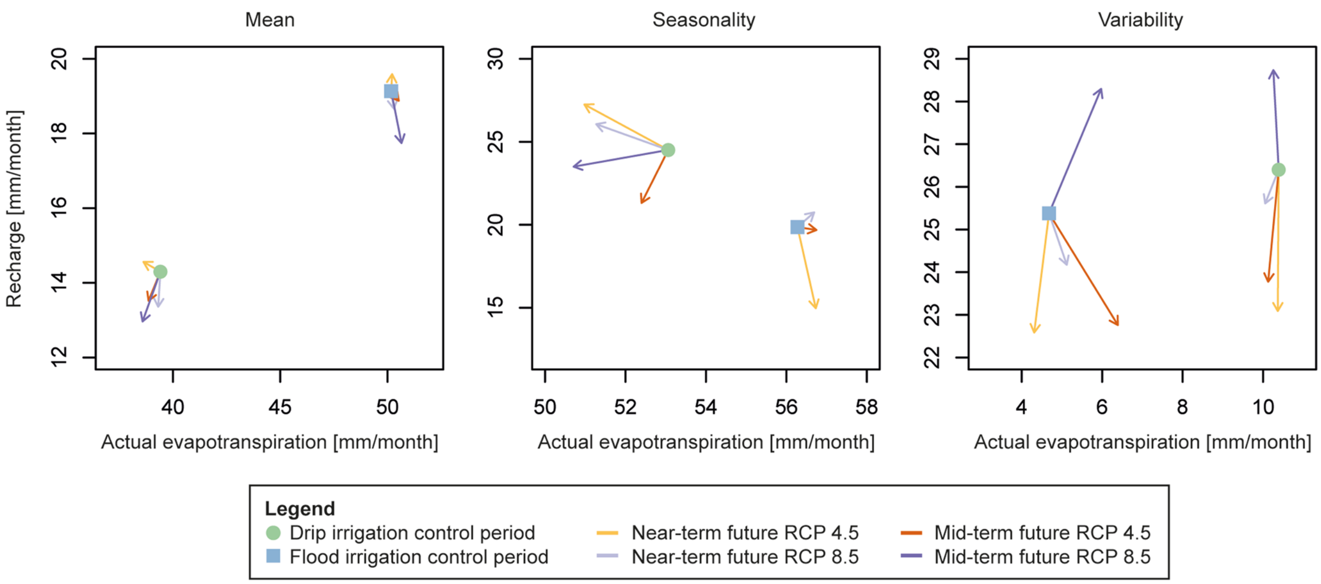

Figure 8. Absolute changes in the regime components of actual evapotranspiration and recharge in drip and flood irrigation. The circles indicate the median value of the five climate models in the control period (1971–2000), and the arrows point to the median value of in the near-term future (2020–2049) and the mid-term future (2045–2074). Values for the median climate model represent the mean of the 12 corresponding hydrological simulations.

irrigation (19.9 mm). The significant future seasonality changes are relatively small in the mid-term future (up to 1.5 mm), but could be comparable (4.9 mm) to the difference between drip and flood irrigation for changes in flood irrigation under the RCP 4.5 near-term future.

The inter-annual variability in ET_a is substantially larger in drip irrigation (10.4 mm) than in flood irrigation (4.7 mm). Climate change is expected to significantly increase the variability in flood irrigation by up to 1.7 mm, which is clearly less than the existing difference caused by the type of irrigation. In contrast, the inter-annual variability in R is similar in drip and flood irrigation with a difference of 1 mm (26.4 and 25.4 mm, respectively). The significant RCP 4.5 near-term future changes of up to 3.3 mm are therefore larger than the changes related to the choice of an irrigation technique.

4.4. Effects of the Planned Transformation From Flood to Drip Irrigation in the Valencia Region

Irrigation modernization plans for the study region include the transformation of another 33% of the agricultural land to drip irrigation until reaching 85% in 2030. Figure 9 shows the effects of the planned transformation as well as the effect of the drip and flood irrigation scenario on short-term ET_a and R.

Annual ET_a in the short-term future is fairly constant with an average of 585–587 mm in flood irrigation and an average of 464–467 mm in drip irrigation. As the transformation is proceeding, ET_a will obviously become more similar to one of the drip irrigations. Extending the drip-irrigated area from 52% to 85% could reduce annual ET_a at a rate of about 3–5 mm/yr for RCP 4.5 and RCP 8.5. In case of a further transformation of the area toward 100% drip irrigation, annual ET_a could reduce by 58 mm by 2030.

Annual R in drip and flood irrigation is prone to a decreasing trend between 2020 and 2030. The reduction in R is further enhanced by the planned transformation. More specifically, average annual R in flood irrigation ranges from 233 to 248 mm and will decrease at a rate of 2.7–4.7 mm/yr for RCP 8.5 and RCP 4.5, respectively. For drip irrigation, annual average R is predicted to decrease by 3.6–5.5 mm/yr between 2020 and 2030, which leads to an average annual R of 169–175 mm for RCP 8.5 and RCP 4.5, respectively. The enhanced negative trend caused by the planned transformation will decrease R by 5.1 mm/yr under RCP 8.5 and 7.0 mm/yr under RCP 4.5. A 100% transformation would accordingly result in a reduction of annual R in the order of 31–35 mm for RCP 8.5 and RCP 4.5.

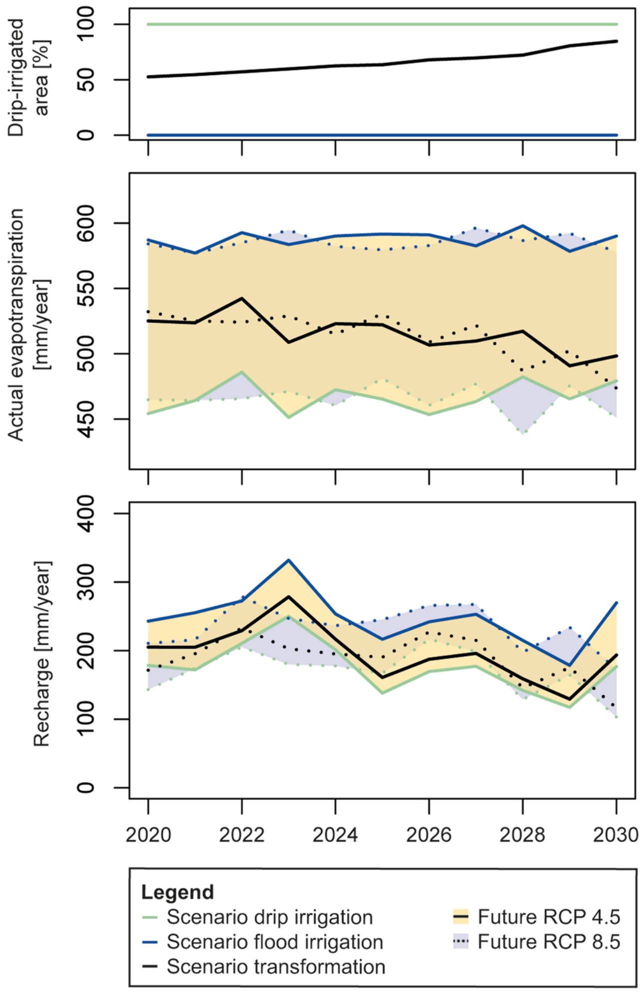

Figure 9. Effect of the planned irrigation transformation on actual evapotranspiration and recharge in the study area. The lines indicate the median value of the five climate models. Values for the median climate model represent the mean of the 12 corresponding hydrological simulations. Results are presented until 2030, when the transformation from flood to drip irrigation is expected to be completed.

5. Discussion

5.1. Comparison to Existing Studies

Recent studies in Southeastern Spain have predicted a decreasing tendency for *R* rates as a direct consequence of climate change in both irrigated agricultural areas (M. Pulido-Velazquez et al., 2015) and (relatively) undisturbed areas (Moutahir et al., 2017; Pulido-Velazquez et al., 2018; D. Pulido-Velazquez et al., 2015; Touhami et al., 2015). Our findings are consistent with this decreasing trend and further agree in the magnitude of change that is expected to range from −3% to −12% in the near- and mid-term future (Pulido-Velazquez et al., 2018; M. Pulido-Velazquez et al., 2015; Touhami et al., 2015). By the end of the century, climate change might considerably reduce *R* in Eastern Spain by −14% up to −58% (D. Pulido-Velazquez et al., 2015; M. Pulido-Velazquez et al., 2015). However, M. Pulido-Velazquez et al. (2015) showed that the impact of climate change on *R* could be dampened by irrigation. Our results thereby suggest that the percent change in *R* will be comparable in drip- and flood irrigated areas, whereas absolute *R* rates will be clearly higher in flood-irrigated fields. Thus, while the direct effect of climate change on *R* can be more important at large scale, the indirect effect (in our case, a change in irrigation technique) can cause considerable changes locally (Holman, 2006).

Agronomic studies in Mediterranean fruit orchards predict an increase in future ET_a provided that the expected rising irrigation water demands can be met (Rodríguez Díaz et al., 2007; Tanasijevic et al., 2014). Since we assumed a *business as usual* scenario for future irrigation volumes, changes in ET_a cannot be directly compared with these studies. Yet, our findings are consistent with the previous studies in two ways. First, annual ET_a in flood irrigation is expected to increase during most of the year. Second, ET_a in drip irrigation is predicted to decrease, especially in summer, which points toward future deficit irrigation in case that irrigation volumes will not be adapted to future requirements.

5.2. Uncertainties in the Predicted Hydroclimates

Predictions of future changes in ET_a and *R* made in this study are associated with uncertainties regarding the magnitude and the sign of change. The lack of agreement between future predictions within a single region is a common observation of many climate impact studies related to irrigation water demands (Fader et al., 2016; Rodríguez Díaz et al., 2007; Tanasijevic et al., 2014) or groundwater *R* (Crosbie, Pickett, et al., 2013; Ng et al., 2010; Niraula et al., 2017) in semi-arid regions. The largest sources of uncertainty in hydrological predictions are typically climate models, followed by the downscaling method and the choice of the hydrological model structure or parameterization (Crosbie, Dawes, et al., 2011; Marcos-Garcia & Pulido-Velázquez, 2017; Melsen et al., 2018). Our results support these findings as the range of predictions from the five GCM-RCMs was typically larger than the range of predictions from the 12 model parameters for a given climate model (Figures 5–7).

Uncertainties in *R* predictions in semi-arid regions are further intensified by the fact that much of the annual *R* can be generated by a few heavy precipitation events (Cheng et al., 2017; Poch-Massegú et al., 2014; Vallet-Coulomb et al., 2017). Uncertainties in the frequency and intensity of these (heavy) precipitation events can translate into considerable variability in *R* predictions (Smerdon, 2017). In our study area, observations (Alpert et al., 2002) and climate models generally indicate a reduction in annual precipitation combined with an increase in the intensity of daily precipitation (not shown here). This combination is typical for Southeastern Spain and results in a wide spread of predictions with a decreasing *R* trend for most climate models (Moutahir et al., 2017; Pulido-Velazquez et al., 2018) and higher future *R* predicted by some individual GCM-RCMs (Pulido-Velazquez et al., 2018).

Despite the uncertainties prevalent in this study, our findings suggest consistent statistically significant changes in the mean component of the ET_a and *R* regime. Furthermore, differences between the drip and flood irrigation regimes are well captured by the simulations with the five climate model inputs and are larger than the related climate prediction uncertainties. Both aspects certainly enhance the robustness of the main findings of this study.

5.3. Major Limitations of This Study

Climate change may affect water management in agricultural areas through direct and indirect changes in natural processes and through socio-economic feedbacks (Cramer et al., 2018; Holman et al., 2012; Iglesias et al., 2012; Taylor et al., 2013). In this study, we considered the direct effects of changes in precipitation and temperature as well as human-induced changes caused by a transformation from flood to drip irrigation. The still ongoing irrigation transformation in the study area was largely motivated by water limitations at regional scale and was implemented in a top-down approach (Ortega-Reig et al., 2017). We therefore focused on future hydroclimatic changes related to the regional changes in irrigation techniques. However, local farmer behavior, such as decisions regarding cropping patterns or groundwater pumping, was not considered in this study although it could substantially influence ET_a and *R* (Holman, 2006; O'Keeffe et al., 2018).

Furthermore, we do not account for climate change impacts related to the natural feedback from vegetation. For example, by applying the identical irrigation schedules in the past and the future, irrigation water demand was assumed to be constant despite changing temperature and precipitation. In case that the expected higher irrigation water requirements in the future can be entirely met (Falloon & Betts, 2010; Rodríguez Díaz et al., 2007; Tanasijevic et al., 2014), ET_a could be larger during the irrigation season than predicted by our simulations. Future ET_a (and indirectly *R*) is additionally dependent on plant physiological responses to elevated atmospheric CO_2 concentrations. Plants become more water efficient with higher CO_2 concentrations, however, the CO_2-fertilization effect might not always be realized due to limitations in water availability (Fader et al., 2016; Fares et al., 2017; Ficklin et al., 2010). Vegetation-related climate change impacts on water resources were beyond the scope of this study but their consideration in future research could provide valuable complementary information for long-term water planning.

Finally, the evolution of vegetation cover was simulated with the FAO crop-coefficient approach (Allen et al., 1998). Changes in vegetation cover or biomass production in periods of water stress were therefore not considered. A dynamic simulation of daily vegetation growth is typically related to a complex parameterization of vegetation processes (Sitch et al., 2003). Estimating plant physiological parameter values is data intensive and a considerable challenge if only hydrological data is available. Given that severe water stress is not common the irrigated citrus orchards of the Valencia region, we argue that the parsimonious FAO crop-coefficient approach is more suitable for this study.

5.4. Implications for Water Resources Management in the Valencia Region

The surface and subsurface water resources in the Jucar River Basin available for a sustainable use are fully allocated (CHJ, 2014). In the situation of such basin closure (Molle et al., 2010), even small changes in the future water balance can have substantial consequences for water users (Crosbie, Pickett, et al., 2013; Green et al., 2011). Our results indicate that climate change will likely significantly affect future annual magnitudes of ET_a and *R* in both drip and flood irrigated agriculture. In contrast, climate impact on future seasonality and inter-annual variability in ET_a and *R* are not entirely consistent. Exceptions are the expected significant decrease in ET_a seasonality in drip-irrigated areas, and the significantly higher future ET_a variability in flood-irrigated areas. Thus, future decisions on water allocations will probably be made in the challenging context of reduced water availability and uncertainty regarding the distribution of expected changes. Despite these uncertainties, the two emission scenarios used in this study can provide helpful benchmarks for testing the robustness of the system under modest climate change mitigation (RCP 4.5) or without any policy measures (RCP 8.5).

Future water availability in the Jucar River Basin will be further constrained by decreasing streamflow (Chirivella Osma et al., 2015; Ferrer et al., 2012; Marcos-Garcia & Pulido-Velázquez, 2017) and more severe summer droughts (Marcos-Garcia et al., 2017). An integrated modeling study for the California Central Valley predicted an increase in the conjunctive use of streamflow and groundwater in response to persistent droughts caused by climate change (Hanson et al., 2012). Similarly, farmers in the Valencia region might more often request a permission for groundwater abstractions in the future to fulfill crop water requirements during dry periods (Carmona et al., 2017). Stakeholder workshops furthermore revealed that farmers in the Valencia region might additionally consider the reuse of irrigation water or the use of alternative water sources (García-Mollá et al., 2013; Ortega-Reig, García-Mollá, et al., 2018).

The allocation of irrigation water resources is regulated at the basin scale through agreements between the Jucar River Basin Authority and several irrigation districts (CHJ, 2014). The agreement includes a reduction of agricultural water rights proportional to the state of the irrigation modernization and a redistribution of freshwater to the protected Albufera coastal wetland. The newly allocated freshwater reaches the wetland through channels and complements groundwater discharge into the wetland. Our findings have implications for the water allocation agreement in two ways. First, more frequent groundwater pumping along with the predicted potential reduction of R rates in flood and drip irrigation will likely decline groundwater levels. Second, the projected reduction in ET_a under drip irrigation points toward a higher irrigation water demand in the future. Both aspects increase the competition for freshwater and can have detrimental impacts on the Albufera coastal wetland. Furthermore, decreasing water levels caused by excessive groundwater abstractions could potentially increase the risk for seawater intrusion into coastal aquifers (Ferguson & Gleeson, 2012).

Climate change and the planned transformation of another 33% of agricultural land to drip irrigation are expected to considerably influence the regional water balance within the next 10 yr. Predictions over the next 55 yr suggest that changes in irrigation technique may have a greater impact on ET_a and R than projected changes in climate. Given the important role of irrigation technique for the local hydroclimate, future irrigation demand and groundwater resources could be influenced by water management decisions. This highlights the importance of an integrated consideration of both climate change and irrigation techniques when assessing future water resources in irrigated arid or semi-arid agriculture. It also strengthens the idea of carefully reviewing the impact of water accounting on water policies based on the generous subsidization of irrigation efficiency (Grafton et al., 2018).

6. Conclusions

This study assessed the impact of climate change and irrigation technique on future hydroclimatic regimes in Mediterranean agriculture. The study was conducted in the region of Valencia (Eastern Spain), which is one of the major citrus producing regions in Europe and is subject to a transformation of irrigation systems from flood to surface drip irrigation. Hydroclimatic predictions were made for the near-term future (2020–2049) and the mid-term future (2045–2079) using 5 GCM-RCM combinations, 2 emission scenarios (RCP 4.5 and RCP 8.5), 12 site-specific parameterizations of the hydrological model, and 2 irrigation scenarios (flood and drip irrigation). The main conclusions of this study are:

1. Climate change is expected to statistically significantly change mean actual evapotranspiration and recharge, whereas patterns in the predicted changes in seasonality and inter-annual variability are less consistent. Among the most relevant changes are the decreasing trend in mean recharge with progressing climate change (up to −6.6% and −9.3% for flood and drip irrigation, respectively), and the opposite trend in mean actual evapotranspiration that is positive in flood irrigation (up to +1%) but clearly negative in drip irrigation (up to −2.1%) under the assumption of a *business as usual* irrigation schedule.
2. Changes in the transformation from flood to drip irrigation may have a greater impact on actual evapotranspiration and recharge than changes in climate. Thereby, flood-irrigated fruit orchards are characterized by higher actual evapotranspiration with higher seasonality and lower variability than drip-irrigated orchards. Similarly, recharge is higher in flood irrigation than in drip irrigation, but has a lower seasonality and a comparable variability.
3. Climate change and irrigation transformation plans until 2030 are expected to considerably influence the regional water balance already within the next 10 yr. Future reductions in precipitation and thus

streamflow could intensify the role of groundwater for irrigation if farmers move toward a regular conjunctive use of streamflow and groundwater.

4. Despite the predicted statistically significant changes and the marked difference between drip and flood irrigation, there remains uncertainty in the magnitude and the sign of future hydroclimatic changes. Future decisions on water allocations in Eastern Spain will therefore likely be made in the challenging context of reduced water availability and considerable uncertainty about the expected changes.

Data Availability Statement

The authors also thank AEMET and UC for the data provided for this work (Spain02 v5 dataset, available at http://www.meteo.unican.es/datasets/spain02). The authors acknowledge the Coordinated Regional Downscaling Experiment for Europe (EURO-CORDEX; https://www.euro-cordex.net/) for the climate model data.

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