Agronomy for Sustainable Development (2024) 44:53
https://doi.org/10.1007/s13593-024-00981-5

RESEARCH ARTICLE

Numerical exploration of the impact of hydrological connectivity on rainfed annual crops in Mediterranean hilly landscapes

Mariem Dhouib[1] · Jérôme Molénat[1] · Laurent Prévot[1] · Insaf Mekki[2] · Rim Zitouna-Chebbi[2] · Frédéric Jacob[1]

Accepted: 12 August 2024

Abstract
Within hilly agricultural landscapes, topography induces lateral transfers of runoff water, so-called interplot hydrological connectivity. Runoff water from upstream plots can infiltrate downstream plots, thus influencing the water content in the root zone that drives crop functioning. The impact of runoff on crop functioning can be crucial for optimizing agricultural landscape management strategies. However, to our knowledge, no study has specifically focused on the impact on crop yield. The current study aims to comprehensively investigate the impact of runoff on crop functioning in the context of Mediterranean rainfed annual crops. To quantify this impact, we conduct a numerical experiment using the AquaCrop model and consider two hydrologically connected plots. The experiment explores a range of upstream and downstream agro-pedo-climatic conditions: crop type, soil texture and depth, climate forcing, and the area of the upstream plot. The experiment relies on data collected over the last 25 years in OMERE, an environment research observatory in northeastern Tunisia, and data from literature. A key finding in the results is that water supply through hydrological connectivity can enhance annual crop production under semiarid and subhumid climate conditions. Specifically, the results show that the downstream infiltration of upstream runoff has a positive impact on crop functioning in a moderate number of situations, ranging from 16% (wheat) to 33% (faba bean) as the average across above ground biomass and yield. Positive impact is mostly found for higher soil available water capacity and under semiarid and dry subhumid climate conditions, with a significant impact of rainfall intra-annual distribution in relation to crop phenology. These research needs to be expanded by considering both a wider range of crops and future climate conditions.

Keywords Hydrological connectivity · Runoff-runon process · Water infiltration · Rainfed agriculture · Annual crops · Crop production · Mediterranean

1 Introduction

Water resources are limited within the Mediterranean basin, with < 1000 m^3/capita/year in the eastern and southern Mediterranean (Fader et al. 2020). These resources are unevenly distributed in time and space, partly due to contrasting rainfall patterns (Blinda and Thivet 2009; Daccache et al. 2016; Fader et al. 2020). This water context is set to worsen because of (1) water resource over-exploitation to meet the growing food demand (Karabulut et al. 2018; Souissi et al. 2019) and (2) climate change consequences such as rainfall decreases, up to 30% (Lange et al. 2020), an increase of evaporative demand (Fader et al. 2020), and a concentration of intra-annual rainfall distributions (Ramos and Martínez-Casasnovas 2006). As the largest water user, the agricultural sector has long been under threat, with subsequent challenges for food security (Yang and Zehnder 2002). Rainfed annual crops are significantly affected by water issues because (1) they fully depend upon rainfall as a water resource, and (2) their shallow root systems make them vulnerable to water shortages (Hossain et al. 2020).

Mediterranean policies for water resources management have mainly oriented to support irrigated agriculture (Besbes et al. 2014; Nouri et al. 2020). As a result, less attention has been given to rainfed agriculture, which uses less water per unit area (Anderson et al. 2016). Nevertheless, it would be

✉ Jérôme Molénat
jerome.molenat@inrae.fr

1 LISAH, INRAE, IRD, Institut Agro, AgroParisTech, University of Montpellier, Montpellier, France

2 University of Carthage, National Research Institute of Rural Engineering, Water and Forests, LR16INRGREF02-LRVENC Ariana, Tunisia

Published online: 23 October 2024

possible to further improve rainfed agricultural productivity by implementing strategies that (1) reduce crop water needs, with species suited to drought conditions, or (2) increase water availability in the root zone by favoring runoff/rainwater infiltration or minimizing evaporative losses. The amount of water that infiltrates the root zone can be increased using water harvesting techniques (e.g., planting pits, terraces) at different spatial scales, from plot to landscape (Yadari et al. 2019; Tadros et al. 2021; Molénat et al. 2023). These techniques are suitable for landscapes with hilly topography that allows for the spatial redistribution of surface runoff (Ammar et al. 2016; Mekki et al. 2018). The benefits of these techniques in reducing runoff, promoting infiltration, increasing the soil water content, and enhancing crop yield have been demonstrated, particularly in Sub-Saharan Africa (see Wolka et al. (2018) for a review). Most of the studies conducted in the Mediterranean basin have demonstrated the benefits of the techniques in terms of reducing runoff or increasing the soil water content (Schiettecatte et al. 2005). To our knowledge, no study has specifically focused on the impact on crop yield.

Hydrological connectivity refers to water transfer across different areas of the landscape (Bracken and Croke 2007). In Mediterranean hilly landscapes, surface runoff predominantly drives interplot hydrological connectivity, redistributing rainfall between plots. This runoff-runon process occurs when runoff from upstream plots infiltrates downslope cultivated plots with greater infiltration capacity (Jones et al. 2013; Van Loo and Verstraeten 2021), thus enhancing water availability in the root zone (Fig. 1) (Howes and Abrahams 2003). While the impact of interplot hydrological connectivity on hydrological processes like stream flow generation is well recognized (Nanda et al. 2019; Zuecco et al. 2019; Saco et al. 2020), few studies evaluate its effect on crop functioning. Typically, crop functioning is studied using multilocal methods that assume hydrological independence among plots, overlooking the influence of hydrological connectivity (Van Gaelen et al. 2017). However, understanding this impact is crucial for optimizing agricultural landscape management strategies, particularly in arid to semiarid Mediterranean regions where water scarcity is a primary limiting factor for crop growth (Daccache et al. 2016; Araya et al. 2017) and where lateral water transfer primarily occurs through surface runoff (Mekki et al. 2006).

Studying the impact of interplot hydrological connectivity on rainfed annual crops in hilly Mediterranean regions requires careful consideration of key environmental factors affecting both downstream crop functioning and upstream runoff generation. Considering these factors enables the exploration of their potential influence on hydrological connectivity. Various elements can influence surface runoff, including rainfall patterns (Chen et al. 2016), hydrodynamic properties, soil moisture (Schoener and Stone 2019), agricultural practices (Prosdocimi et al. 2016), vegetation cover type (Nunes et al. 2011; Liu and Lobb 2021), and the impluvium area, representing the upstream contributing area for runoff input (Gnouma 2006). Furthermore, the functioning of downstream crops can be affected by the infiltration of upstream runoff and other environmental factors, such as climate (comprising rainfall and evapotranspiration demand), soil properties (such as the organic matter content and available water capacity), and agricultural practices (including fertilization and soil management) (Mbava et al. 2020). Investigating the potential influences of these environmental factors on hydrological connectivity can be pursued through

Fig. 1 A typical Mediterranean hilly landscape showing hydrological connectivity (arrows) between agricultural upstream and downstream plots (surrounded by a solid line) as well as the hydrographic network (long dashed line). The landscape is located in Tunisia—Kamech catchment (© photo J. Molénat).

field campaigns or numerical experiments using modeling. The latter approach is more suitable, as it allows for (1) the consideration of a wide range of environmental factors and (2) the disentanglement of the combined effects of environmental factors with hydrological connectivity.

The objective of this article is to study the impact of water infiltration due to the runoff-runon process on crop functioning. We focus on rainfed annual crops in a Mediterranean hilly landscape, emphasizing two main agronomic variables: above ground biomass and yield. In Section 2, we introduce the numerical experiment by describing the chosen modeling approach, the various influential factors to consider, and the strategy for analyzing the results. Section 3 presents and discusses the analysis of modeling simulations: we first examine the occurrence of situations with a significant impact on hydrological connectivity and then assess the importance of environmental conditions (climate, upstream runoff, soil texture, and depth) on this impact. Finally, we discuss the prospects of this study, considering that it represents a preliminary step toward an integrated catchment-scale approach.

2 Materials and methods

2.1 General framework

The numerical experiment is based on simulating crop functioning in a downstream plot receiving surface runoff from an upstream plot that is hydrologically connected, and by considering crops, soils, and climate typical of Mediterranean conditions (Fig. 2). The downstream plot is supplied with water from both rainfall and runoff simulated in the upstream plot. Assumptions include homogeneity in parameters, state variables, and fluxes within each plot, as well as complete transfer of upstream runoff to the downstream plot due to hydrological connectivity. Here, we provide an overview of the numerical experiment setting, and a detailed presentation is provided in Supplementary materials - Section 1.

The numerical experiment is conducted using the AquaCrop model (Raes et al. ,2009; Steduto et al. 2009), chosen for its performances to simulate crop functioning as well as surface runoff in water-driven conditions typical of arid to semiarid Mediterranean regions. Furthermore, AquaCrop has been extensively validated for a range of state variables related to water budgets and crop growth across various Mediterranean conditions (Garcia-Lopez et al, 2014, Toumi et al. 2016), especially under the conditions considered in the current study (Dhouib et al. 2022).

The simulations of downstream crop functioning with additional water supply from upstream runoff, span a wide range of typical Mediterranean conditions. This includes a diversity of environmental drivers that influence crop functioning, such as (1) varying crop types with distinct hydrological functioning and phenology, (2) different soil available water capacity in relation to varying soil depth and texture via hydrodynamic properties (Cousin et al. 2022), and (3) inter- and intra-annual variability of climate forcing over decades, including rainfall, temperature, and reference evapotranspiration.

In the downstream plot, we consider a range of upstream runoff magnitudes to account for the Mediterranean hydrological variability. The upstream runoff is simulated based on environmental factors like crop type, soil available water capacity, and climate forcing. An additional factor is the drained area of the upstream plot, hereafter referred to as the impluvium, and characterized using the ratio of upstream to downstream plot areas. A low ratio indicates a downstream plot near a hillslope summit in a landscape, while a high ratio signifies a downstream plot along or at the bottom of a hillslope.

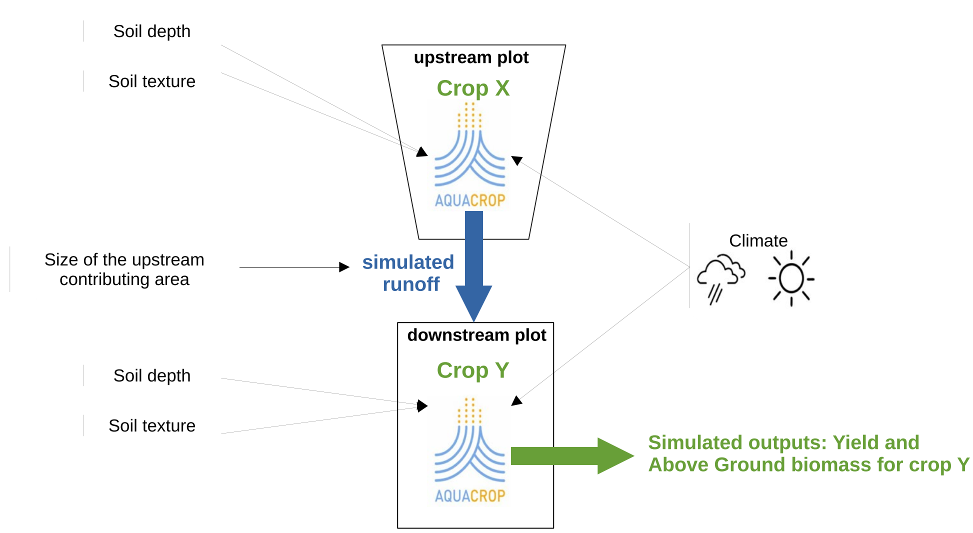

Fig. 2 Representative diagram of the numerical experiment setting. It includes the spatial layout of the two upstream and downstream plots, connected by runoff water from the upstream. The table lists the factors considered for each plot, and the ranges of attributes/values are discussed hereafter. Every crop (“crop X” or “crop Y”) corresponds to either to faba bean or wheat, the setup of which is given in Section 2.3.1.

To simulate typical Mediterranean conditions, we use the OMERE observatory database (www.obs-omere.org, Molénat et al. 2018) that meets specific requirements. It encompasses a range of climate forcings that span the last three decades and observations collected within the Kamech catchment (Cap Bon Peninsula, northeastern Tunisia) that is representative of semiarid Mediterranean regions in terms of crops, soil, and climate.

2.2 Overview of the AquaCrop crop model

Detailed presentations of AquaCrop (https://www.fao.org/aquacrop/en/) are provided by Raes et al. (2009) and Steduto et al. (2009). Here, we outline the specificities related to our methodological choices.

AquaCrop is a crop model designed to simulate crop functioning and the principal components of the water balance. Specifically, tailored for arid and semiarid environments, it is categorized as a water-driven model (Todorovic et al. 2009). Indeed, it adjusts crop growth based on vegetation transpiration, itself driven by root zone soil moisture. This characteristic makes it well suited for Mediterranean regions, where water acts as the principal limiting factor for agricultural production.

AquaCrop simulates, on a daily time step, the components of soil water balance across the soil−plant-atmosphere continuum (infiltration and runoff, deep percolation and capillary rise, soil evaporation, and vegetation transpiration), as well as plant growth and production (canopy crop cover, root growth, above ground biomass, yield). Crop transpiration (Tr) is derived from canopy crop cover (CC) and reference evapotranspiration (ET_0). Above ground biomass (AGB) is then derived from Tr and normalized water productivity (WP*), which accounts for atmospheric CO_2 concentration. Yield (Yld) is calculated as the product of AGB and the harvest index (HI). Runoff is determined using the empirical curve number method that accounts for crop type, agricultural practice, and hydrological soil group in relation to the soil infiltration rate and antecedent soil moisture. The soil water balance is calculated by discretizing the soil into five horizons based on pedological characteristics.

The AquaCrop forcing variables encompass climate data (e.g., air temperature, reference evapotranspiration ET_0, rainfall, and atmospheric CO_2 concentration) on a daily timescale. The model parameters consist of soil properties (texture and depth, soil moisture at field capacity, permanent wilting point and saturation, saturated hydraulic conductivity), cultural parameters (e.g., maximum canopy cover, crop coefficient), and agricultural practice data (e.g., fertilization, sowing date).

2.3 Setting the agro-pedo-climatic conditions

We assumed the same variability for the agro-pedological conditions within the upstream and downstream plots. All possible scenarios for each of the two plots are next combined to ensure the representativeness of the resulting AquaCrop simulations. When dealing with climate conditions, including rainfall, air temperature and $ET_{0,}$ for instance, we assumed uniformity across the two plots.

2.3.1 Crop types and subsequent crop parameters

We chose wheat as the cereal crop and faba bean as the legume crop for two main reasons. First, they are among the main rainfed crops in the Kamech catchment (Mekki et al. 2006) and the broader Mediterranean region (Jourdan 2022). Second, wheat and faba bean differ significantly in phenological cycle duration, agricultural practices (sowing and harvest dates), and in hydrological functioning (different soil cover rates implying different infiltration-runoff ratios). Faba bean, a row crop with a short phenological cycle, contrasts with wheat, a cover crop with a longer phenological cycle. Crop parameters for wheat and faba bean used in the model are detailed in the Table 1. Supplementary materials - Sections 2 details the setting, according to the study area, of the choice of sowing dates and the fertilization rates.

2.3.2 Soil characteristics and hydrodynamic properties

Soil hydrodynamic properties include (1) soil moisture at field capacity (FC), at permanent wilting point (PWP), and at saturation (Sat), as well as (2) the saturated hydraulic conductivity (Ksat). These properties are determined based on soil textures estimated from 10 soil pits collected at various locations within Kamech catchment according to the USDA classification (Coulouma et al. 2017). Then, the soil textures are converted into hydrodynamic properties using the nominal values proposed by the AquaCrop user guide (Table 2). Three different depths, namely, 0.5 m, 1 m, and 1.5 m, are chosen on the basis of the variability of soil depth observed in Kamech catchment (Molénat et al. 2018). By combining three soil textures and three soil depths, we simulate nine situations for soil available water capacity.

2.3.3 Climate forcing

A 25-year climate period from September 1, 1995, to August 31, 2019 is chosen, corresponding to the maximum window for which the OMERE data are available. The climate forcing data are air temperature, rainfall, and reference evapotranspiration ET_0.

For this climate series, the annual averages for rainfall, air temperature during the vegetation growing season

Table 1 Crop parameters values used for AquaCrop simulations. Conservative (i.e., independent of species, practices, and climate) and non-conservative (i.e., dependent on species, practices, and climate) are presented (Alaya et al., 2019). GDD refers to Growing Degree Days.

Crop parameters	Wheat	Faba bean
Conservative parameters		
Base temperature (°C)	0	5.5
Cutoff temperature (°C)	26	30
Canopy cover per seedling at 90% emergence (CC_o) (cm^2)	1.5	5
Canopy growth coefficient (CGC) (in fraction CC per GDD)	0.0052	0.0105
Maximum canopy cover (CC_x) in fraction soil cover	0.99	0.8
Crop coefficient for transpiration at CC = 100%	1.1	1.1
Decline in crop coefficient after reaching CC_x (%/day)	0.15	0.15
Canopy decline coefficient (CDC) (in fraction per GDD)	0.004	0.008
Water productivity normalised for ET_o and CO_2 (WP*) (g/m^2)	13.4	13
Leaf growth threshold (Pupper)	0.2	0.25
Leaf growth threshold (Plower)	0.65	0.6
Leaf growth stress coefficient curve shape	5	3
Stomatal conductance threshold (Pupper)	0.65	0.6
Stomata stress coefficient curve shape	2.5	3
Senescence stress coefficient (Pupper)	0.7	0.75
Senescence stress coefficient curve shape	2.5	3
Non-conservative parameters		
GDD from sowing to emergence	140	122
GDD from sowing to maximum rooting depth	1670	741
GDD from sowing to start senescence	1861	1286
GDD from sowing to maturity (length of crop cycle)	2777	1411
GDD from sowing to flowering	1543	879
Length of the flowering stage (GDD)	189	128
GDD building up of harvest index during yield formation	980	495
Reference harvest index (HI_o) (%)	45	30

Table 2 Soil parameters values used for AquaCrop simulations. C, CL, and SCL correspond to clay, clay-loam, and sandy-clay-loam textures, respectively. PWP, FC, and Sat correspond to soil moisture at the permanent wilting point, at field capacity, and at saturation, respectively. Ksat corresponds to saturated hydraulic conductivity.

Soil parameters				
Hydrodynamic properties	Unit	Texture		
		C	CL	SCL
PWP	m^3/m^3	0.39	0.23	0.20
FC	m^3/m^3	0.54	0.39	0.32
Sat	m^3/m^3	0.55	0.50	0.47
Ksat	mm/j	35	125	225

(October to May), and ET_0 are 629 mm, 14.8 °C, and 1310 mm, respectively (Supplementary Materials - Section 3, Fig. SF2). The years 1996 and 2019 are the wettest, with cumulative rainfall of 1036 mm and 862 mm, respectively. The years 1997, 2002, and 2016 are the driest, with cumulative rainfall of 406 mm, 394 mm, and 416 mm, respectively. Regarding air temperature, 1999 and 2009 are the coldest years, with an average air temperature of 14.2 °C over the crop growth period (October–May). The years 2001, 2002, and 2007 are the warmest, with an average air temperature of 15.4 °C over the crop growth period (October–May) (Supplementary Materials - Section 3, Fig. SF2).

To deepen the analysis of AquaCrop simulations, we classify the years of the climate series using the FAO aridity index (Spinoni et al. 2014). This index expresses aridity as the ratio of atmospheric water supply (rainfall) to atmospheric water demand (ET_0). We opt for this index because (1) it considers several climate variables when using ET_0 to quantify aridity, and (2) it is suitable for analyzing AquaCrop simulations since AquaCrop involves ET_0 when calculating the above ground biomass. According to the FAO aridity index, the climate series comprises two subhumid years (SH), 10 dry subhumid years (DSH), and 13 semiarid years (SA), accounting for occurrences of 8%, 40%, and 52%, respectively (Fig. 3). Additional details about the calculation of the FAO aridity index are provided in the Supplementary Materials - Section 3.

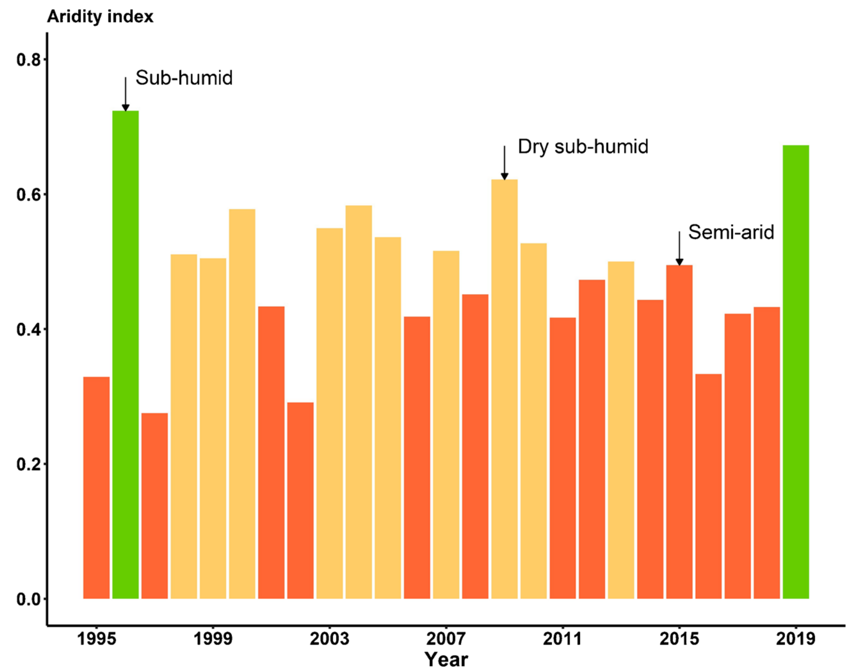

Fig. 3 Classification of climate years according to the FAO aridity index. Each year Y is a hydrological year that spans from the beginning of September of calendar year [Y-1] to the end of August of the year [Y].

2.4 Simulating the upstream runoff

The upstream runoff is quantified using AquaCrop simulations based on the agro-pedo-climatic conditions discussed in Section 2.3. The agro-pedo-climatic conditions include two crop types, nine situations for soil available water capacity (three soil textures and three soil depths), and 25 years of climate. To account for the impluvium area, simulated upstream runoff is weighted by the α ratio, that is, the ratio of the upstream to the downstream plot area (Fig. 2), which is set to three nominal values: 0.5, 1, and 2. By combining two crop types, nine conditions for soil available water capacity, and three ratios of the upstream to the downstream plot area, we obtain 54 situations of upstream runoff and thus 54 simulated time series of runoff, each spanning 25 years. Subsequently, each simulated time series of upstream runoff is added to the corresponding time series of rainfall in the downstream plot.

The set of simulated time series of upstream runoff, after weighting by the α ratio, depicts a range of annual cumulative values from 9 to 691 mm, representing 2 to 97% of the annual rainfall, depending on the year. To further analyze the impact of upstream runoff on downstream crop functioning, we classify these annual cumulative values into four classes relative to three quartiles (Table 3). We refer hereafter to classes of upstream runoff.

Table 3 Classification of the cumulative values of upstream runoff. R1, R2, R3, and R4 correspond to Classes 1, 2, 3, and 4, respectively, of cumulative values of upstream runoff. Q1, Q2, and Q3 correspond to the 1st quartile, median, and 3rd quartile, respectively.

Runoff class	Quartiles for the annual cumulative values of runoff
Class 1 (R1)	Cumulative annual runoff < 51 mm (Q1)
Class 2 (R2)	51 mm (Q1) ≤ Cumulative annual runoff < 95 mm (Q2)
Class 3 (R3)	95 mm (Q2) ≤ Cumulative annual runoff < 170 mm (Q3)
Class 4 (R4)	Cumulative annual runoff ≥ 170 mm (Q3)

2.5 Simulating downstream crop functioning

Downstream crop functioning is simulated with AquaCrop, considering the agro-pedo-climatic conditions (Section 2.3) and the upstream runoff (Section 2.4). For each of the two downstream crops (wheat and faba bean) and each of the nine downstream situations in terms of soil available water capacity, 54 AquaCrop simulations are run, varying in the simulated input of upstream runoff. This results in 486 simulations for each of the two downstream crops to be linked for comparison purposes to the corresponding nine reference simulations (3 soil depths, 3 soil textures) of crop functioning without upstream runoff from connectivity. On a yearly basis, these 486 simulations amount to 12,150 simulations for each downstream crop, totaling 24,300 for both.

2.6 Simulation analysis

To study the impact of water infiltration due to the runoff-runon process on downstream crop functioning, we focus on two agronomic variables driven by crop functioning, namely, above ground biomass (AGB) and yield (Yld). We conduct a quantitative analysis, which involves calculating the relative differences in AGB and Yld between simulations with and without connectivity (Eq. 1, X_{WC} and X_{OC} stand for the value of the simulated variable with and without connectivity, respectively). This allows us to (1) globally quantify, for all considered situations, the impact of upstream runoff by hydrological connectivity on the functioning of the downstream crops (wheat and faba bean) and (2) understand the influence, on this impact, of environmental conditions within the downstream plot (upstream runoff, climate forcing, soil texture and depth, crop).

$$\Delta\ (ABG\ or\ Yld) = \frac{Xwc - Xoc}{Xoc} \quad (1)$$

For each of the two downstream crops, the relative difference Δ is calculated at the annual timescale along the 25-year time series for any of the 486 combinations (3 soil depths, 3 soil textures, 54 upstream runoff). A year Y is considered a hydrological year spanning from the beginning of September of the calendar year [Y-1] to the end of August of the calendar year [Y]. This results in a total of 12,150 relative differences calculated for AGB and Yld for each crop in the downstream plot and for each of the 25 years. $\Delta > 0$ ($<$ 0) indicates that additional water input through hydrological connectivity has a positive (negative) impact, since it leads to an increase (a decrease) in AGB and Yld compared to the case without connectivity.

Before analyzing all relative differences Δ, it is necessary to define criteria for selecting only realistic and accurate simulations used in the analysis:

- The first criteria relies on the crop yield. For this, we filter AquaCrop simulations based on an agro-economic constraint, namely, yield. Following field-based expert recommendations, we select simulations with Yld (wheat) > 0.5 ton/ha and Yld (faba bean) > 0.25 ton/ha, knowing that yields below these values are considered null from an agro-economic constraint. To avoid eliminating significant impact changes between with and without connectivity, this filter is applied to simulations with connectivity if $\Delta > 0$ and without connectivity if $\Delta < 0$.
- A second criteria defines a threshold value for a significant change (Δ) to account for uncertainties in the AquaCrop simulations. For this, we refer to Dhouib et al. (2022), who reported that the model satisfactorily simulates AGB, with a relative error between observations and simulations of approximately 11%. Therefore, we choose a threshold of 0.11 for the absolute value for Δ, above which the impact of water input through connectivity is considered significant as it exceeds the modeling uncertainty. If negative (positive) Δ values are greater (lower) than or equal to −0.11 (0.11), we consider that the impact of water input through hydrological connectivity on crop functioning is insignificant. Since the model has not been evaluated for yield in the study area, we use the same threshold on Δ for AGB and Yld.

3 Results and discussion

3.1 Above ground biomass (AGB) and yield (Yld)

The analysis of relative differences between simulations with and without connectivity indicates that in most situations (combinations of soil available water capacity derived from soil texture and depth, upstream runoff, and climate year), the contribution of hydrological connectivity through runoff infiltration has a nonsignificant impact on AGB/Yld. This holds true for both downstream crops of wheat and faba bean, with more than 85%/77% and 67%/62% of the calculated differences falling between −0.11 and 0.11, respectively (Fig. 4, Fig. SF3 and SF4 in Supplementary Materials – Section 4).

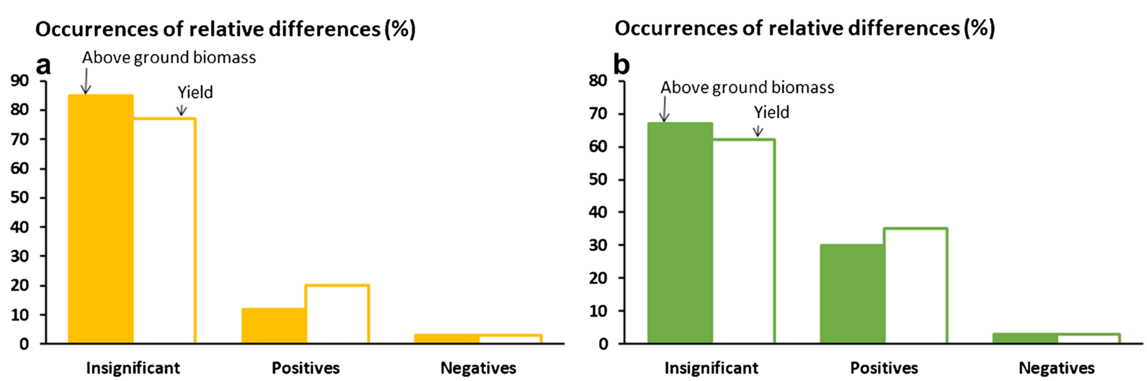

Fig. 4 Occurrences of insignificant, positive, and negative relative differences calculated for wheat (**a**) and for faba bean (**b**). The fully colored bars and the white bars outlined in color correspond to the above ground biomass and the yield, respectively.

Beyond the overall results, there are situations in which the contribution of hydrological connectivity through runoff infiltration significantly increases AGB and Yld for both wheat and faba bean crops. The increase is more pronounced for faba bean than for wheat, with 33% of the relative differences (average over AGB and Yld values) being greater than 0.11 for faba bean, compared to 16% only for wheat. This suggests that faba bean is more sensitive to water shortages than wheat and that additional water input via the infiltration of upstream runoff contributes to alleviating this shortage. This is confirmed by the analysis of the water stress coefficient Ks. Indeed, in 69% of the situations considered, faba bean is more often stressed than wheat since it has a lower Ks (Fig. SF5 in Supplementary Materials - Section 5), while the increase in Ks induced by upstream runoff averages 9% for faba bean and only 2% for wheat (data not shown). This greater sensitivity of faba bean to water shortage can be explained by (1) a shorter phenological cycle, making its functioning more sensitive to intra-annual variations in rainfall, and (2) a shorter root system (Hamblin and Tennant 1987) that does not allow the crop to use water stored in deeper soil layers. These simulation results converge with the observations of Daryanto et al. (2017), who reported a drought-based yield reduction more important for legume crops than for cereal crops.

When a positive impact is observed, the increase induced by water input through hydrological connectivity is higher for grain yield (Yld) than for above ground biomass (AGB). This is ascribed to the way that AquaCrop calculates Yld as the product of AGB and the harvest index (HI), where HI is sensitive to water stress (Ali and Talukder 2008; AquaCrop user manual). Thus, the latter has a double effect on Yld via both AGB and HI.

We also observe another type of situation, much rarer (only 3% of relative differences), where water input through hydrological connectivity leads to negative relative differences (Fig. 4). This indicates a decrease in both above ground biomass (AGB) and yield (Yld), which may be attributed to waterlogging (Liu et al. 2020). Since the frequency of such a situation is low, we mainly focus on situations with a positive impact of hydrological connectivity for the remainder of this paper.

3.2 Influence of environmental conditions

We investigate the influence of environmental conditions of the downstream plot (hydrological conditions, soil texture and depth, and climate) to understand how some of these conditions can lead to positive impacts. For each downstream crop, we categorize the set of significant Δ values ($\Delta > 0.11$) for both above ground biomass (AGB) and yield (Yld) based on the respective classes of a given environmental factor (i.e., four classes for upstream runoff, three classes for texture, three classes for soil depth, and three classes for climate years). Thus, the cumulative distribution across all classes for any environmental factor and any Δ type (AGB, Yld) adds up to 100%. The resulting statistics are presented in Table 4, ST3, ST4, and ST6 and are utilized in the subsequent three subsections.

3.2.1 Hydrological conditions

We emphasize three significant results related to the simulated water dynamics, from runoff to the soil water content, in connection with AGB and Yld variations.

First, in situations with insignificant impact ($\Delta \in [-0.11; +0.11]$), the occurrences of the Δ values are evenly distributed across the four classes of upstream runoff (Supplementary materials - Section 6, Table ST3). In situations with positive impact, the occurrences of the Δ values are lower for the first two classes of upstream runoff that correspond to the lowest cumulative values (R1 and R2 classes in Table 3), as they account for 40 to 46% of cases depending on the crop and the production variable (AGB or Yld). Conversely, the occurrence of the Δ values is larger for the last two classes (R3 and R4) that correspond to the highest cumulative values, with 54 to 60% of cases.

Second, in situations with a positive impact, the increase in the water infiltration amount induced by upstream runoff averages 10% and 7% relative to wheat and faba bean,

Table 4 Percentage occurrence of significant and positive relative differences ($\Delta > 0.11$) categorized by environmental factors. The abbreviations SH, DSH, and SA represent subhumid, dry subhumid, and semiarid years, respectively. The labels R1, R2, R3, and R4 correspond to upstream runoff classes 1, 2, 3, and 4, respectively. The labels C, CL, and SCL stand for clay, clay-loam, and sandy-clay-loam textures, respectively. AGB and Yld are the above ground biomass and the yield, respectively.

Crop	Variable	Climate			Upstream runoff				Texture			Soil depth		
		SH	DSH	SA	R1	R2	R3	R4	C	CL	SCL	0.5 m	1.0 m	1.5 m
Wheat	AGB	0	44	56	22	24	27	27	33	45	22	12	31	57
	Yld	0	40	60	16	25	30	29	31	47	22	20	32	48
Faba bean	AGB	5	49	46	17	23	30	30	25	50	25	15	42	43
	Yld	4	45	51	18	24	28	30	29	45	26	15	42	43

respectively (Table ST4). Meanwhile, the increase in infiltration for situations with an insignificant impact is only 8% and 6% for the two crops.

Third, situations with a positive impact show an average increase in the simulated root zone water content (wRZ) over the crop cycle of 41% and 24% for wheat and faba bean, respectively (Table ST4). In contrast, for situations with an insignificant impact, the simulated root zone water content increases by only 2% and 1% for these crops.

From these three main results, we can infer first and clearly that the hydrological connectivity in Mediterranean regions can have an impact on crop growth. Nevertheless, these results suggest that the increase in AGB and Yld depends only partially on the amount of upstream runoff. While positive impact situations are predominantly associated with a significant increase in upstream runoff, even small increases in upstream runoff (Class R1 in Tables 3 and ST3) and in the resulting infiltration (Table ST3) can also lead to positive impacts. For our case study, the impact of hydrological connectivity through the runoff-runon process on crop production seems to be primarily determined by the increase in the root zone water content during the crop cycle. Our study suggests thus that the impact of hydrological connectivity is not solely determined by the total annual water amount brought by runoff and subsequent infiltration to downslope plot. Rather, it is more influenced by the relationship between runoff (and subsequent infiltration) and the increase of soil water in the root zone during the crop cycle. The remaining results of our study provide insights in this relationship.

3.2.2 Soil texture and depth

For both crops (wheat and faba bean) and both agronomic variables (above ground biomass AGB and yield Yld), the deeper the soil, the larger the occurrence of significant Δ values (Table 4). Indeed, the occurrence intervals are (12–15%), (31–42%), and (43–57%) for 0.5-, 1-, and 1.5-m deep soil, respectively. When dealing with soil texture, a large occurrence of significant Δ values is observed for clay-loam (CL) soils, with an average value of 47% when merging the two crops and two agronomic variables (Table 4). Compared to CL soils, lower occurrences are observed for C and SCL, with average values (over the two crops and two agronomic variables) of 30% and 24%, respectively (Table 4).

These results are consistent with the concept of soil available water capacity and align with recent literature on this topic. We observed increases in above ground biomass (AGB) and yield (Yld) following the infiltration of upstream runoff, mainly for clay-loam (CL) soils and deeper soils. This observation is explained by (1) a larger soil available water capacity for CL and deeper soils, allowing for a greater storage of water in the root zone (Alkassem et al. 2022; Cousin et al. 2022) and (2) a soil conducive to root zone development in terms of depth (van Leeuwen 2022).

To illustrate these statements, we use the example of wheat sown in 2002 in clay-loam soil and compare crop functioning across the three soil depths considered (Fig. 5). For the same temporal pattern and amount of water received from upstream runoff through hydrological connectivity (α ratio is 2 in the simulations of Fig. 5), the above ground biomass increases from 1.5 ton/ha at a soil depth of 0.5 m to 6.1 ton/ha at a soil depth of 1.5 m. This difference can be explained by changes in the root zone water content in relation to soil depth. Indeed, upstream runoff increases the amount of water that infiltrates into the soil by 8% for the three soils between simulations with and without connectivity (data not shown). This further increases wRZ by 2%, 35%, and 88% for the 0.5-m, 1-m, and 1.5-m soil depths, respectively, between simulations with and without connectivity (data not shown). These changes in the root zone water content can be related to changes in crop functioning throughout the crop growth cycle, as discussed below.

- The comparison of crop functioning variables for different soil depths, including water storage in the root zone, transpiration, canopy cover, and above ground biomass, suggests that from the beginning of the crop cycle to January 10, the wheat crop exhibits a similar rooting depth for the three soil depths, thus accessing the same amount of water in the soil.
- From January 10 onwards, the crop roots continue to expand downward in the 1-m and 1.5-m deep soils, while they reach their maximum growth in the shallow soil (0.5-m depth). Consequently, the root zone water content decreases for the crop in the shallow soil (0.5-m depth), whereas it increases for the crop in the deeper soils (1-m and 1.5-m depth). This leads, for the shallow soil, to reductions in canopy cover (CC), crop transpiration (Tr), and above ground biomass (AGB) 50 days later (March 1) when the root zone water content reaches a critical level. Conversely, these reductions are not observed for the crop in the 1-m and 1.5-m deep soils that still benefit from sufficient water content within the root zone.
- For wheat sown in 1-m and 1.5-m deep soils, the initial deviation between the two temporal courses of the root zone water content occurs on March 2. Specifically, the root zone water content slightly increases for the 1.5-m deep soil due to deepening root growth, whereas it decreases for the 1-m deep soil as the root system has reached its maximum depth. This leads, for the 1-m depth soil, to reductions in CC, Tr, and AGB 50 days later (April 15), when the soil water content reaches a critical level. Conversely, these reductions are not observed until senescence of the crop in the 1.5-m deep soils that still benefit from sufficient water content within the root zone.

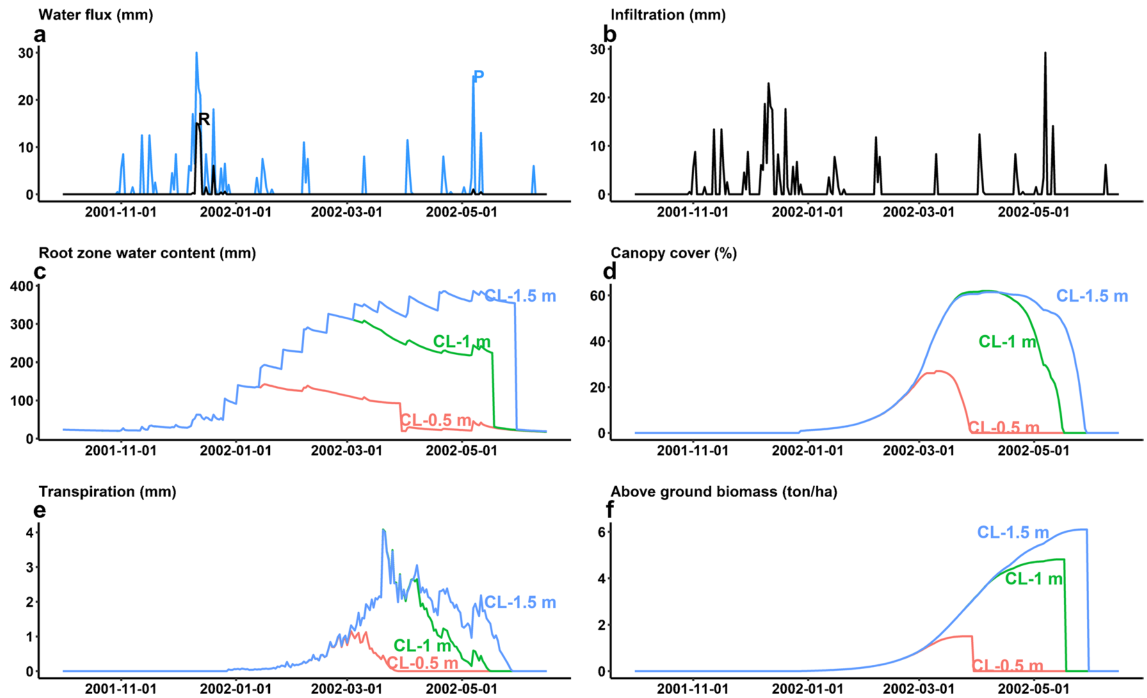

Fig. 5 Comparison of the temporal evolution of the (**a**) runoff (R) and precipitation (P), **b** infiltration (Infl), **c** root zone water content (wRZ), **d** canopy cover (CC), **e** transpiration (Tr), and **f** above ground biomass (AGB) among three different soil depths for wheat sown in 2002 in clay-loam soil, with the same amount of infiltrated upstream runoff. CL-0.5 m, CL-1 m, and CL-1.5 m correspond to clay-loam soil depths of 0.5 m, 1 m, and 1.5 m, respectively. In all of these simulations, the α ratio is 2, indicating that the upslope runoff (R) in (**a**), used as a water input, is multiplied by 2.

3.2.3 Climate forcing

When the influence of climate conditions is analyzed, the increases in above ground biomass (AGB) and yield (Yld) due to water input through hydrological connectivity are primarily noticeable in dry subhumid (DSH) and semiarid (SA) years, while being almost negligible in subhumid (SH) years (Table 4). Indeed, occurrence intervals for significant Δ values ($\Delta > 0.11$) are (0–5%), (40–49%), and (46–60%) for the SH, DSH, and SA years, respectively. For wheat, 0% of significant Δ values are observed in SH years, 42% in DSH years, and 58% in SA years. For faba bean, 4% of significant Δ values are observed in SH years, and the remainder are evenly distributed between DSH and SA years (approximately 48%). Notably, these results may be biassed by the uneven distribution of climate years, comprising 8% of SH years, 40% of DSH years, and 52% SA years. This uneven distribution is an inherent limitation of the study that relies on field observations of climate forcing, although the distribution of significant Δ values does not completely align on that of climate years.

During semi-arid years During SA years, the downstream infiltration of upstream runoff, even in small quantities, increases the water content in the root zone, thereby increasing AGB and Yld. On average, during these years, the increase in the soil water content in the root zone due to upstream runoff is 29% for wheat and 18% for faba bean (Supplementary materials - Section 6, Table ST5). The example of the year 2016 is characteristic of the increase in the root zone water content induced by infiltration. This year is classified as an SA year according to the FAO aridity index (Fig. 3), with annual rainfall accumulation largely below the 25-year average (Supplementary materials - Section 3, Fig. SF2). During this year, the downstream plot benefits from additional runoff between a lower value of 9 mm and an upper value of 105 mm (data not shown), depending on the environmental conditions of the upstream plot (soil, crop, and impluvium area). For the two limits mentioned above, infiltration in the downstream plot (cultivated with wheat) increases by 1% and 18%, respectively, wRZ increases by 4% and 29%, AGB increases by 27% and 112%, and Yld increases by 35% and 406% (median values of all downstream soils, data not shown).

During dry subhumid years The influence of climate forcing on the increase in above ground biomass (AGB) and yield (Yld) may be linked to the intra-annual variability in rainfall, especially in dry subhumid years. Indeed, when analyzing the occurrences of positive impact, calculated for faba bean in dry subhumid years considering all downstream soil textures and depths and all runoff amounts (Supplementary Materials - Section 7, Fig. SF6), we note the following trends.

- On the one hand, water input through hydrological connectivity has a frequent positive impact on AGB and Yld (occurrence > 10% in Fig. SF6) for a group of years, namely, 1998, 1999, 2004, 2010, and 2013. These years are characterized by annual rainfall accumulations of 750 mm, 700 mm, 708 mm, 650 mm, and 622 mm, respectively (Supplementary materials - Section 3, Fig. SF2).
- On the other hand, water input through connectivity has a less frequent positive impact on AGB and Yld (occurrence < 10% in Fig. SF6) for 2003, 2005, and 2009, characterized by very similar annual rainfall accumulations: 728 mm, 651 mm, and 793 mm, respectively (Supplementary materials - Section 3, Fig. SF2).

Therefore, the infiltration of runoff water from upstream is more likely to increase the above ground biomass (AGB) and yield (Yld) of the faba bean crop for the first group of years, but this is less likely for the second group. To gain further insight into this observation, we examine simulations without hydrological connectivity considering a clay-loam soil with a 1-m depth for two dry subhumid years: in 2003 (728 mm of rainfall), the occurrence of positive impacts among all tested situations is rather low (8%), whereas it is much greater (61%) in 2004 (708 mm of rainfall) (Supplementary Materials - Section 7, Fig. SF6). In the situation without hydrological connectivity, AGB and Yld are lower in 2004 than in 2003. Therefore, the potential crop production increase by upstream runoff is higher for 2004 than for 2003. The analysis of monthly rainfall (Fig. 6a) reveals differences in the intra-annual distribution of rainfall between the 2 years, leading to subsequent variations in crop growth.

- During the hydrological year 2004, September, December, and March are characterized by high monthly rain-

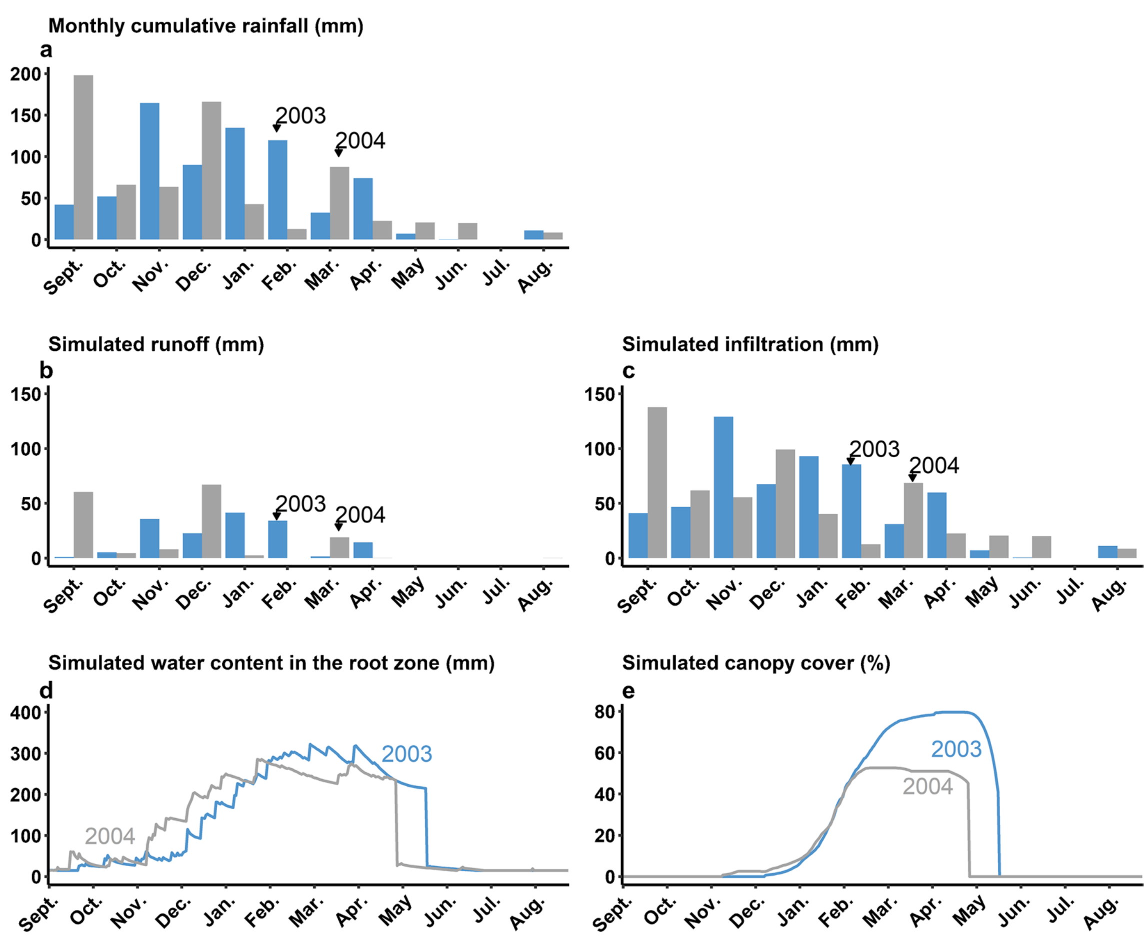

Fig. 6 **a**–**c** Monthly cumulative rainfall, simulated runoff, and simulated infiltration, respectively, in 2003 (blue bars) and 2004 (grey bars). **d**, **e** Simulated water content in the root zone (wRZ) and simulated canopy cover (CC), respectively, without connectivity in 2003 (blue line) and 2004 (grey line) for faba bean sown in a clay-loam soil with a 1-m depth.

fall, thereby increasing the amount of water that infiltrates into the soil (Fig. 6c). In contrast, the hydrological year 2003 has a drier start compared to 2004 (except for November). From January onwards, the rainfall in 2003 is more substantial than that in 2004. This intra-annual distribution of rainfall results in a higher water content in the root zone between September and February in 2004 than in 2003 (Fig. 6d). However, this difference in the soil water content between the 2 years does not have a particularly positive impact on the growth of faba bean in 2004, as the crop is in the early stages of its cycle (Fig. 6e).

- From February onwards, the water content in the root zone in 2003 is higher than that in 2004 due to greater rainfall in January, February, and April. This explains the better vegetation development in 2003.

To compare the impact of hydrological connectivity on crop production during these 2 years (2003 and 2004), we consider the same agro-pedological situation considered above (faba bean cultivated in a clay-loam soil with 1-m depth) for a downstream plot receiving typical upstream runoff (from an upstream plot cultivated with faba bean in a 1-m deep clayey soil). Then, water input from hydrological connectivity increases infiltration and wRZ by 8% and 10%, respectively, in 2004 and by 11% and 6% in 2003, respectively. Furthermore, the resulting increase in yield is far larger in 2004 (73%) than in 2003 (13%), which is ascribed to the intra-annual variability in rainfall discussed above.

4 Conclusion

We report the first complete numerical experiment aimed at quantifying the impact of hydrological connectivity between plots on Mediterranean rainfed crop production.

The results show that water input through hydrological connectivity has a positive impact on agricultural production depending on environmental conditions related to crops, climate forcing, and soil properties. Climate forcing significantly influences the impact of hydrological connectivity from both yearly rainfall and the intra-annual distribution of rainfall. A positive impact is observed in dry subhumid and semiarid climate years, suggesting that this impact may become more pronounced in light of the forecasted climate change.

These novel results pave the way of optimizing agricultural landscape management strategies. Future investigation should expand environmental conditions and address the current study's assumptions. It should include detailed spatial and temporal variability in agricultural plots, considering how upstream runoff and agricultural practices modify soil properties. The cumulative impact of runoff across successive plots and the role of subsurface water flow, particularly in hilly Mediterranean regions, also need investigation. Lastly, coupling crop models with distributed hydrological models could enhance the relevance of runoff simulations within cultivated landscapes.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s13593-024-00981-5.

Acknowledgements The OMERE observatory (www.obs-omere.org), funded by the French institutes INRAE and IRD and coordinated by INAT Tunis, INRGREF Tunis, UMR Hydrosciences Montpellier and UMR LISAH Montpellier, is acknowledged for providing a portion of the data used in this study. The OMERE observatory is part of OZCAR Research Infrastructure (https://www.ozcar-ri.org/) that is supported by the French Ministry of Research, French Research Institutions and Universities.

Authors' contributions Conceptualization: F.J., I.M., J.M., L.P., and R.Z-C.; methodology: F.J., J.M., L.P., and M.D.; software: M.D.; validation: F.J., I.M., J.M., L.P., M.D., and R.Z-C.; formal analysis: J.M., L.P., and M.D.; investigation: F.J., I.M., J.M., L.P., M.D., and R.Z-C.; resources: I.M. and R.Z-C.; data curation: M.D.; writing—original draft preparation: F.J., J.M., L.P., and M.D.; writing—review and editing: F.J., J.M., and M.D.; visualization: M.D.; supervision: F.J. and J.M.; project administration: F.J.; funding acquisition: F.J., I.M., J.M., M.D., and R.Z-C.

Funding This work was financially supported by the Tunisian Ministry of Higher Education and Scientific Research (MESRS), the French National Research Institute for Sustainable Development (IRD). The current study is part of the ALTOS project in the framework of the PRIMA 2018 program, with financial contributions from France and Tunisia.

Data availability The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Code availability Code will be made available on request.

Declarations

Ethics approval Not applicable.

Consent to participate Not applicable.

Consent for publication Not applicable.

Competing interests The authors declare no competing interests.

References

Ali MH, Talukder MSU (2008) Increasing water productivity in crop production—a synthesis. Agr Water Manage 95:1201–1213. https://doi.org/10.1016/j.agwat.2008.06.008

Alkassem M, Buis S, Coulouma G et al (2022) Estimating soil available water capacity within a Mediterranean vineyard watershed

using satellite imagery and crop model inversion. Geoderma 425:116081. https://doi.org/10.1016/j.geoderma.2022.116081
Ammar A, Riksen M, Ouessar M, Ritsema C (2016) Identification of suitable sites for rainwater harvesting structures in arid and semi-arid regions: a review. Int Soil Water Cons Res 4:108–120. https://doi.org/10.1016/j.iswcr.2016.03.001
Anderson W, Johansen C, Siddique KHM (2016) Addressing the yield gap in rainfed crops: a review. Agron Sustain Dev 36:18. https://doi.org/10.1007/s13593-015-0341-y
Araya A, Kisekka I, Gowda PH, Prasad PVV (2017) Evaluation of water-limited cropping systems in a semi-arid climate using DSSAT-CSM. Ag Syst 150:86–98. https://doi.org/10.1016/j.agsy.2016.10.007
Besbes M, Chahed J, Hamdane A (2014) Sécurité hydrique de la Tunisie: gérer l'eau en conditions de pénuries. l'Harmattan, Paris
Blinda M, Thivet G (2009) Ressources et demandes en eau en Méditerranée : situation et perspectives. Sécheresse 20:009–016. https://doi.org/10.1684/sec.2009.0162
Bracken LJ, Croke J (2007) The concept of hydrological connectivity and its contribution to understanding runoff-dominated geomorphic systems. Hydrol Process 21:1749–1763. https://doi.org/10.1002/hyp.6313
Chen L, Sela S, Svoray T, Assouline S (2016) Scale dependence of Hortonian rainfall-runoff processes in a semiarid environment: scale dependence of semiarid rainfall-runoff processes. Water Resour Res 52:5149–5166. https://doi.org/10.1002/2015WR018315
Coulouma G, Ciampalini R, Annabi M et al (2017) Synthèse de la prospection pédologique sur le bassin versant de kamech dans le cadre du projet MASCC. UMR LISAH, Montpellier
Cousin I, Buis S, Lagacherie P et al (2022) Available water capacity from a multidisciplinary and multiscale viewpoint. A review. Agron Sustain Dev 42:46. https://doi.org/10.1007/s13593-022-00774-8
Daccache A, Elbana MA, Fouial A, et al (2016) Gestion des ressources en eau. In: Mediterra: zéro gaspillage en Méditerranée : ressources naturelles, alimentations et connaissances. Centre international de hautes études agronomiques méditerranéennes (CIHEAM) et Organisation des Nations unies pour l'alimentation et l'agriculture (FAO)
Daryanto S, Wang L, Jacinthe P-A (2017) Global synthesis of drought effects on cereal, legume, tuber and root crops production: a review. Agr Water Manage 179:18–33. https://doi.org/10.1016/j.agwat.2016.04.022
Dhouib M, Zitouna-Chebbi R, Prévot L et al (2022) Multicriteria evaluation of the AquaCrop crop model in a hilly rainfed Mediterranean agrosystem. Agr Water Manage 273:107912. https://doi.org/10.1016/j.agwat.2022.107912
Fader M, Giupponi C, Burak S, et al (2020) A 2020 Water. In: Climate and environmental change in the Mediterranean basin – current situation and risks for the future. First Mediterranean Assessment Report. Union for the Mediterranean, Plan Bleu, UNEP/MAP Marseille France, pp. 181-236
García-López J, Lorite IJ, García-Ruiz R et al (2014) Evaluation of three simulation approaches for assessing yield of rainfed sunflower in a Mediterranean environment for climate change impact modelling. Climatic Change 124:147–162. https://doi.org/10.1007/s10584-014-1067-6
Gnouma R (2006) Aide à la calibration d'un modèle hydrologique distribué au moyen d'une analyse des processus hydrologiques : application au bassin versant de l'Yzeron PhD dissertation, INSA Lyon
Hamblin AP, Tennant D (1987) Root length density and water uptake in cereals and grain legumes: how well are they correlated. Aust J Agric Res 38:513–527. https://doi.org/10.1071/ar9870513
Hossain A, Sab AE, Barutcular C et al (2020) Sustainable crop production to ensuring food security under climate change: a Mediterranean perspective. Aust J Crop Sci 14:439–446. https://doi.org/10.3316/informit.121077065862236
Howes DA, Abrahams AD (2003) Modeling runoff and runon in a desert shrubland ecosystem, Jornada Basin, New Mexico. Geomorphology 53:45–73. https://doi.org/10.1016/S0169-555X(02)00347-1
Jones OD, Sheridan GJ, Lane PN (2013) Using queuing theory to describe steady-state runoff-runon phenomena and connectivity under spatially variable conditions. Water Resour Res 49:7487–7497. https://doi.org/10.1002/2013WR013803
Jourdan R (2022) L'agriculture pluviale face aux changements climatiques en Afrique du Nord – Impact et perspective avec l'agroécologie. FAO. Tunis. https://doi.org/10.4060/cc0014fr
Karabulut AA, Crenna E, Sala S, Udias A (2018) A proposal for integration of the ecosystem-water-food-land-energy (EWFLE) nexus concept into life cycle assessment: a synthesis matrix system for food security. J Clean Prod 172:3874–3889. https://doi.org/10.1016/j.jclepro.2017.05.092
Lange MA, Llasat MC, Snoussi M, et al (2020) First Mediterranean assessment report – chapter 1: introduction. In: Climate and environmental change in the Mediterranean basin – current situation and risks for the future. First Mediterranean Assessment Report, Union for the Mediterranean, Plan Bleu, UNEP/MAP, Marseille, France, pp. 41-58. https://doi.org/10.5281/zenodo.7100592
Liu J, Lobb DA (2021) An overview of crop and crop residue management impacts on crop water use and runoff in the Canadian prairies. Water-Sui 13:2929. https://doi.org/10.3390/w13202929
Liu K, Harrison MT, Shabala S et al (2020) The state of the art in modeling waterlogging impacts on plants: what do we know and what do we need to know. Earth's Future 8:e2020EF001801. https://doi.org/10.1029/2020EF001801
Mbava N, Mutema M, Zengeni R et al (2020) Factors affecting crop water use efficiency: a worldwide meta-analysis. Agr Water Manage 228:105878. https://doi.org/10.1016/j.agwat.2019.105878
Mekki I, Albergel J, Ben Mechlia N, Voltz M (2006) Assessment of overland flow variation and blue water production in a farmed semi-arid water harvesting catchment. Phys Chem Earth Parts A/B/C 31:1048–1061. https://doi.org/10.1016/j.pce.2006.07.003
Mekki I, Zitouna-Chebbi R, Jacob F, et al (2018) Impact of land use on soil water content in a hilly rainfed agrosystem: a case study in the Cap Bon peninsula in Tunisia. AGROFOR 3. https://doi.org/10.7251/AGRENG1801064M
Molénat J, Raclot D, Zitouna R et al (2018) OMERE: a long-term observatory of soil and water resources, in interaction with agricultural and land management in Mediterranean hilly catchments. Vadose Zone J 17:180086. https://doi.org/10.2136/vzj2018.04.0086
Molénat J, Barkaoui K, Benyoussef S et al (2023) Diversification from field to landscape to adapt Mediterranean rainfed agriculture to water scarcity in climate change context. Cur OpinEnv Sust 65:101336. https://doi.org/10.1016/j.cosust.2023.101336
Nanda A, Sen S, McNamara JP (2019) How spatiotemporal variation of soil moisture can explain hydrological connectivity of infiltration-excess dominated hillslope: observations from lesser Himalayan landscape. J Hydrol 579:124146. https://doi.org/10.1016/j.jhydrol.2019.124146
Nouri H, Stokvis B, Chavoshi Borujeni S et al (2020) Reduce blue water scarcity and increase nutritional and economic water productivity through changing the cropping pattern in a catchment. J Hydrol 588:125086. https://doi.org/10.1016/j.jhydrol.2020.125086
Nunes AN, de Almeida AC, Coelho COA (2011) Impacts of land use and cover type on runoff and soil erosion in a marginal area of

Portugal. Appl Geogr 31:687–699. https://doi.org/10.1016/j.apgeog.2010.12.006

Prosdocimi M, Jordán A, Tarolli P et al (2016) The immediate effectiveness of barley straw mulch in reducing soil erodibility and surface runoff generation in Mediterranean vineyards. Sci Total Environ 547:323–330. https://doi.org/10.1016/j.scitotenv.2015.12.076

Raes D, Steduto P, Hsiao TC, Fereres E (2009) AquaCrop -the FAO crop model to simulate yield response to water: II. Main algorithms and software description. Agron J 101:438–447. https://doi.org/10.2134/agronj2008.0140s

Ramos MC, Martínez-Casasnovas JA (2006) Trends in precipitation concentration and extremes in the Mediterranean Penedès-Anoia Region, Ne Spain. Climatic Change 74:457–474. https://doi.org/10.1007/s10584-006-3458-9

Saco PM, Rodríguez JF, Moreno-de las Heras M, et al (2020) Using hydrological connectivity to detect transitions and degradation thresholds: applications to dryland systems. Catena 186:104354. https://doi.org/10.1016/j.catena.2019.104354

Schiettecatte W, Ouessar M, Gabriels D et al (2005) Impact of water harvesting techniques on soil and water conservation: a case study on a micro catchment in southeastern Tunisia. J Arid Environ 61:297–313. https://doi.org/10.1016/j.jaridenv.2004.09.022

Schoener G, Stone MC (2019) Impact of antecedent soil moisture on runoff from a semiarid catchment. J Hydrol 569:627–636. https://doi.org/10.1016/j.jhydrol.2018.12.025

Souissi A, Mtimet N, Thabet C et al (2019) Impact of food consumption on water footprint and food security in Tunisia. Food Sec 11:989–1008. https://doi.org/10.1007/s12571-019-00966-3

Spinoni J, Vogt J, Naumann G et al (2014) Towards identifying areas at climatological risk of desertification using the Köppen-Geiger classification and FAO aridity index: towards identifying areas at climatoligical risk of desertification. Int J Climatol 35:2210–2222. https://doi.org/10.1002/joc.4124

Steduto P, Hsiao TC, Raes D, Fereres E (2009) AquaCrop-the FAO crop model to simulate yield response to water: I. Concepts and underlying principles. Agron J 101:426–437. https://doi.org/10.2134/agronj2008.0139s

Tadros MJ, Al-Mefleh NK, Othman YA, Al-Assaf A (2021) Water harvesting techniques for improving soil water content, and morphophysiology of pistachio trees under rainfed conditions. Agr Water Manage 243:106464. https://doi.org/10.1016/j.agwat.2020.106464

Todorovic M, Albrizio R, Zivotic L et al (2009) Assessment of AquaCrop, CropSyst, and WOFOST models in the simulation of sunflower growth under different water regimes. Agron J 101:509–521. https://doi.org/10.2134/agronj2008.0166s

Toumi J, Er-Raki S, Ezzahar J, Khabba S et al (2016) Performance assessment of AquaCrop model for estimating evapotranspiration, soil water content and grain yield of winter wheat in Tensift Al Haouz (Morocco): application to irrigation management. Agric Water Manage 163:219–235. https://doi.org/10.1016/j.agwat.2015.09.007

Van Leeuwen C (2022) 9 - Terroir: the effect of the physical environment on vine growth, grape ripening, and wine sensory attributes. In: Reynolds AG (ed) Managing wine quality (second edition). Woodhead Publishing, pp 341–393

Van Loo M, Verstraeten G (2021) A spatially explicit crop yield model to simulate agricultural productivity for past societies under changing environmental conditions. Water-Sui 13:2023. https://doi.org/10.3390/w13152023

Van Gaelen H, Vanuytrecht E, Willems P et al (2017) Bridging rigorous assessment of water availability from field to catchment scale with a parsimonious agro-hydrological model. Environ Model Softw 94:140–156. https://doi.org/10.1016/j.envsoft.2017.02.014

Wolka K, Mulder J, Biazin B (2018) Effects of soil and water conservation techniques on crop yield, runoff and soil loss in Sub-Saharan Africa: a review. Agr Water Manage 207:67–79. https://doi.org/10.1016/j.agwat.2018.05.016

Yadari HE, Chikhaoui M, Naimi M et al (2019) Techniques de conservation des eaux et des sols au Maroc: Aperçu et perspectives. Rev Mar Sci Agron Vet 7(2):343–355

Yang H, Zehnder AJB (2002) Water scarcity and food import: a case study for Southern Mediterranean countries. World Dev 30:1413–1430. https://doi.org/10.1016/S0305-750X(02)00047-5

Zuecco G, Rinderer M, Penna D et al (2019) Quantification of subsurface hydrologic connectivity in four headwater catchments using graph theory. Sci Total Environ 646:1265–1280. https://doi.org/10.1016/j.scitotenv.2018.07.269