Received: 19 March 2023 | Revised: 3 July 2023 | Accepted: 8 July 2023
DOI: 10.1002/ldr.4838

RESEARCH ARTICLE

WILEY

Modeling-based performance assessment of an indigenous macro-catchment water harvesting technique (Marab) in the Jordanian Badia

Niccolò Renzi[1] | Lorenzo Villani[1,2] | Mira Haddad[3,4] | Stefan Strohmeier[5] | Muhi el Din[3] | Jaafar Al Widyan[6] | Elena Bresci[1] | Giulio Castelli[1,7,8]

[1]Department of Agriculture, Food, Environment and Forestry (DAGRI), Università degli Studi di Firenze, Florence, Italy
[2]Hydrology and Hydraulic Engineering Department, Vrije Universiteit Brussels (VUB), Brussels, Belgium
[3]Restoration Initiative on Dryland Ecosystem, Resilient Agrosilvopastoral Systems (RASP), International Center for Agricultural Research in the Dry Areas (ICARDA), Amman, Jordan
[4]Geosciences, Department of Physical Geography, Utrecht University, Utrecht, The Netherlands
[5]Department of Water, Atmosphere and Environment, Institute of Soil Physics and Rural Water Management, University of Natural Resources and Life Sciences, Vienna, Austria
[6]National Agricultural Research Center (NARC), Amman, Jordan
[7]UNESCO Chair in Hydropolitics, University of Geneva, Genève, Switzerland
[8]Environmental Governance and Territorial Development Hub (GEDT), University of Geneva, Genève, Switzerland

Correspondence
Giulio Castelli, Department of Agriculture, Food, Environment and Forestry (DAGRI), Università degli Studi di Firenze, Florence, Italy.
Email: giulio.castelli@unifi.it

Funding information
U.S. Forest Service

Abstract

Water resources management is fundamental for rural communities in drylands, where water harvesting technologies (WHT) can be used for intercepting surface runoff and storing water in soils. The so-called "Marab" WHT was initially developed by Middle Eastern agro-pastoralists that reside or commute in semi-arid and arid rangelands. The Marab WHT is a macro-catchment measure consisting of earth dams and stone spillways along the contours of a lowland depression or floodplain. Dependent on the local context (i.e., climate, soil, management, etc.), the established Marabs show highly variable effectiveness and little scientific evidence is supporting the scaling out of the technology. This study aims at filling the knowledge gap on the Marab performance in different environments by simulating its hydro-agrological effects for different soils and climatic conditions using the AquaCrop model. A case study performed for a Jordanian Marab over three seasons (2019–2022) confirms its huge improvement potential for barley production. Through Marab-based farming, barley production reached 8.37 t ha^{-1} on average, versus highly variable 0.34 t ha^{-1} without the WHT. The simulation-based assessment of soil textures identified that silty soils have the largest potential for producing up to 9.25 t ha^{-1} barley, compared to 6.60 t ha^{-1} produced in clay soils. Assessing different climate scenarios, a slight increase in daily average temperatures (+0.5°C) led to a considerable production decline of 4%–8%, while a significant reduction of precipitation (−20%) decreased biomass production by a similar rate (4%–10%). This underlines the robustness of the "Marab" WHT to rainfall amount variation. However, simulations also highlight the sensitivity of timing and frequency of flood events: removing the last and the first flood event reduced biomass production by approximately 50% and 80%, respectively, while the barley fails to develop if both events were suppressed.

KEYWORDS
AquaCrop, climate change, drylands, modelling, rainwater harvesting, rangelands

1 | INTRODUCTION

Drylands cover 48% of the earth's surface and are particularly vulnerable to climate change (F. Haddad & Herrera, 2022). Rangelands are among the drylands' most productive ecosystems covering vast areas with native vegetation, predominantly grasses, and shrubs that have the potential to be grazed and serve as a habitat for wildlife and livestock (V. G. Allen et al., 2011). A large extent of Middle East arid rangelands is degraded due to overgrazing, intensive cultivation, collection of fuelwoods, exploitation of herbal and medicinal plants, quarrying activities (Abu-Zanat et al., 2020) as well as climate change (Godde et al., 2020). However, rangelands still provide a wide range of goods and services, including livestock fodder (FAO, 2017), eventually supporting the livelihood of millions of people (Lee et al., 2021). Sustainable management solutions that increase and stabilize the rural dryland communities' food production and their resilience to shocks are therefore crucial.

Jordan is a net food-importer country, importing staple food valued at 947 million US$. The main exported agricultural product is livestock for a value of 157 million US$ versus 213 million US$ of barley imported (WTO, 2019), mostly used as livestock feed. Only 11% of the total land area is cultivated (World Bank, 2020); out of that, less than 1% is equipped with irrigation systems (AQUASTAT, 2019). More than 90% of Jordan's territory is classified arid and receives less than 200 mm of average annual rainfall (Figure 1), forming a dry rangeland environment called "Badia" (FAO, 2008; Tamura et al., 2021). The

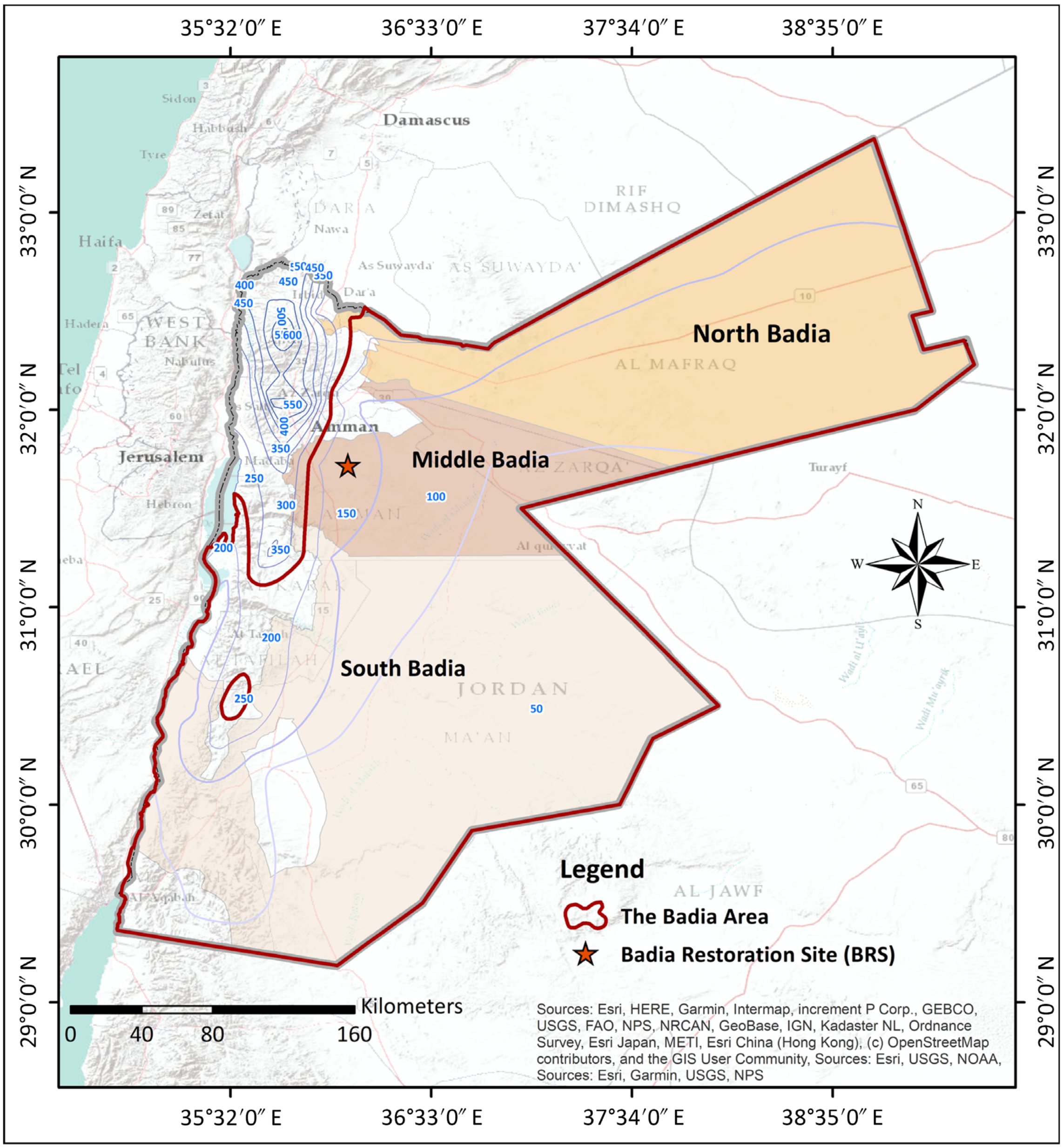

FIGURE 1 Jordan map showing the Badia Area's spatial extent, rainfall isohyet, and the location of the Badia Research Site. [Colour figure can be viewed at wileyonlinelibrary.com]

Badia ecosystem expands from north to south along the country's eastern border (Nawash et al., 2013).

The low precipitation largely constrains crop and fodder production in the Badia (Karrou et al., 2011). Among other threats, introducing mechanized tillage systems has led to a vast removal of the native steppe vegetation (Al Karadsheh et al., 2013). As the overexploitation of ecosystem services and climate change further accelerate the degradation of Jordan's arid rangelands, the uncovered and crusted soils increase surface runoff and erosion (Strohmeier, Fukai, et al., 2021; Strohmeier, Haddad, et al., 2021).

In addressing the seasonal dryness and considerable surface runoff losses, water harvesting technologies (WHT) can aid in enhancing the use of limited and erratic rainwater resources (Dhehibi et al., 2020). Water harvesting is defined as the collection of runoff flows for productive purposes (Critchely, 1991); WHTs aim to collect and store water in times of excess (e.g., heavy rainstorms and flood events) and release it in situations of shortage (Mekdaschi Studer & Liniger, 2013). This results in better water availability over time and represents one of the most important approaches for coping with water shortages and temporal variation in arid and semi-arid regions (Castelli et al., 2018; M. Haddad, Sterk, & Strohmeier, 2022; M. Haddad, Strohmeier, et al., 2022; Rockström & Falkenmark, 2015; Strohmeier, Fukai, et al., 2021; Strohmeier, Haddad, et al., 2021). The ratio between the water-collecting Catchment size and targeted Cultivated Area (C:CA) is commonly used to classify water harvesting systems. Three types are commonly distinguished: (i) floodwater harvesting (C:CA = 100:1–10,000:1, Lawrence et al., 2010); (ii) macro catchment water harvesting systems (C:CA = 10:1–100:1); (iii) micro catchment water harvesting systems (C:CA = 1:1–10:1, Oweis, 2017).

Despite their huge potential, one reason for the improper implementation of WHT is the lack of involvement of the beneficiary farmers (Castelli et al., 2018). The adoption by a critical mass of farmers and the multi-level institutional support are key to successfully scaling those WHTs (Piemontese et al., 2021). Sixt et al. (2018) identified three principal constraints to the WHT technology transfer and upscaling in Jordan: (1) inadequate financial resources to support innovation; (2) lack of a common vision across the government and ministries; (3) institutional issues that inhibit legitimizing the technology. Furthermore, erroneous reports on dryland threats, their causes and consequences, unsustainable management of natural resources (Al-Adamat et al., 2010) and the lack of well-targeted methodologies and design (Ziadat et al., 2012) slow down the implementation. However, increasing efforts are being undertaken to evaluate the performance of WHTs in Jordan's Badia under local communities' management, including the scientific assessment of mechanized micro water harvesting conducted by M. Haddad, Sterk, and Strohmeier (2022), M. Haddad, Strohmeier, et al. (2022), Strohmeier, Fukai, et al. (2021), Strohmeier, Haddad, et al. (2021) and Tatsumi et al. (2021).

With the aim to enhance indigenous knowledge-based technologies' performances and to fill the gap between actual and potential rainfed production, the International Center for Agricultural Research in the Dry Areas (ICARDA) and the National Agricultural Research Center (NARC) of Jordan, together with the local community, developed a pilot watershed in the Jordanian Badia: the Badia Research Site (BRS) (Dhehibi et al., 2020; M. Haddad, Sterk, & Strohmeier, 2022; M. Haddad, Strohmeier, et al., 2022; Mudabber, 2017; Strohmeier, Fukai, et al., 2021; Strohmeier, Haddad, et al., 2021; Tatsumi et al., 2021, Figure 2).

The BRS has been equipped with a combination of WHTs to rehabilitate degraded rangelands: in the upper part of the watershed, a mechanized Vallerani micro-catchment intervention was implemented to capture the excess rainfall for increased shrub-forage production and to reduce surface runoff and consequential erosion along the steep hillslopes. Within the gully system, a series of small check dams were placed to reduce the erosive force of channel runoff and to trigger sedimentation. In the downstream floodplain, a so-called "Marab" macro catchment WHT was established, which is the target of the present research. The Arabic word "Marab" describes a natural depression where runoff cumulates and spreads (Mudabber, 2017). A technical "Marab" structure facilitates those natural depression benefits and enhances its performance through earth dams and stone-made spillways that further decelerate and pond the runoff for deep infiltration into the soil. The increased soil moisture eventually supports the crop water requirements for increased agricultural production.

This study aims to investigate key hydrological, pedological, and crop-development characteristics of the Marab WHT implemented in the central-northern Jordanian Badia (BRS, Figures 1 and 2). Furthermore, the obtained monitoring data are used to set up, calibrate and validate a process-based crop model (FAO AquaCrop) to compare various crop-development scenarios with and without WHT treatment. Eventually, the validated model is used to investigate the Marab WHT performance under different pedological and climatic scenarios to better understand its robustness under variable Badia environments and climate change conditions. The results of this study will support the decision-making and scaling process of the Marab WHTs in dry rangeland agroecosystems of the Middle East with the aim to provide a viable option to increase the local fodder production and strengthen rural livelihoods.

2 | MATERIALS AND METHODS

2.1 | Study area

ICARDA and NARC established the BRS together with the local community of Al Majeddyeh village (31°43′12.69″ N, 36°7′52.06″ E) located around 30 km southeast of Amman. The climate is arid, and the BRS landscape is covered by degraded rangeland and barley cultivated areas (M. Haddad, Sterk, & Strohmeier, 2022; M. Haddad, Strohmeier, et al., 2022). The long-term average annual rainfall is estimated around 150 mm and it was 149 mm for the period 2010–2022 based on Queen Alia International Airport (QAIA) meteorological station data. However, there is an observable reduction of 10%–15% of QAIA rainfall records to the 13 km further west located BRS (Strohmeier, Fukai, et al., 2021; Strohmeier, Haddad, et al., 2021). The rainy season ranges from October to May with a predominant precipitation occurrence from December to February. According to QAIA meteorological data

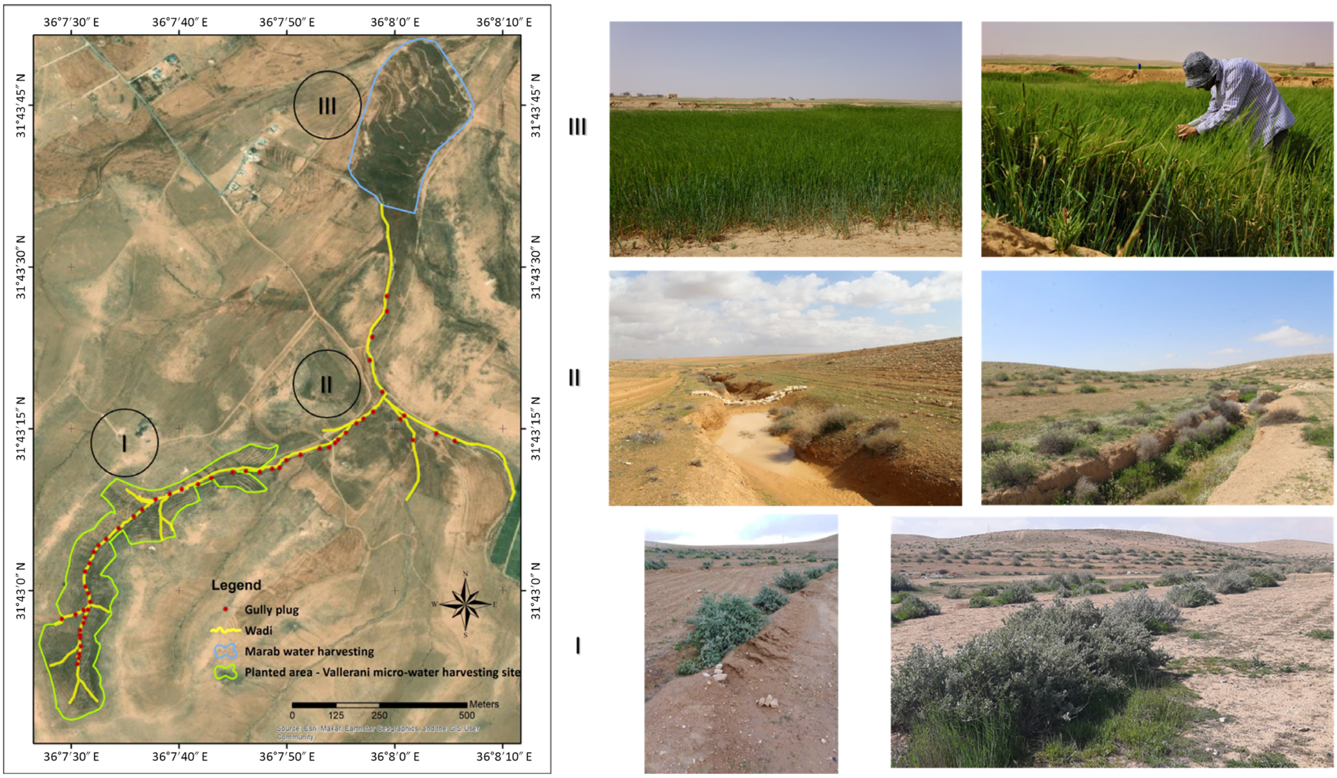

FIGURE 2 Overview of the Badia Research Site: (I) "Vallerani" micro-catchment technology; (II) check dams in gullies—sully plugs; (III) Marab water harvesting technology. [Colour figure can be viewed at wileyonlinelibrary.com]

(2010–2022), the average daily temperature is 7.5°C in the coldest month (January) and 25.0°C in the hottest month (August), respectively. The elevation of the site is approximately 820 m a.s.l (M. Haddad, Sterk, & Strohmeier, 2022; M. Haddad, Strohmeier, et al., 2022). The soil type is a Calcisol above a chert-limestone formation with variable soil depths, degradation stages, and textures changing from upstream to downstream areas. The dominant soil textures are silty clay loam, clay loam, and clay (Strohmeier, Fukai, et al., 2021; Strohmeier, Haddad, et al., 2021). Traditionally, farmers plough the gentle hillslopes and the flatter areas in late summer or autumn for extensive barley cultivation (Al-Bakri & Suleiman, 2004; Al-Karablieh & Salman, 1999; Strohmeier, Fukai, et al., 2021; Strohmeier, Haddad, et al., 2021).

2.2 | Marab WHT

The Marab WHT at the BRS is an innovative community-based technology introduced in 2010 by ICARDA and NARC and implemented through the "Water and Livelihood Initiative" in Al Majeddyeh and Muhareb villages (Mudabber, 2017) thanks to the participation of the local inhabitants. Initially, three Marab WHT prototypes were constructed, then in 2016 the one in Al Majeddyeh village was expanded up to its actual form, while research activities were not developed in the other two. This WHT consists of 11 distinct compartments (blocks) separated by earth dams (Figure 3). The Marab WHT was

FIGURE 3 Bund (a), and spillway (b) of the Marab built at the Badia Research Site (Photo: Niccolò Renzi). [Colour figure can be viewed at wileyonlinelibrary.com]

established at a natural slope of 0.1%–1.5% across the BRS downstream depression; lateral soil leveling of the single compartments serves the even spreading of water. The established earth dams along the contours have an average height of 0.7–1.0 m, a width of 2.0–3.0 m, and a compartment interspace ranging between 10 and 50 m. Around the center of each earth dam one or two stone-covered spillways of approximately 8–10 cm height and 2.2–2.5 m width have been constructed to route the excess runoff further downstream (WOCAT, 2020, Figure 3b). The soil leveling inside the Marab compartments is designed so that retained (ponded) water at the spillway crest nearly reaches the basement of the further upstream earth dam. A flood event typically endures several hours after the rainfall event, and the concentrated runoff toward the Marab WHT submerges all compartments. At the end of a runoff event, the ponding water approximates the upstream dam at its base, generating around 45 mm deep flood-irrigation layer across the agricultural area. For the areal extent of the 12 ha Marab in the BRS, a conservative estimate of the flood-water storage is approximately 5400 m^3, neglecting the potential amounts infiltrated during the event.

2.3 | Data collection

Climate data were retrieved from the QAIA meteorological station, and the reference evapotranspiration (ET0) was calculated using the FAO-56 Penman-Monteith method (R. G. Allen & Pereira, 1999). Several seasons of surface runoff occurrence and barley biomass yield were documented through a combination of scientific and citizen science approaches performed by ICARDA, NARC, and local farmers (M. Haddad, Sterk, & Strohmeier, 2022; M. Haddad, Strohmeier, et al., 2022). The Marab was subdivided according to the earth dam divided into compartments (from now reported as blocks), and each was numbered from up to downstream (Figure 4). Inside each block, the above-ground biomass of barley was sampled from four plots, and the sampling was performed by cutting and collecting the crops using an array of 0.25 cm × 0.25 cm. Samples were then weighted, dried at 62°C for 24 h, and reweighted.

Detailed agro-hydrological monitoring was carried out at the BRS during the cropping season 2021–2022; Table 1 reports the method, tools, and measurement unit used.

Plant morphological characteristics (height and density) were measured from six plots of 0.20 cm × 0.20 cm. Then, 30 spikes for each block were collected, hence the spikes were weighted with and without the rachis to assess the grains weight of the spike. The biomass samplings were performed four times to cover all Marab blocks; the plant density samples were collected twice, and the spike sampling was performed in four times. Analysis of variances for each trait was conducted; in case of reaching the significance level at $p < 0.05$, a comparison between blocks' means was performed using the Dunn and Tukey test (Dunn, 1964). Toward the end of the growing period (May 10, 2022), soil sampling was undertaken to retrieve information regarding the soil moisture condition along the Marab. From upstream, middle, and downstream blocks only one soil sample was taken in 10 and 25 cm depth for soil moisture analysis. The samples were weighted, oven-dried at 105°C until constant mass, and then reweighted to derive water content.

2.3.1 | Remote sensing images and normalized difference vegetation index analysis

The normalized difference vegetation index (NDVI) is a vegetative index for solar radiation absorption at different wavelengths (visible and near-infrared) that supports the remote vegetation growth and health stage assessment (Pettorelli et al., 2005). Previous studies conducted by Tenreiro et al. (2021) describe the relation between NDVI and the fraction of green canopy cover (CC) applied in this study, which is the fraction of the soil surface covered by the canopy. The Marab WHTs barley cover CC was spatially assessed using NDVI images from the Sentinel-2 satellites retrieved from Cropmonitor.com (https://crop-monitoring.eos.com/main-map/fields/all, last access: November 11, 2022) website for three cropping seasons: 2019/2020; 2020/2021; 2021/2022. The images of March 25, 2020, March 6, 2021, and February 26, 2022 were checked as the dates corresponded to the maximum above-ground plant development during each growing season, according to the NDVI value. The Marab was then sub-partitioned into clusters according to single blocks' performance.

2.4 | Crop modeling

The AquaCrop model (FAO; Vanuytrecht et al., 2014) is a widely applied dynamic crop model that performs daily-based agro-biophysical simulations at the field scale considering multiple farm management operations. The model differentiates the fractions of ET (evapotranspiration) into transpiration (Tr) and evaporation (E) (Equation (1)):

$$\mathrm{ET} = \mathrm{Tr} + E \tag{1}$$

Crop biomass development is simulated as a function of the water that transpired (Steduto et al., 2012). Using the normalized water productivity (WP*) assumption, the model calculates daily aboveground biomass production from the daily transpiration and the corresponding daily evaporative demand of the atmosphere (Equation (2)). Crop yield (Equation (3)) is obtained by multiplying the biomass (B) with the according harvest index (HI, Steduto et al., 2012):

$$B = \mathrm{WP}* \times \sum \mathrm{Tr} \tag{2}$$

$$Y = B \times \mathrm{HI} \tag{3}$$

In the AquaCrop model, foliage development is expressed as CC and is fundamental to assess plant transpiration and subsequent biomass development. The maximum canopy cover (CCx) is the upper

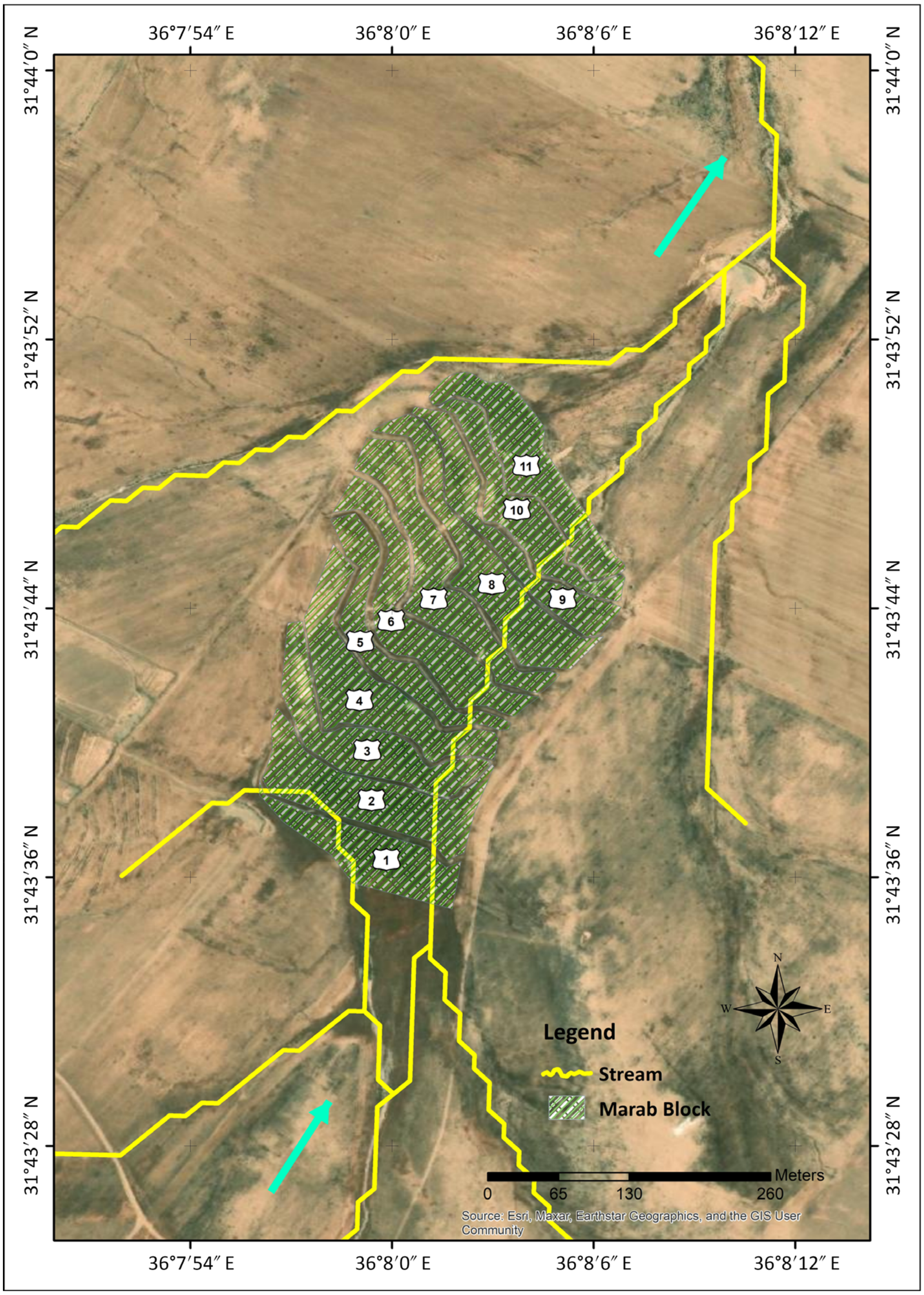

FIGURE 4 Marab block subdivision from upstream to downstream. [Colour figure can be viewed at wileyonlinelibrary.com]

TABLE 1 Data collection.

Parameter	Method	Measurement and tools	Unit and precision
Soil moisture	Gravimetric assessment	UF 750 oven; PGL 10001 electronic scale	g (±0.01)
Plant density	Manual sampling in 6 units per block	Flexometer model FMHT0-36337	Number of plants; tiller; spike, height (±0.01 m)
Plant biomass	Above ground biomass in 4 units per block	UF 750 hoven; PGL 10001 electronic scale	g (±0.01)
Spike weight	Collection of 30 spikes per block	Precision Scale Sartorius model Cubis	g (±0.001)
Runoff depth	Water level assessment	Cipolletti wires and Bushnell 20 MP trophy cam	mm (±1)

threshold that the plant can reach during growth. To simulate the development of the canopy cover and biomass, the model requires input data on climate, crop type, soil, and agricultural management. The climate module requires maximum and minimum temperature, ET0, and rainfall insert on daily bases. While the soil module includes the soil hydraulic properties, that is, fully saturated water content, field capacity, wilting point, and saturated hydraulic conductivity. For the crop module, AquaCrop utilizes conservative and non-conservative crop parameter estimates to consider cultivar-specific crops for robust simulation in areas different from the standardized average climate conditions (Steduto et al., 2012). Non-conservative parameters describe the geographic area, cultivation method, and the applied crop cultivar. Management and irrigation modules allow the selection of different agronomic practices such as the type and quantity of irrigation application.

2.4.1 | AquaCrop set-up

The climate module was set up through daily data obtained from QAIA weather station for a 13 years' time-period (2010–2022). According to a previous study conducted by Strohmeier, Fukai, et al. (2021) and Strohmeier, Haddad, et al. (2021), QAIA rainfall was reduced by 15% to consider the average rainfall reduction observed through few seasons of local monitoring.

The Marab's soil is a clay loam (M. Haddad, Sterk, & Strohmeier, 2022; M. Haddad, Strohmeier, et al., 2022; Strohmeier, Fukai, et al., 2021; Strohmeier, Haddad, et al., 2021), the soil texture was retrieved from a survey conducted by NARC in 2016 at a specific location of the Marab (31°43′39.04″ N, 36°8′2.17″ E). With the texture data, the soil hydraulic properties indicated in Table 2 were estimated by applying pedo-transfer functions used in the soil water characteristic equations. The derived moisture prediction equations were verified by comparisons with mean texture class values of several datasets. A 2000 sample USDA soil texture classes were compared to estimated values by the correlation equation (Saxton & Willey, 2006). The model has already been used in similar climatic contexts (Castellini & Iovino, 2019; Tsegay et al., 2015). For the AquaCrop, simulation was assumed a homogeneous soil.

In the crop module, barley was selected considering that it was the one actually planted and dominant crop in Jordan's Badia for livestock fodder production. The sowing date and the phenological calendar were adjusted based on field operations and observations. Plant density was set to 110 plants m^{-2} according to the estimation made using monitoring plots. Maximum canopy cover was set using the data retrieved from the NDVI-CC correlation. The Harvest Index was measured through local grain analysis. Conservative parameters were retrieved from the study of Abi Saab et al. (2015) which assessed and simulated barley development under semi-arid conditions. The canopy growth coefficient and the canopy decline coefficient were manually calibrated (Table 3).

In the management module, earth-dams with 1 m height were added to reduce the runoff coefficient and an irrigation schedule was created adding 45 mm surface irrigation every time there was an overflow through the Marab spillway and the available volume is filled up with water.

TABLE 3 Crop parameters for AquaCrop set-up.

User-specific parameters (calibrated)	Calibrated value	Units/meaning
Maximum effective rooting depth	0.9	m
Effect of canopy cover in late season	67	(%) CC effect on soil evaporation
Soil surface covered by an individual seedling	1.5	At 90% emergence (cm^2)
Number of plants per hectare	1,100,000	Plants ha^{-1}
Canopy growth coefficient[a]	6.6	per day % CC increase
Maximum canopy cover	96	%
Canopy decline coefficient[a]	7.6	per day % CC decrease
Time from sowing to emergence	23	Calendar days
Time from sowing to maximum rooting depth	86	Calendar days
Time from sowing to start senescence	162	Calendar days
Time from sowing to maturity	216	Calendar days
Time from sowing to flowering	134	Calendar days
Length of the flowering stage	12	Calendar days
Building up of Harvest Index	30	From flowering (days)
Reference Harvest Index (Hio) (%)	44	%

[a]Calibrated value.

TABLE 2 Marab water harvesting technology soil hydraulic characteristic measured with the SPAW (Soil-Plant-Air-Water) model (Saxton & Willey, 2006) and input in the AquaCrop soil module.

Depth (m)	Thickness (m)	Saturation (vol%)	Field capacity (vol%)	Wilting point (vol%)	Saturated hydraulic conductivity (mm day^{-1})
0.0–0.34	0.34	45.9	32.9	17.6	185.3
0.34–0.67	0.33	49.3	38.2	22.4	87.6
0.67–1.05	0.38	49.3	38.2	22.4	87.6
1.05–1.30	0.25	51	40.4	25.6	72.4
1.30–1.69	0.39	52.1	41.7	27.8	67

Note: Layers were isolated with semi-equal depth.

2.4.2 | Hydrological analysis

To simulate the Marab flooding frequency, a simple hydrological analysis was conducted. The upstream watershed is 6.3 km^2 large and the Marab, when flooded, maintains an average water level of 4.5 mm across its extension of 12 ha. The event-based runoff depth required to flood the entire Marab was related to the upstream watershed area (Figure 5); the according rainfall amount required to produce the max. Marab retention volume was then calculated by applying a holistic runoff coefficient considering multiple landscape elements.

Experimental event-based runoff coefficients were assessed through five events observed in the BRS from December 2018 to February 2019. Two observation gauges using Cipoletti weirs enabled the observation of the upstream sub-catchments' surface runoff response in 5 min temporal resolution. The twin-catchment monitoring approach enabled verification of the surface runoff occurrence and magnitudes representing both land treatments, (i) Vallerani WH treated and (ii) traditionally ploughed (untreated) landscapes.

For each event, the relative runoff coefficient was calculated for both the (i) treated and (ii) untreated sub-watersheds accordingly. Both land treatments were scaled across the entire Marab-upstream watershed according to their percentage land cover for calculating a holistic runoff coefficient. Eventually, based on the ratio of the Marab upstream watershed area and the Marab water storage capacity, only 0.86 mm of surface runoff led to a complete Marab filling (i.e., 45 mm flood-irrigation), while the excess is discharged further downstream over the Marab spillway system; therefore, the potential uncertainties related to large rainfall events do not further affect the Marab filling calculation.

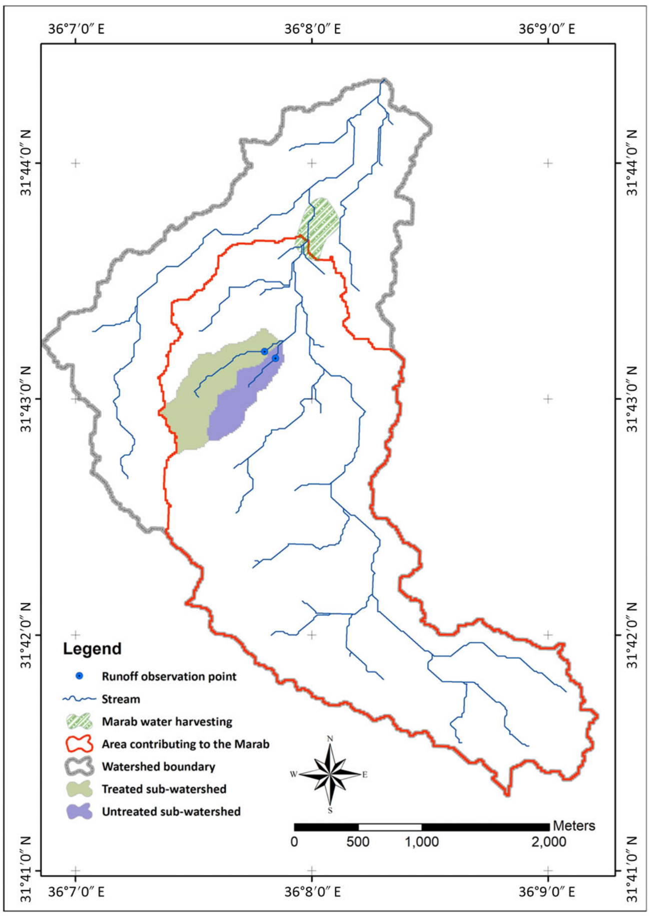

FIGURE 5 Badia Research Site watershed with sub-watershed and run-off observation points. [Colour figure can be viewed at wileyonlinelibrary.com]

2.5 | Model calibration and validation

The sole calibration variable of the modeling procedure was the observed barley biomass. Both field measurements and remote NDVI analyses were applied to consider the spatial inhomogeneities within the Marab. To increase the modeling robustness, two scenarios were created: (1) high-performance WHT, where all earth-bunds are perfectly intact and the blocks store the maximum water amounts, and (2) low-performance WHT, where the blocks fail to retain the entire 45 mm due to occasional breakages throughout the rainy season that require maintenance. The calibration was executed for the 2021/2022 agricultural season, where detailed and continuous crop-development monitoring was performed. In the first step, the high-performance WHT scenario was set up for calibration of the canopy growth coefficient and the canopy decline coefficient. After that, the low-performance WHT scenario was set up, reducing the reference value of 45 mm irrigation per flood event until the simulated biomass production matched the observed in the low-producing zones of the Marab.

Validation of the two cropping seasons, 2019/2020 and 2020/2021, was performed by changing the agricultural management according to the documented management only (e.g., sowing dates) and applying the according seasons' meteorological data. The biomass simulation results were compared with the harvest records provided by ICARDA and NARC using multiple 1 m^2 plots for above-ground biomass monitoring. Due to the lack of availability of crop data separated per block, the mean of the biomass yield obtained in the two WHT performance scenarios was used as the variable for the validation. Different statistical indicators were used to evaluate simulation performance (Equations (4)–(6)): The standard and normalized root mean square errors (RMSE and NRMSE, respectively) and Wilmott's Index of Agreement (d_{iA}). The RMSE, NRMSE, and Wilmott's Index of Agreement were calculated using the following equations:

$$\mathrm{RMSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(S_i - M_i)^2} \tag{4}$$

$$\mathrm{NRMSE} = \frac{\mathrm{RMSE}}{\overline{M}} \times 100 \tag{5}$$

$$d_{iA} = \frac{\sum_{i=1}^{n}(M_i - S_i)^2}{\sum_{i=1}^{n} 2\left(\left|S_i - \overline{M}\right| + \left|M_i - \overline{M}\right|\right)^2} \tag{6}$$

where S_i represents the simulated value of biomass, M_i the observed biomass, $\overline{M}$ represents the mean of the observed biomass value, and n is the number of observations. For the NRMSE a value below 15% is considered a good performance; a di_A values above 80% represents a good performance.

2.6 | Scenario analysis

After calibration and validation of the model, the simulations of barley development for the cropping seasons 2019/2020, 2020/2021, and 2021/2022 were run without the Marab WHT settings to simulate biomass yield using the common agricultural practice applied in the Badia. Thereafter, alternative climate and soil scenarios were generated to assess the robustness and scaling potential of the approach. As a first attempt, an average climatic year was created using 12 years of temperature and rainfall observation; however, the daily average precipitation resulted in a value lower than the minimum threshold needed to generate a flood event. Indeed, the intrinsic nature of dryland rainstorms, as occurring in the Jordanian Badia, is described by a few intense events; rainy days with more than 5 mm precipitation statistically occur on 5–6 days per season only. Hence, the calibration year 2021/2022 was used as a reference to modify the pedoclimatic conditions and to test the performance of the Marab under varying environments. To analyze the effectiveness of Marab WHT under different combinations of temperature and precipitation change, heatmap plots (Gehlenborg & Wong, 2012) were generated. Starting from baseline conditions, heatmaps enable the successive performance visualization of the Marab with different soils and climate conditions. Four common soil textures were selected to simulate soil classes present in the Jordanian Badia: clay, clay-loam, silty-clay-loam, and silt. For each soil type, different simulations were tested, progressively reducing the daily precipitation amounts by 5%–20%, and by increasing daily temperatures by 0.5–2.0°C according to the procedure of Pirttioja et al., 2015. A second series of heatmaps was created to investigate the effects of flood-event occurrence through (i) the removal of the first flooding event, (ii) the removal of the last flooding event, (iii) and the removal of both the first and last flooding event.

3 | RESULTS

3.1 | Statistical analysis

Block-specific values for crop morphological characteristics monitored are summarized in Table 4. Overall, the blocks significantly differ ($p < 0.005$) for population density and plant height. Also, aboveground biomass and spike weight have statistically significant variability across the Marab ($p < 0.05$). After the performance of a Dunn and Tukey test, the upstream blocks (1–5 blocks) were aggregated to a quasi-homogeneous high-performance zone and the downstream blocks (6–11 blocks) were aggregated to a lower productive zone. Block 2 was the most homogeneous and well-developed according to population density and plant height with 108 plants m^{-2}, 621 spikes m^{-2}, and 89 cm height. The lowest values were observed in block 11, with 63 plants m^{-2} and 92 plants m^{-2} and 38 cm height. A downstream decreasing biomass trend is evident with a maximum value measured in the 3rd block (900 g m^{-2}) and a minimum in the 11th block (314 g m^{-2}). Only the spikes' weight had an inverse trend with the most filled caryopsis recorded in the 11th block (0.64 g), while the 2nd block produced lighter spikes (0.43 g). From the soil moisture sampling pursued on May 10 (Table 5), larger moisture values after the weighting and drying process, occurred in the subsoil (25 cm) reaching 10% in the 1st and the 11th block, and 12% in the 6th block. Topsoil moisture (10 cm) showed increasing values from the upstream to the downstream Marab with 6% in the 1st block, 9% in the 6th block, and 10% in the 11th block. The observed value was affected by the sampling timing, as on the date of the sampling the soil was

TABLE 4 Marab water harvesting technology morphological traits for each block.

Block	Spike/m^2	Σ	Plant height (m)	σ	Plant/m^2	σ	Plant biomass/m^2 (g)	σ	Spike weight (g)	σ
Block 1	329abc	244	0.60bc	0.23	104abc	25	803.2b	307.2	0.53bc	0.17
Block 2	621a	277	0.89a	0.05	108ab	20	769.2b	274.8	0.43d	0.28
Block 3	533ab	229	0.78ab	0.22	113ab	14	900.0a	442	0.57b	0.24
Block 4	483b	198	0.75ab	0.11	121a	10	875.6a	638	0.47c	0.25
Block 5	592ab	219	0.74ab	0.2	121a	10	722.0ab	443.6	0.46c	0.23
Block 6	446b	191	0.76ab	0.25	83bc	20	466.8abc	209.1	0.48c	0.2
Block 7	454b	238	0.63bc	0.25	88b	21	285.2c	196.1	0.47c	0.17
Block 8	379abc	327	0.51bc	0.33	104abc	19	218.0c	110.6	0.52bc	0.21
Block 9	213c	225	0.37c	0.18	79c	10	498.4abc	176.6	0.48c	0.22
Block 10	288c	206	0.60bc	0.24	79c	19	340.0bc	131.9	0.49c	0.29
Block 11	92e	107	0.38c	0.17	63d	21	314.0c	203.4	0.64a	0.24
p-Value	0.004		<0.001		<0.001		0.02		0.02	

Note: Different letters indicate statistically different values, the letters represent statistical classes and have a downward trend, where “a” class as the highest mean value.

TABLE 5 Soil moisture sampling results (sampling date: May 10, 2022).

Block	Soil weight dry 10 cm (g)	Water weight (g)	Moisture content (%)	Soil weight 25 cm (g)	Water weight (g)	Moisture content (%)
1	44.0	2.6	6	29.6	3.0	10
6	48.5	4.6	9	33.2	3.9	12
11	33.0	3.3	10	40.2	4.2	10

TABLE 6 Surface runoff observation in the upstream Marab treated and untreated sub-catchments in the 2018/2019 rainy season.

Date	Precipitation (mm)	Runoff treated (mm)	Runoff untreated (mm)
December 28, 2018	2.8	0.0	0.5
February 7, 2019	11.5	0.0	2.5
February 9, 2019	5.0	0.0	1.3
February 10, 2019	1.8	0.0	0.0
February 28, 2019	35.8	6.4	12.0

TABLE 7 Mean normalized difference vegetation index canopy cover (NDVI-CC) measurements following the methodology of Tenreiro et al. (2021).

	NDVI max		CCx	
Year	High productivity	Low productivity	High productivity (%)	Low productivity (%)
2019	0.74	0.56	96	80
2020	0.66	0.46	90	70
2021	0.66	0.48	90	73

already dry due to the scarce rainy season, only 119 mm for the 2021/2022 season.

Table 6 reported the results of the direct observations for the precipitation runoff events during the rainy season 2018/2019 for both treated and untreated sub-catchments of the watershed of the study area. The most intense event was recorded on February 28 with 35.80 mm of precipitation and 6.40 mm of runoff in the Vallerani-treated sub-catchments and 12 mm runoff in the untreated one. This value where used to estimate the watershed runoff coefficient.

The NDVI-CC analysis (Table 7) confirmed the heterogeneity pattern of the crop development observed through field surveys (Figure 6). The first five blocks have developed better and more homogeneously compared to the blocks 6–11. The NDVI of the Marab was largest in the 2019/2020 season. All three seasons showed a similar development pattern: the first five blocks responded with a high CCx (from 90% to 96%) and the last six with lower CCx (from 70% to 80%). Accordingly, 96% of CCx was used as the maximum threshold of canopy cover development in the model.

3.2 | Model set-up, calibration, and validation

The overall calculated runoff coefficient was 0.19. The runoff coefficient was applied to investigate the number and timing of flood events in all three seasons for calibration and validation procedures. During the calibration season 2021/2022 five flood events were computed equivalent to five irrigation events of 45 mm depth, while excess runoff is routed further downstream via the spillway system. Four (flood irrigation) events were calculated for the 2020/2021 season and 10 events were calculated for the cropping season 2019/2020. The first step of the calibration led to a growth coefficient of 6.6% day^{-1} and a canopy decline coefficient of 7.6% day^{-1}. For the low-efficiency WHT scenario, the number of events was kept constant, but runoff depth was set to 30 mm, calculated by calibrating the low-productivity scenario. Manual calibration was performed matching the 8.13 t ha^{-1} biomass observed through 8.04 t ha^{-1} simulated for the high-efficiency Marab WHT scenario. For low-efficiency conditions, 3.50 t ha^{-1} was simulated versus 3.54 t ha^{-1} observed. The RMSE for the high-efficiency scenario is 0.09 t ha^{-1} and 2% for the NRMSE, while the Index of agreement is 0.91. The low-efficiency calibration achieves 0.04 t ha^{-1} for RMSE, 1% for NRMSE, and 0.99 for the d_{iA} (Table 8).

The validation was performed through adjusting the Marab seedbed preparation date as reported and setting the irrigation events according to the flooding events calculated. Overall, the validation shows good performance. RMSE, NRMSE, and d_{iA} are 0.2 t ha^{-1}, 4%, and 0.99 for the season 2020/2021, and 0.80 t ha^{-1} (RMSE), 14% (NRMSE), and 0.66 (d_{iA}) for 2019/2020, respectively.

3.3 | Scenario analysis

3.3.1 | Rangeland barley production

The first simulations were run to compare Marab WHT performance with the traditional extensive barley cropping procedure applied in the Badia (Table 9). The simulation unveils barley growth almost failed

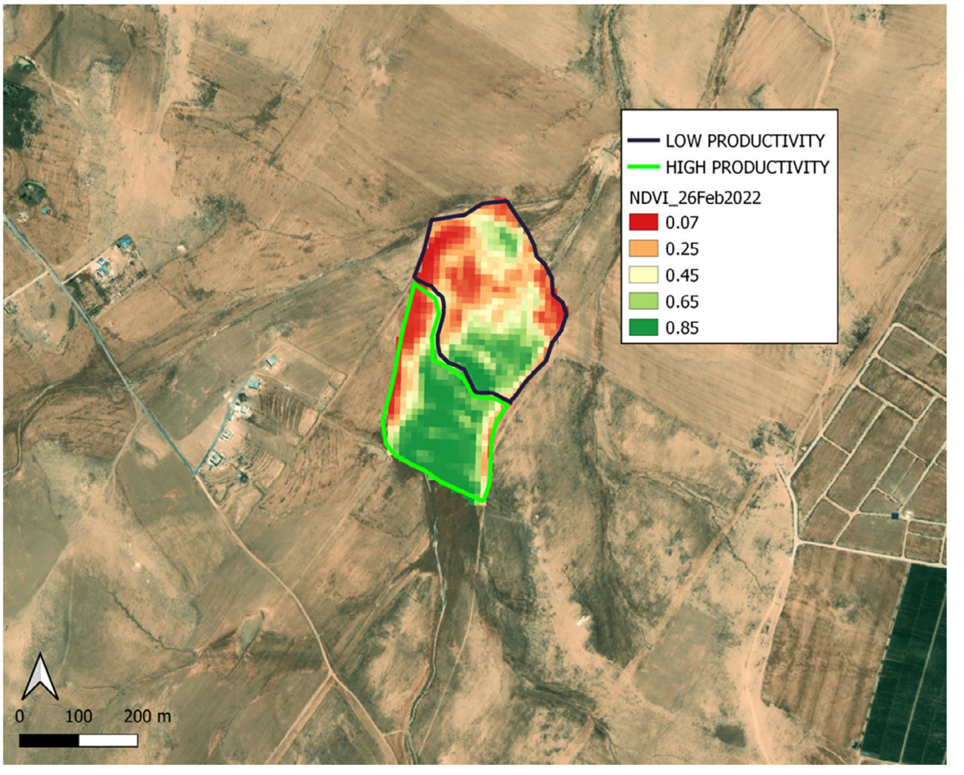

FIGURE 6 Homogenous development areas in the Marab, according to the normalized difference vegetation index (NDVI) value: black corresponds to low-efficiency water harvesting technology; green to high-efficiency WHT (February 26, 2022). [Colour figure can be viewed at wileyonlinelibrary.com]

TABLE 8 Calibration–validation results, for barley in the Marab WHT for cropping season 2021/2022, 2020/2021, and 2019/2020.

	Observed biomass (t ha^{-1})	Simulated biomass (t ha^{-1})	Dev (%)	RMSE (t ha^{-1})	NRMSE (%)	d_{iA}
Calibration						
2021 High efficiency	8.13	8.04	6	0.09	2	0.91
2021 Low efficiency	3.54	3.50	2	0.04	1	0.99
Validation						
2019	5.89	6.7	56	0.81	14	0.66
2020	5.65	5.41	11	0.24	4	0.99

TABLE 9 Marab water harvesting technology (WHT) biomass production against traditional rainfed Badia cropping system.

Season	Marab WHT (t ha^{-1})	Rainfed (t ha^{-1})
2019–2020	9.78	1.00
2020–2021	7.31	0.02
2021–2022	8.01	0.01

in two seasons (2020/2021 and 2021/2022) due to the lack of sufficient rainfall at the beginning of the season. Opposed, in the 2019/2020 cropping season, due to the heavy rainfall events in autumn, barley without Marab WHT produced around 1.0 t ha^{-1} of biomass.

3.3.2 | Impact of soil texture and temperature

The results of the heatmap analysis are shown in Figure 7. For all tested soil types, the main driver of biomass reduction was temperature. Cumulative precipitation shows a lower impact on crop development, as the number of flooding events remained. Even the reduced rainfall amount generated the required minimum runoff filling the Marab WHT. All soil textures show a maximum impact (biomass yield reduction) for the worst-case scenario combining −20% daily precipitation and +2.0°C daily min. and max. temperatures. The clay loam soil type experienced the maximum biomass yield decrease of 3.91 t ha^{-1}, which is less than half of the reference biomass (8.14 t ha^{-1}). Barley crop production is lowest in clay soils; around half of the reference production (6.69 t ha^{-1}) is lost in the 1.0°C scenario, and up to 85% is lost in the +2.0°C scenario. In silty clay loam, biomass yield declined to 2.69 t ha^{-1} in the worst-case scenario, which is 68% less than the silty clay loam reference production (8.25 t ha^{-1}). Silty soil conditions relate with the largest and most robust production; under worst climatic conditions silty soils produce up to 4.20 t ha^{-1}, which is around 55% reduction of the reference production (9.25 t ha^{-1}).

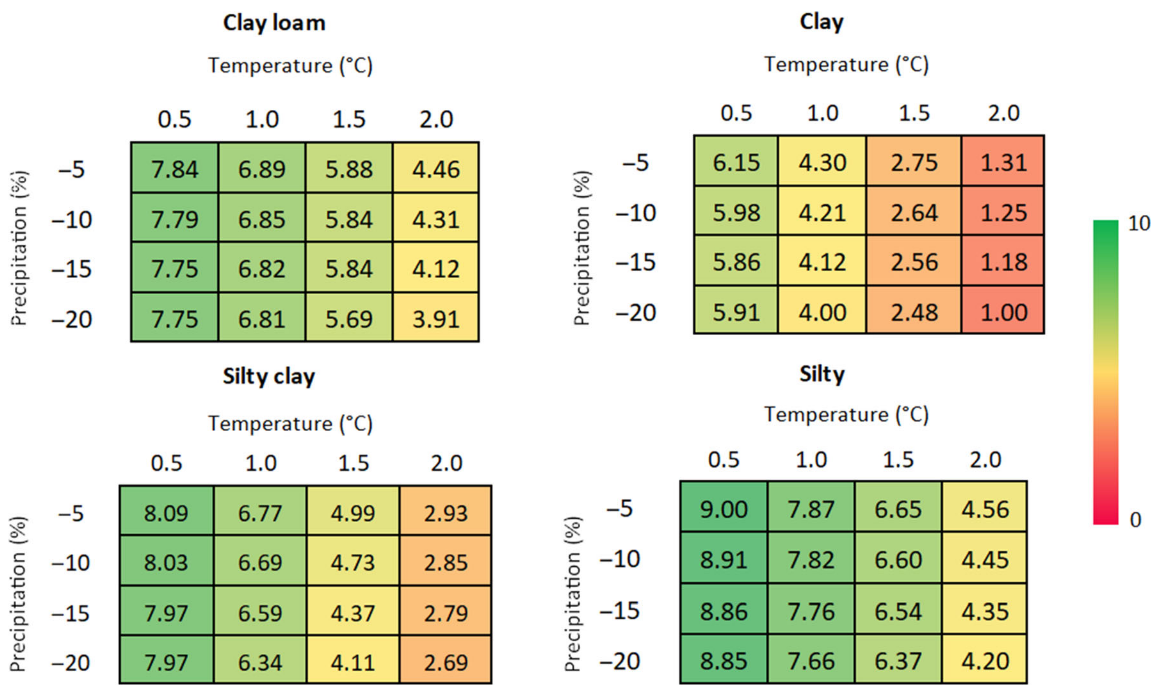

FIGURE 7 Heatmaps for Marab water harvesting technology with different soil textures, increasing temperature, and decreasing annual cumulative precipitation (values in t ha^{-1}). [Colour figure can be viewed at wileyonlinelibrary.com]

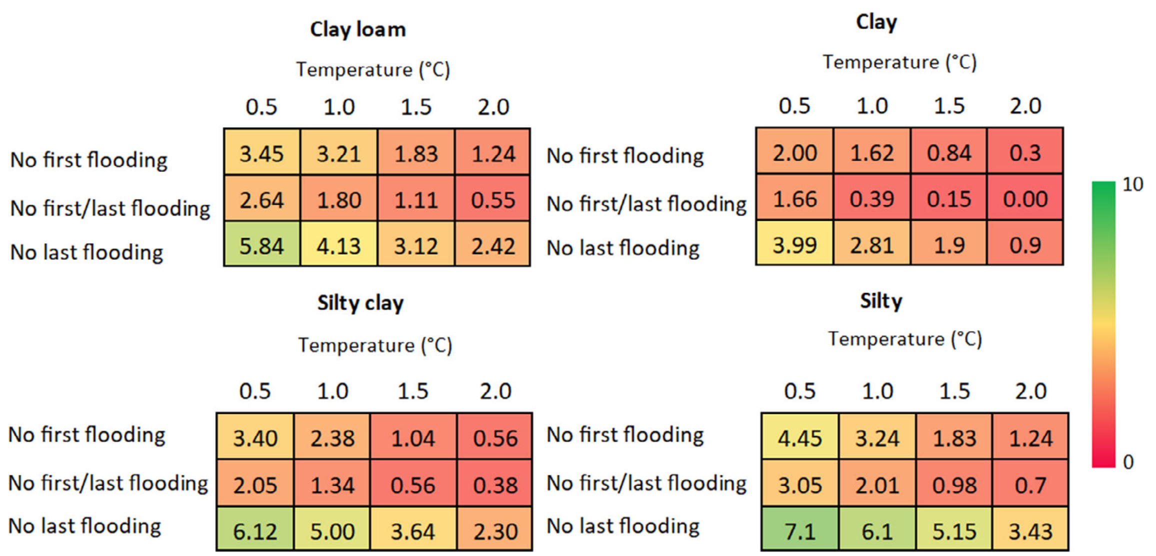

FIGURE 8 Heatmaps for Marab water harvesting technology with different soil textures, reducing the number of annual flooding events and increasing the temperature (values in t ha^{-1}). [Colour figure can be viewed at wileyonlinelibrary.com]

3.3.3 | Impact of flood events occurrence

Heatmaps for three different scenarios of flood-event occurrence (reduction of first, last, and both first and last events) for different soil and temperature change conditions are provided in Figure 8. Suppressing the first seasonal flood event (removed flood-irrigation), even with a slight 0.5°C increase in temperature, all soil types reduce crop production by 40%–50%. Suppressing the last event affects production to a lower extent; the Marab WHT produces harvestable biomass ranging from 7.10 to 3.99 t ha^{-1} in the +0.5°C scenario to 3.43–2.42 t ha^{-1} in the +2.0°C scenario. The largest reduction occurs when removing the first and last flooding event where all soil types fail or nearly fail crop production in the +2.0°C scenario. Again, clay soils are the most affected.

4 | DISCUSSION

Water harvesting represents one valuable resource for many communities in drylands (Castelli et al., 2018). Water resources management using flash floods is fundamental for those communities that must face worsening climate change (Fadul et al., 2020) and the Marab WHT unleashes the potential of the burst rainy event on the Badia. Based on the number of flood events observed and simulated, the Marab WHT provides sufficient additional water (around 180–225 mm) for enhanced crop production under arid dryland conditions of Jordanian Badia (Table 9). However, despite the temporally (seasonal) robust crop production, field monitoring and remote sensing data (NDVI) unveil a non-homogeneous spatial crop performance within the Marab (Figure 6, Table 7). The observed performance variability between the blocks (compartments) might be due dam breakages, as evidenced in the 6th block at the end of the vegetation period in 2022 (Figure 9). However, a lower crop performance in the further downstream blocks might be also due to occasionally low runoff events yielding runoff to the uppermost blocks first/only. Nonetheless, in most downstream blocks, even with the lowest barley population density and biomass yield, the barley developed the largest quantity spikes, which might relate to reduced competition between plants (Rahman Mohammad Al Tawaha et al., 2015). Moreover, grain weight seems rather constant along the Marab, only the last block (11) shows higher grain fillings. Soil moisture sampling conducted at a mature crop stage in late spring 2022 showed higher soil moisture values in the further downstream blocks of the Marab WHT, which might relate to a lower evapotranspiration rate due to the lower biomass and crop coverage (Table 5). Eventually, the Marab WHT achieves exceptionally high biomass (8.13 t ha^{-1} in cropping season 2021/2022) under the severely water-stressed conditions of the Jordanian Badia. Particularly increasing soil moisture (plant-available water) during the initial stages of development boosts crop production (Al-Karablieh & Salman, 1999) evidenced by our simulations (Table 9).

AquaCrop enables the simulation of scenarios for improved crop management in dry areas (Araya et al., 2010). In the present case study, AquaCrop simulations matched the crop development observed in the Marab WHT by using field and NDVI information for set-up and calibration following the crop cover calculation approach

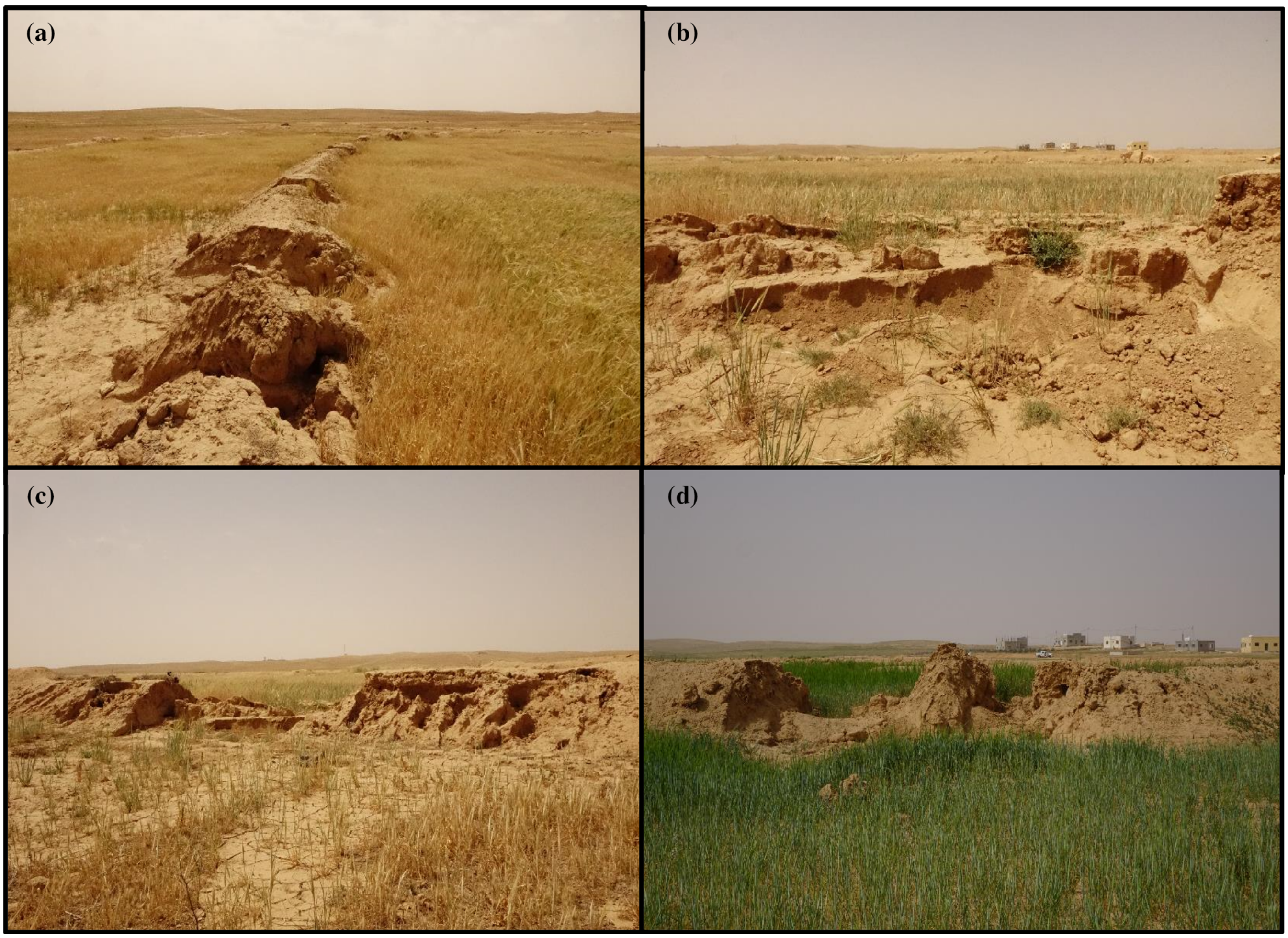

FIGURE 9 Photos from the Marab water harvesting technology showing the collapsing of the soil bunds in different blocks: (a) block 6, (b) block 7, (c) block 8, (d) block 9. [Colour figure can be viewed at wileyonlinelibrary.com]

pursued by Tenreiro et al. (2021). The AquaCrop simulations unveil the positive impact of the Marab particularly comparing WHT with the traditional barley cultivation. Simulations underline that limited precipitation (dry years: 2020/2021; 2021/2022) resulted in nearly complete crop failure, whereas the Marab WHT still produced >7.30 t ha^{-1}. This is nearly one order of magnitude larger compared to the traditionally cultivated biomass yields in wet years (e.g., 2019/2020). Crop failure in the drier rainy seasons has been also reported by the Al Majeddyeh local community serving as citizen scientists and substantially contributing to the BRS monitoring system.

The climate scenarios may be interpreted as possible climate change effects as well as shifting the BRS Marab spatially toward hotter and drier areas within the Badia ecosystem, that is, up to −20% average annual precipitation approximate the 100 mm average annual rainfall zones. The climate scenario results have been illustrated as heatmaps, indicating a strongly adverse effect of temperature on biomass yield. Increased temperatures directly influence evapotranspiration (ET), which results in larger soil water requirements (Figures 7 and 8). The constrained soil water availability, that is, through a limited number of flood events, resulted in increased crop stress, particularly toward the end of the vegetation period inhibiting growth. However, (moderately) decreasing daily precipitation, in our study, did not significantly impact crop development. A biomass yield reduction from 1% to 10% was observed keeping the increasing temperature constant but progressively reducing precipitation (Figure 7). This relates to the fact that few heavy and surface runoff-producing rainfall events still (completely) fill the Marab even with the reduced event-rainfall amount. However, even if climate change is expectedly linked with a likely declining seasonal rainfall in the Jordanian Badia, this does not necessarily apply to the occurrence of heavy rainstorms, as elaborated by the IPCC special report (2019), Strohmeier, Fukai, et al. (2021) and Strohmeier, Haddad, et al. (2021). Nevertheless, the hypothetical reduction of heavy rainstorm occurrence (e.g., flood-causing events) during the rainy season has a potentially huge impact, as soil water availability is reduced at critical stages of the barley phenology: the emergence stage and/or the maturity stage (Figure 8). Removing the first flood event has a larger impact than removing the last one and removing both (first and last flood event), in most cases, results in a biomass reduction of 80%–100% in all soil textures. This also applies to the temperate increase, as additional soil moisture stress, due to larger evapotranspiration at the early crop stages affects the entire plant development. However, future studies should focus on a more in-depths hydrological assessment of the magnitudes, occurrence and uncertainty of flood events in combination with temperature and the according to soil moisture conditions. Anyhow, the present study tackles the performance and robustness of the Marab WHT under typical Badia conditions (soil and climate), which vary across the vast dry-rangeland ecosystem, rather than pursuing an in-depth hydrological study reflecting the target site conditions (BRS) only. Silty soils, due to their large plant available water content (i.e., difference between field capacity and permanent wilting point) cope better with the upcoming dryness and water stress compared to the clayey soils toward the end of the rainy season. Clay soils showed the worst performance due to its predominant micro pore system that holds back moisture with a large potential (matric potential) beyond the plant's capacity for root-water uptake. Moreover, heavy clay soils in dryland conditions can tend to a deep soil crack development (e.g., Vertisols) that potentially deep-infiltrate water during the onset of the rainy season into the deeper soil layers below the root zone of field crops.

4.1 | Limitations of the approach and future developments

This study focused on Badia-typical soil, climate, and cultivation operations. The perturbation of the conditions through heatmaps allowed testing the transferability of the Marab WHT in other contexts, showing a discrete potential for adaptation. Further analysis of the transferability of the Marab will require a requires a wider range of soil, climate, and crop type assessment, which in turn will need additional sets of calibration and/or validation data from substantially different environments, crops and management procedures.

Moreover, watershed-scale assessment may be required to investigate the upstream and downstream consequences of the Marab. Eventually, also the adaptation of the Marab WHT design might improve the efficiency of water storage and endurance, such as through more robust dam systems (e.g., stone-protected bunds; gabion-based spillways; etc.).

5 | CONCLUSION

The study demonstrates (i) a good match between the observed and simulated crop production of a Marab WHT in Jordan's Badia, and (ii) underlines the remarkably enhanced and robust crop performance achieved through the Marab WHT compared with traditional cultivation practices. The performed multi-scenario assessment draws the following conclusions:

1. The Marab WHT largely improved biomass yield; the WHT exceeded biomass yield by roughly one order of magnitude during wet years and outperformed the nearly complete crop failure of the traditional cultivation practice during dry years through producing barley with around 25% biomass yield decrease (comparing best [wet year] with lowest production [driest year]).
2. The Marab WHT performs under most Badia soil texture conditions; best performance was achieved in silty soils (9.25 t ha^{-1}) versus the lowest production was achieved in clayey soils (6.53 t ha^{-1}).
3. Declining precipitation hardly affects the Marab WHT production; an up to 10% biomass yield decrease was simulated by reducing daily rainfall amounts by 20%.
4. The increasing temperature may result in a substantial production decrease; barley biomass yield decreased between 3% and 12% for +0.5°C, and between 45% and 85% for +2.0°C temperature scenarios, depending on the underlying soil type.

5. Frequency and timing of heavy rainstorms (runoff producing events) have a potentially huge impact on the crop production; removing the first and last flood event led to a nearly complete crop failure for increasing temperature scenarios.

The performed ex-ante assessment identifies important aspects of the Marab WHT performance under variable climatic and soil conditions. The gained knowledge can help to identify potential areas for out-scaling considering the techniques' implementation and maintenance costs and the likely achieved gains through enhanced crop production. Further research should target different approaches for transferring Marab WHT in other contexts, modelling different crops cultivation, the effect of the Marab at watershed scale and on groundwater recharge.

AUTHOR CONTRIBUTIONS

Niccolò Renzi: Conceptualization; methodology; formal analysis; investigation; data curation; writing—original draft; writing—review and editing; visualization. **Lorenzo Villani**: Formal analysis; investigation; writing—review and editing. **Mira Haddad**: Conceptualization; methodology; formal analysis; investigation; data curation; writing—review and editing; visualization; supervision; project administration. **Stefan Strohmeier**: Conceptualization; methodology; formal analysis; investigation; data curation; writing—review and editing; supervision; funding acquisition; project administration. **Muhi el Din**: Investigation; data curation; writing—review and editing; supervision; funding acquisition; project administration. **Jaafar Al Widyan**: Investigation; data curation; writing—review and editing. **Elena Bresci**: Conceptualization; methodology; investigation; writing—review and editing; supervision. **Giulio Castelli**: Conceptualization; methodology; formal analysis; investigation; data curation; writing—original draft; writing—review and editing; supervision.

ACKNOWLEDGMENTS

The authors are grateful to the Al Majeddyeh local community for their hosting, continuous support, and knowledge sharing. We also thank the US Forest Service for the long-term partnership and funding of the project "Watershed Restoration in Badia Areas of Jordan—Technology Packages for Controlling and Monitoring Gully Erosion." The research was carried out in the framework of the Master Course in "Natural Resources Management for Tropical Rural Development" of the University of Florence.

CONFLICT OF INTEREST STATEMENT

There is no conflict of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

ORCID

Lorenzo Villani https://orcid.org/0000-0002-4241-7619
Mira Haddad https://orcid.org/0000-0002-9450-1599
Giulio Castelli https://orcid.org/0000-0002-0209-0869

REFERENCES

Abi Saab, M. T., Todorovic, M., & Albrizio, R. (2015). Comparing aquaCrop and cropSyst models in simulating barley growth and yield under different water and nitrogen regimes: Does calibration year influence the performance of crop growth models? *Agricultural Water Management*, *147*, 21–33. https://doi.org/10.1016/j.agwat.2014.08.001

Abu-Zanat, M. M. W., Al-Ghaithi, A. K., & Akash, M. W. (2020). Effect of planting Atriplex seedlings in micro-catchments on attributes of natural vegetation in arid rangelands. *Journal of Arid Environments*, *180*, 104199. https://doi.org/10.1016/j.jaridenv.2020.104199

Al Karadsheh, E., Akroush, S., & Mazahreh, E. S. (2013). Land degradation in jordan-review of knowledge resources, Working Papers 253829, International Center for Agricultural Research in the Dry Areas (ICARDA).

Al-Adamat, R., Diabat, A., & Shatnawi, G. (2010). Combining GIS with multicriteria decision making for siting water harvesting ponds in Northern Jordan. *Journal of Arid Environments*, *74*, 1471–1477. https://doi.org/10.1016/j.jaridenv.2010.07.001

Al-Bakri, J. T., & Suleiman, A. S. (2004). NDVI response to rainfall in different ecological zones in Jordan. *International Journal of Remote Sensing*, *25*(19), 3897–3912. https://doi.org/10.1080/01431160310001654428

Al-Karablieh, E. K., & Salman, A. Z. (1999). Forecasting models for barley production in Jordan. *Emirates Journal of Food and Agriculture*, *11*, 59–81. https://doi.org/10.9755/ejfa.v11i1.4947

Allen, R. G., & Pereira, L. S. (1999). *Crop Evapotranspiration (guidelines for computing crop water requirements)*.

Allen, V. G., Batello, C., Berretta, E. J., Hodgson, J., Kothmann, M., Li, X., McIvor, J., Milne, J., Morris, C., Peeters, A., & Sanderson, M. (2011). An international terminology for grazing lands and grazing animals. *Grass and Forage Science*, *66*, 2–28. https://doi.org/10.1111/j.1365-2494.2010.00780.x

AQUASTAT. (2019). *AQUASTAT statistics bulk download*. https://www.fao.org/aquastat/en/

Araya, A., Habtu, S., Hadgu, K. M., Kebede, A., & Dejene, T. (2010). Test of AquaCrop model in simulating biomass and yield of water deficient and irrigated barley (*Hordeum vulgare*). *Agricultural Water Management*, *97*, 1838–1846. https://doi.org/10.1016/j.agwat.2010.06.021

Castelli, G., Bresci, E., Castelli, F., Hagos, E. Y., & Mehari, A. (2018). A participatory design approach for modernization of spate irrigation systems. *Agricultural Water Management*, *210*, 286–295. https://doi.org/10.1016/j.agwat.2018.08.030

Castellini, M., & Iovino, M. (2019). Pedotransfer functions for estimating soil water retention curve of Sicilian soils. *Archives of Agronomy and Soil Science*, *65*(10), 1401–1416. https://doi.org/10.1080/03650340.2019.1566710

Critchely, W. (1991). *WATER HARVESTING (AGL/MISC/17/91) a manual for the design and construction of water harvesting schemes for plant production. Conservation Agronomist Centre for Development Cooperation Services*.

Dhehibi, B., Haddad, M., Strohmeier, S., & al Hiary, M. (2020). *Enhancing a traditional water harvesting technique in Jordan's agro-pastoral farming system*.

Dunn, O. J. (1964). Multiple comparisons using rank sums. *Technometrics*, *6*(3), 241–252.

Fadul, E., Masih, I., de Fraiture, C., & Suryadi, F. X. (2020). Irrigation performance under alternative field designs in a spate irrigation system with large field dimensions. *Agricultural Water Management*, *231*, 105989. https://doi.org/10.1016/j.agwat.2019.105989

FAO. (2008). *Country profile-Jordan*.

FAO. (2017). *Near east forestry and range commission rangelands management in the near east and north Africa region: Bridging the gap between growing needs and shrinking resources*.

Gehlenborg, N., & Wong, B. (2012). Points of view: Heat maps. *Nature Methods*, *9*, 213. https://doi.org/10.1038/nmeth.1902

Godde, C. M., Boone, R. B., Ash, A. J., Waha, K., Sloat, L. L., Thornton, P. K., & Herrero, M. (2020). Global rangeland production systems and livelihoods at threat under climate change and variability. *Environmental Research Letters*, *15*, 044021. https://doi.org/10.1088/1748-9326/ab7395

Haddad, F., & Herrera, M. (2022). *Grazing with trees*. FAO. https://doi.org/10.4060/cc2280en

Haddad, M., Sterk, G., & Strohmeier, S. M. (2022). *Lushoto WOTRO project View project Aeolian sand transport View project*. https://doi.org/10.5194/egusphere-egu22-13446

Haddad, M., Strohmeier, S. M., Nouwakpo, K., Rimawi, O., Weltz, M., & Sterk, G. (2022). Rangeland restoration in Jordan: Restoring vegetation cover by water harvesting measures. *International Soil and Water Conservation Research*, *10*, 610–622. https://doi.org/10.1016/j.iswcr.2022.03.001

IPCC. (2019). *IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems*. Chapter 3: Desertification. Coordinating Lead authors: Mirzabaev, A., Wu J. https://www.ipcc.ch/site/assets/uploads/2019/08/2d.-Chapter-3_FINAL.pdf

Karrou, M., Oweis, T., Ziadat, F., & Awawdeh, F. (2011). *Water benchmarks of CWANA community-based optimization of the management of scarce water resources in agriculture in central and west Asia and North Africa project rehabilitation and integrated management of dry rangelands environments with water harvesting*.

Lawrence, P., Wallingford, H. R., Salman, M., Faurès, J.-M., Anderson, I. M., Nawaz, K., & Ratsey, J. (2010). *Guidelines on spate irrigation FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS*.

Lee, R. H., Navarro-Navarro, L. A., Ley, A. L., Hartfield, K., Tolleson, D. R., & Scott, C. A. (2021). Spatio-temporal dynamics of climate change, land degradation, and water insecurity in an arid rangeland: The Río San Miguel watershed, Sonora, Mexico. *Journal of Arid Environments*, *193*, 104539. https://doi.org/10.1016/j.jaridenv.2021.104539

Mekdaschi Studer, R., & Liniger, H. (2013). *Guidelines to good practice water harvesting*.

Mudabber, M. (2017). *Marab water harvesting technique in Jordan improving the food security and climate change adaptability of livestock producers using the rainfed barley-based system in Iraq and Jordan*, Funded by IFAD and ICARDA View project Watershed Restoration in Jordan Badia View project Muna Saba Self-employed. https://doi.org/10.13140/RG.2.2.19088.35840

Nawash, O., Shudiefat, M., Al-Tabini, R., & Al-Khalidi, K. (2013). Ethnobotanical study of medicinal plants commonly used by local bedouins in the badia region of Jordan. *Journal of Ethnopharmacology*, *148*, 921–925. https://doi.org/10.1016/j.jep.2013.05.044

Oweis, T. Y. (2017). Rainwater harvesting for restoring degraded dry agro-pastoral ecosystems: A conceptual review of opportunities and constraints in a changing climate. *Environmental Reviews*, *25*, 135–149. https://doi.org/10.1139/er-2016-0069

Pettorelli, N., Vik, O. J., Mysterud, A., Gaillard, J., Compton, J. T., & Stenseth, N. C. (2005). Using the satellite-derived NDVI to assess ecological responses to environmental change. *Trends in Ecology & Evolution*, *20*(9), 503–510. https://doi.org/10.1016/j.tree.2005.05.011

Piemontese, L., Kamugisha, R. N., Tukahirwa, J. M. B., Tengberg, A., Pedde, S., & Jaramillo, F. (2021). Barriers to scaling sustainable land and water management in Uganda: A cross-scale archetype approach. *Ecology and Society*, *26*, 6. https://doi.org/10.5751/ES-12531-260306

Pirttioja, N., Carter, T. R., Fronzek, S., Bindi, M., Hoffmann, H., Palosuo, T., Ruiz-Ramos, M., Tao, F., Trnka, M., Acutis, M., Asseng, S., Baranowski, P., Basso, B., Bodin, P., Buis, S., Cammarano, D., Deligios, P., Destain, M. F., Dumont, B., … Rötter, R. P. (2015). Temperature and precipitation effects on wheat yield across a European transect: A crop model ensemble analysis using impact response surfaces. *Climate Research*, *65*, 87–105. https://doi.org/10.3354/cr01322

Rahman Mohammad Al Tawaha, A., Aziz Turk, M., & Al-Rifaee, K. (2015). *Awnless Barley response to crop managements under Jordanian environments adaptation to climate change in WANA marginal environment through sustainable crop and livestock diversification View project*.

Rockström, J., & Falkenmark, M. (2015). Agriculture: Increase water harvesting in Africa. *Nature*, *519*, 283–285.

Saxton, K. E., & Willey, P. H. (2006). The SPAW model for agricultural field and pond hydrologic simulation. In V. P. Singh & D. K. Frevert (Eds.), *Watershed models* (pp. 401–435). CRC Press.

Sixt, G. N., Klerkx, L., & Griffin, T. S. (2018). Transitions in water harvesting practices in Jordan's rainfed agricultural systems: Systemic problems and blocking mechanisms in an emerging technological innovation system. *Environmental Science & Policy*, *84*, 235–249. https://doi.org/10.1016/j.envsci.2017.08.010

Steduto, P., Hsiao, T., Ferreres, E., & Raes, D. (2012). *Crop yield response to water*.

Strohmeier, S., Fukai, S., Haddad, M., AlNsour, M., Mudabber, M., Akimoto, K., Yamamoto, S., Evett, S., & Oweis, T. (2021). Rehabilitation of degraded rangelands in Jordan: The effects of mechanized micro water harvesting on hill-slope scale soil water and vegetation dynamics. *Journal of Arid Environments*, *185*, 104338. https://doi.org/10.1016/j.jaridenv.2020.104338

Strohmeier, S., Haddad, M., Alwidyan, J., & Dhehibi, B. (2021). *Marab – Water harvesting based floodplain agriculture [Jordan]*. WOCAT SLM Database. https://qcat.wocat.net/en/wocat/technologies/view/technologies_5770/

Tamura, M., Oweis, T., Nangia, V., & Strohmeier, S. (2021). *Managing scarce water resources in the drylands of west Asia and North Africa: Review of joint research between ICARDA and Japanese researchers*.

Tatsumi, C., Taniguchi, T., Yamanaka, N., Yamamoto, S., Fukai, S., Strohmeier, S., Haddad, M., & Oweis, T. (2021). Micro-catchment water harvesting-based rehabilitation ameliorated soil microbial abundance, diversity and function in a degraded dryland. *Applied Soil Ecology*, *164*, 103938. https://doi.org/10.1016/j.apsoil.2021.103938

Tenreiro, T. R., García-Vila, M., Gómez, J. A., Jiménez-Berni, J. A., & Fereres, E. (2021). Using NDVI for the assessment of canopy cover in agricultural crops within modelling research. *Computers and Electronics in Agriculture*, *182*, 106038. https://doi.org/10.1016/j.compag.2021.106038

Tsegay, A., Vanuytrecht, E., Abrha, B., Deckers, J., Gebrehiwot, K., & Raes, D. (2015). Sowing and irrigation strategies for improving rainfed tef (*Eragrostis tef* (Zucc.) Trotter) production in the water scarce Tigray region, Ethiopia. *Agricultural Water Management*, *150*(1), 81–91. https://doi.org/10.1016/j.agwat.2014.11.014

Vanuytrecht, E., Raes, D., Steduto, P., Hsiao, T. C., Fereres, E., Heng, L. K., Garcia Vila, M., & Mejias Moreno, P. (2014). AquaCrop: FAO's crop water productivity and yield response model. *Environmental Modelling and Software*, *62*, 351–360. https://doi.org/10.1016/j.envsoft.2014.08.005

WOCAT. (2020). *Marab - Water harvesting based floodplain agriculture [Jordan]*. WOCAT SLM Database. https://qcat.wocat.net/en/wocat/technologies/view/technologies_5770/

World Bank. (2020). *Jordan economic indicator*. https://data.worldbank.org/country/jordan

WTO. (2019). *Jordan country economics*. https://www.wto.org/english/res_e/res_e.htm

Ziadat, F., Bruggeman, A., Oweis, T., Haddad, N., Mazahreh, S., Sartawi, W., & Syuof, M. (2012). A participatory GIS approach for assessing land suitability for rainwater harvesting in an arid rangeland environment. *Arid Land Research and Management*, *26*, 297–311. https://doi.org/10.1080/15324982.2012.709214

How to cite this article: Renzi, N., Villani, L., Haddad, M., Strohmeier, S., el Din, M., Al Widyan, J., Bresci, E., & Castelli, G. (2023). Modeling-based performance assessment of an indigenous macro-catchment water harvesting technique (Marab) in the Jordanian Badia. *Land Degradation & Development*, *34*(17), 5191–5206. https://doi.org/10.1002/ldr.4838