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Climate change and the water cycle in newly irrigated areas

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Abstract Climate change is affecting agriculture doubly: evapotranspiration is increasing due to increments in temperature while the availability of water resources is decreasing. Furthermore, irrigated areas are expanding worldwide. In this study, the dynamics of climate change impacts on the water cycle of a newly irrigated watershed are studied through the calculation of soil water balances. The study area was a 752-ha watershed located on the left side of the Ebro river valley, in Northeast Spain. The soil water balance procedures were carried out throughout 1827 consecutive days (5 years) of hydrological and agronomical monitoring in the study area. Daily data from two agroclimatic stations were used as well. Evaluation of the impact of climate change on the water cycle considered the creation of two future climate scenarios for comparison: 2070 decade with climate change and 2070 decade without climate change. The main indicators studied were precipitation, irrigation, reference evapotranspiration, actual evapotranspiration, drainage from the watershed, and irrigation losses. The aridity index was also applied. The results represent a baseline scenario in which adaptation measures may be included and tested to reduce the impacts of climate change in the studied area and other similar areas.

Keywords Crop adaptations · Climate change · Agricultural water management · Environmental impacts · Aridity index

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Introduction

The constant increase in water demand for agricultural, urban, and industrial uses, combined with potentially substantial climate change impacts to the hydrologic cycle, could endanger water availability for the next years in many parts of the world (IPCC 2007). In agricultural areas, changes in climate may interact with stresses that result from actions to increase agricultural production, affecting crop yields and productivity in different ways, depending on the types of practices and systems in place (IPCC 1998, 2007).

Climate projections for the Ebro river watershed (Spain) suggest increases in temperature and decreases in precipitation at the end of the twenty-first century, which will result in impacts on water quantity and quality in the area (García-Ruiz et al. 2011). The Ebro river watershed (approximately 85,000 km^2) is one of the main European watersheds and encompasses an important agricultural area (10 %), in which irrigation activities are in progressive expansion (Causapé et al. 2004, 2006; Abrahao et al. 2011a). This expansion means that irrigation water is applied to rainfed agricultural areas or previously natural areas, involving a major change in water use. In newly irrigated areas, irrigation water usually exceeds the total volume of all other water inputs to the system (Charbonneau and Kondolf 1993) and is added to the previously available water resources such as precipitation and natural flows (Abrahao et al. 2011a; García-Garizábal et al. 2011).

The combined impacts of unsustainable management and climate change may accelerate the degradation of lands such as newly irrigated areas in arid or semi-arid climates. Approximately 6 million km^2 of drylands worldwide bear a legacy of degradation that can take the form of soil erosion, nutrient depletion, water scarcity, altered salinity, or even disruption of biological cycles (UN 2011). Thereby, newly irrigated areas are ideal study areas to understand the impacts of climate change and its adaptation measures such as sustainable management. In this study, a representative watershed of the newly irrigated areas in the Ebro river watershed was used for the assessment of the impacts of climate change on the water cycle.

Materials and methods

The study area corresponds to the Lerma watershed (752 ha), located on the left side of the Ebro river valley, in Northeast Spain (Fig. 1). This watershed is being deeply monitored since October 2003, before the implantation of irrigation in the area. Irrigation activities began in 2006 and all 55 existing agricultural fields have been monitored since (i.e., crop diversity, agricultural management, irrigation amounts, and irrigation timing). The monitoring network includes a gauging station at the outlet of the watershed (water quantity and quality), 6 surface water sample points, and 12 piezometers (Fig. 1). The geology of the watershed has been investigated as well (Abrahao et al. 2011a, b; Merchán et al. 2013).

There are two agroclimatic stations close to the watershed (Tauste—5 km and Ejea—6 km: http://oficinaregante.aragon.es). Reference evapotranspiration (ET_0) was derived according to Penman–Monteith (Allen et al. 1998). With ET_0 and the monthly crop coefficients (kc) obtained from Martínez-Cob (2004) for the study zone, the daily crop evapotranspiration (ET_c) was calculated according to the methodology proposed by Allen et al. (1998):

$$ET_c = ET_0 \times kc \quad (1)$$

The estimation of drainage (D) and actual evapotranspiration (ET_a) exported from the watershed was

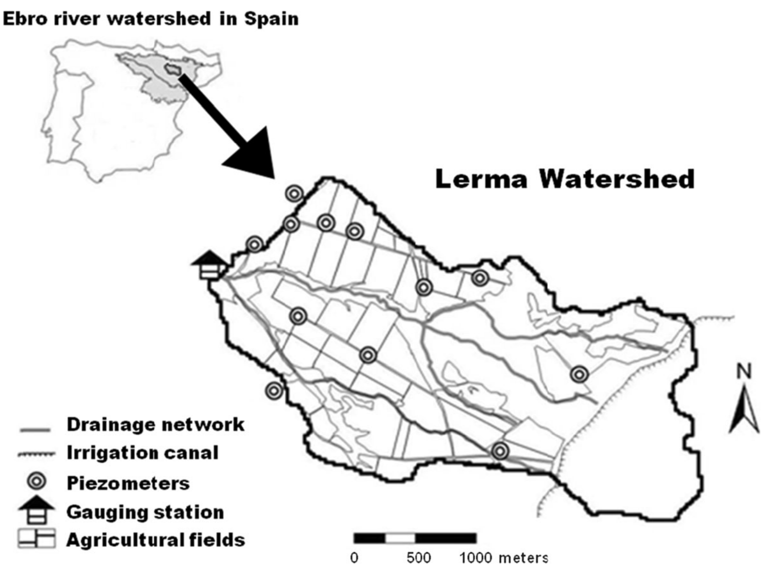

Fig. 1 Study area location (Lerma watershed) with location of monitoring equipment, agricultural fields, irrigation canal, and drainage network

carried out based on daily calculations of water balance in the soil (Causapé 2009). Starting from an initial volume of available water in the soil (AW), and taking into consideration the water holding capacity of the soil (WHC) for each agricultural field, the daily inputs where added (e.g., irrigation—I, precipitation—P). Irrigation losses (I_{losses}) were calculated in accordance with Playán et al. (2005) and represent the combined losses of both evaporation and wind drift of sprinkler irrigation.

ET_c was subtracted only if there was sufficient AW. In this way, ET_a could be estimated, as well as the drainage exported from the agricultural fields, the latter occurring when the field capacity of soils was surpassed (i.e., $AW_{initial}+P+I-I_{losses}-ET_a>WHC$). A simplified representation of the process can be observed in Fig. 2.

These procedures were carried out throughout 1827 consecutive days (years 2004–2008) of hydrological and agronomical monitoring in the Lerma watershed and are fully explained in Abrahao et al. (2011a). The accuracy of the method was verified through the comparison of the sum of the estimated drainage from all agricultural fields in the watershed ($D_{estimated}$) and the drainage measured at the gauging station (D_{obs}) through the drainage error equation (Causapé 2009). Water storage in the aquifer was estimated based on the aquifer area (310 ha), the saturated thickness of a representative piezometer, and the effective porosity of the aquifer (25 %). The resulting drainage error was then calculated using the following:

$$\text{Drainage error (\%)} = 200 \times \left[(D_{estimated} - D_{obs} - \text{storage}) \Big/ (D_{estimated} + D_{obs} + \text{storage})\right] \quad (2)$$

In order to evaluate the impact of climate change on the water cycle, two future climate scenarios were created for comparison: 2070 decade with climate change (FS CC) and 2070 decade without climate change (FS NO CC). Projections of mean monthly precipitation, temperature, and humidity to the 2070 decade were derived from the HadCM3 global climate model, under IPCC emission scenario A1B (moderate greenhouse gases emissions). A1B is a conservative scenario and was selected with the intention of understanding if even minimum climate changes could affect the water cycle in the watershed. Daily historic weather data from the two nearby climatic stations was obtained for FS NO CC.

Reference evapotranspiration (ET_0) for the 2070's was calculated according to Allen et al. (1998) with the projected climatic data. The correspondent projected precipitation and ET_0 changes for the 2070 decade were introduced daily, and the calculations of water balance in the soil were carried out on a daily basis. Irrigation was based on 2008 values. This process allowed for the computation of ET_a, I_{losses} and drainage for the 2070 decade.

The aridity index (AI) for the monitored period and for FS CC was calculated according to UNEP (1992):

$$AI = P \Big/ ET_0 \quad (3)$$

The aridity index is the ratio between average monthly or annual precipitation and average monthly or annual reference evapotranspiration. Drylands can be further subdivided into hyperarid deserts (AI<0.05), arid (0.05<AI<0.20), semiarid (0.20<AI<0.50), and dry subhumid (0.50<AI<0.65) (UNEP 1992; UN 2011).

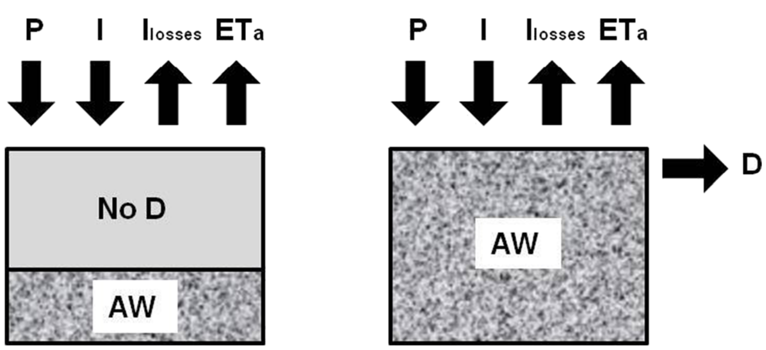

Fig. 2 Representation of the water balances in the soil, by which actual evapotranspiration (ET_a) and drainage (D) from the agricultural fields were computed, based on the available water in the soil (AW), irrigation losses (I_{losses}), and precipitation (P), and irrigation (I) inputs

Results and discussion

The climate of the study area is semiarid, with hot summers and cold winters. Average annual precipitation in the watershed during the monitored period was 408 mm, whereas the average reference evapotranspiration (ET_0), calculated via Penman–Monteith equation, was three times higher (1261 mm/year). Considering the climate of the area, irrigation becomes indispensable for the development of crops with high water requirements (e.g., maize and tomatoes), besides being fundamental for the achievement of higher productivity in crops with lower water demands (e.g., winter cereals). The monitored years embraced an unirrigated period (2004–2005) and different intensities of irrigation activity (2006, 31 %; 2007, 68 %; and 2008, 85 % of the area) in the Lerma watershed. Throughout these five monitored years, weather variations occurred, with wet (2004; P=628 mm), dry (2005; P=212 mm), and regular years (2006–2008). Hence, this intensely monitored study period is representative of different situations that can impact the water cycle in the watershed. Moreover, the comparison between $D_{estimated}$ and D_{obs} at the gauging station confirmed the accuracy of the methodology applied for simulation of drainage, with annual drainage errors between 0.9 and -1.6 %. This provided reliability to the estimations of future responses of the watershed to climate change.

The HadCM3 climate model projected a 10 % decrease in annual precipitation, an 8 % decrease in annual mean relative humidity, and a 3.7 °C increase in annual mean temperature for the 2070 decade in the area, which will represent an increase of approximately 30 % in ET_0. These changes will not be uniform throughout the year, being more pronounced for precipitation and relative humidity during summer, and for temperature in winter.

During the monitored period, the main water inputs in the watershed were precipitation and irrigation, and the main water outputs were ET_a and drainage (Table 1). If no climate change occurred (FS NO CC), the water cycle in the watershed during the 2070 decade would be very similar to that observed during the most irrigated years (2007 and 2008), but with higher drainage being exported from the watershed, since the system will be in equilibrium, with no important storage in the aquifer as verified during the monitored years (Abrahao et al. 2011a).

On the other hand, climate change (FS CC) will suppose important changes to the water cycle. Higher temperatures and lower humidity will increase ET_a by 9 % and I_{losses} by 22 %. The I_{losses} are an important issue in the watershed, since 86 % of the area is under sprinkler irrigation. Current climate would attribute 11 % of I_{losses} to all irrigation water applied (sprinkler and drip). Impacts from a changing climate could increase these (already high) losses to 14 %, resulting in lower water use efficiency. As a consequence of the aforementioned changes, drainage will be reduced by 34 %. This reduction will occur mainly during the irrigation season, when the drainage network may be dry during some periods, as occasionally occurred before the implementation of irrigation in the watershed.

When the climate model projections were applied to the real baseline, the projected 10 % decrease in annual precipitation translated into a 0.2 % decrease in precipitation values. This happened because the months of significant reduction in precipitation (summer) are already extremely dry, and during winter and fall, the climate model projected some increases in precipitation. This result represents, in part, the previsions of more

Table 1 Main water inputs [precipitation (P), irrigation (I)] and outputs [actual evapotranspiration (ET_a), drainage (D), and irrigation losses (I_{losses})] in the Lerma watershed for the entire monitored period (2004–2008), most irrigated years (2007–2008), and for future climate scenarios considering no climate changes (FS NO CC) and climate changes (FS CC) in the 2070 decade

	Period	Inputs (mm/year)		Outputs (mm/year)		
		P	I	ET_a	D	I_{losses}
Monitored period	Entire period	408	212	456	69	27
	Most irrigated years	386	458	650	84	58
Future scenarios (FS)	FS NO CC	408	518	663	205	59
	FS CC	407	518	722	135	72

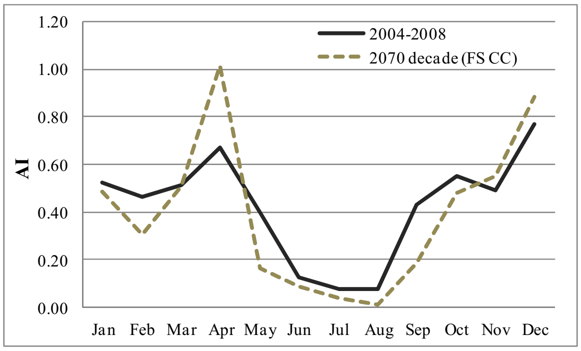

Fig. 3 Monthly aridity index (AI) for the entire monitored period (2004–2008) and for future climate scenarios considering climate changes (FS CC) in the 2070 decade

frequent extreme weather events in the future (IPCC 2007, 2012).

The aridity index applied to the monitored years (2004–2008) classified the climate of Lerma watershed as semiarid (AI=0.32), with a variability comprehending annual indexes between 0.18 (2005, arid classification) and 0.46 (2004, semiarid classification). Considering the 2070 decade with climate change (FS CC), there is a 25 % reduction in the index value (AI=0.24), which still is included in the semiarid classification, however, very close to the arid classification (0.05<AI<0.20). The variability during the 2070 decade may include arid (AI=0.14) and semiarid years (AI=0.34).

Climate change may also lead to changes in seasonal variability. The monthly aridity index applied indicated that the dry season may start earlier and that dry months may become even drier (Fig. 3). Moreover, some months such as April, may become less arid due to increases in precipitation, although ET_0 will also increase during this month. These changes will impose modifications in crop variety, irrigation amounts, and irrigation timing, with early adaptation measures being essential to reduce future losses.

The results of this study represent changes under the assumptions that crops, crop practices, and water available for irrigation will not change. This means that FS CC is not the representation of the watershed's reality in the 2070 decade, but a baseline in which adaptation measures will be included and tested for avoiding or decreasing the impacts of climate change.

Conclusions

The results of this study evidence that even moderate changes in climate can affect the water cycle in irrigated watersheds. The projections of climate change into the 2070 decade under moderate greenhouse gases emissions (A1B) suggest an important reduction in the aridity index in the study area, which means a more arid climate due, mainly, to increases in evapotranspiration. Irrigation losses may also increase, requiring adaptation measures that will need to consider the changed climate, crop variety, agricultural management and water availability. These results represent a baseline scenario in which adaptation measures may be included and tested to reduce the impacts of climate change in the studied area and other similar areas.

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