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Safeguarding Mediterranean Agroecosystems Under Climate Change: Ex-Parcel Runoff as Hydrologic Buffer for Viticulture and Oliviculture

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Abstract

Global climate change is intensifying water scarcity in Mediterranean agroecosystems, demanding a transition from rainfed to irrigated management for high-value crops like vineyards and olive groves. This study introduces a novel hydrologic framework to assess field-scale rainwater harvesting potential across nearly 60,000 individual vineyard and olive grove parcels in continental Portugal. Unlike conventional valley-focused models that delineate catchments at drainage junctions, our approach uses high-resolution digital elevation models and open-source spatial libraries (Python's Fiona, Rasterio, Whitebox) to link every agricultural pixel to its unique upstream hillslope catchment. We quantify and compare "in-parcel" resources (direct precipitation, *Vp*) with "ex-parcel" resources (upstream runoff, *Vup*) under historical (1981–2010) and future (2041–2070) climate scenarios (CMIP6; SSP1-2.6, SSP3-7.0, and SSP5-8.5). A central contribution of this study is the evaluation of water security, defined here as the relative safety buffer between harvested water and the biological irrigation requirements (*Vip*) prescribed for both cultures in each of seven agroclimatic zones defined across the country. Security categories are based on the ratio $(Vp - Vip)/Vip$ for in-parcel resources and $(Vup - Vip)/Vip$ for ex-parcel resources, where values above zero indicate a sustainable surplus, and negative values signify a state of insecurity. Results demonstrate that ex-parcel resources are significantly more substantial, offering 2.5 to 35 times the potential of in-parcel counterparts. While vineyards currently exhibit high security nationwide, southern olive groves face a critical degradation from "secure" to "insecure" status by 2070 under fossil-fueled pathways (SSP5-8.5), with security indices dropping as low as −33.2 in the southern Alentejo region. This highlights ex-parcel runoff as a vital, underutilized hydrologic buffer that can safeguard Mediterranean agriculture against projected climate-induced deficits.

Keywords: hillslope hydrology; parcel-centered vs. valley bottom water resources; permanent cultures; supplemental irrigation; climate change; Mediterranean region

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1. Introduction

The fundamental paradigm of surface water hydrology has historically centered on the drainage network [1–3]. For decades, the watershed—defined by its outlet at the stream

junction or river mouth—has been the primary unit of analysis for water resources management [4,5]. While this valley-centric approach is robust for designing large-scale hydraulic infrastructure and assessing regional water yields, it creates a hydrologic disconnection for most agricultural systems located on hillslopes. In the Mediterranean context, and specifically in continental Portugal, high-value perennial crops like vineyards and olive groves are typically situated on these inter-fluvial slopes, far removed from the primary drainage junctions where water is traditionally monitored and captured. Thus, a current hydro-agronomic challenge lies in this spatial mismatch between valley- and hillslope-centered water resources assessment. Moreover, as climate change intensifies and traditional centralized reservoirs face increasing reliability deficits [6] (https://sir.dgadr.gov.pt/, accessed on 15 December 2025), there is a scientific imperative to shift the hydrologic scale of observation. Research must move from the stream junction to the individual agricultural grid cell, treating the hillslope not merely as a transit zone for runoff directed toward a river but as primary catchment from which the water resource for irrigation is to be assessed, collected and stored.

The literature on hillslope-centered hydrology divides among decentralized water harvesting and micro-scale hydrology, which closely links to a couple of scientific pathways. The first pathway comprises reviews and syntheses on rainwater and atmospheric water harvesting that address implementation, treatment, research trends, and system limits [7–13]. The second involves micro-scale hydrological studies that explain how rainfall is converted into runoff, infiltration, soil moisture change, and small-catchment water balance under hillslope, plot, and micro-catchment conditions [14–23]. The bridge between these two bodies of work is the set of site-selection and process-based studies showing that slope, soil depth, microtopography, antecedent soil moisture, and hydrological connectivity strongly control whether harvesting systems are effective in practice [24–33]. Despite being abundant, none of all these studies has looked at the hillslopes of a hydrographic basin together as a mosaic of individual catchments and proposed a hydrologic model to assess their micro- and macro-scale water resources. That's the gap this studied contributed to filling in.

Mediterranean hydrology is characterized by extreme intra-annual variability and a high sensitivity to precipitation thresholds [34]. Historically, the "stationary" assumption in the field of hydrology allowed for the planning of large dams based on predictable return periods [35]. However, recent climatic shifts have disrupted these patterns [36]. Increasing temperature and evapotranspiration and the rising frequency of consecutive dry years have altered the initial abstraction dynamics of catchments [37], notably those situated in the Mediterranean region. In many southern Portuguese watersheds, the threshold for runoff generation is no longer consistently met at the basin scale, leading to a non-linear breakdown in reservoir inflows [38]. This systemic vulnerability necessitates a decentralized hydrologic strategy. By transitioning the unit of analysis to the hillslope level, we can identify localized runoff opportunities that are otherwise omitted in the aggregated modeling of large basins. Capturing water at the head of a slope—closer to the point of use—minimizes the conveyance losses and environmental trade-offs associated with large-scale valley-bottom diversions.

From an agricultural perspective, the hydrology of vineyards and olive groves is undergoing a fundamental transformation. These species, biologically adapted to the Mediterranean summer drought, have historically relied on deep root systems and soil-water storage. However, the modern demand for yield stability and the mitigation of heat stress has pushed these systems toward mandatory supplemental irrigation [39]. The hydrologic deficit at the parcel level is now a permanent feature of the growing season. While the literature has extensively covered "in-parcel" rainwater harvesting—focusing on

maximizing the infiltration of direct precipitation—there remains a critical lack of research on "ex-parcel" hillslope hydrology. Ex-parcel resources represent the lateral flow and surface runoff generated by the immediate upstream contributing area of a specific field. Understanding the interaction between these two distinct hydrologic sources is essential for designing resilient, field-scale storage systems that can bridge the summer deficit without over-reliance on declining groundwater reserves.

To translate hillslope hydrology into a viable adaptation strategy, the legal and political frameworks governing water use must evolve. Current water policy in the Mediterranean often treats small-scale, decentralized storage as a marginal activity compared to large-scale irrigation districts. However, the socioeconomic survival of permanent cultures depends on making hillslope rainwater harvesting an actionable alternative. A "parcel-centric" hydrologic framework can serve as the scientific basis for new regulatory instruments. By quantifying the security of hillslope runoff, we can provide the evidence needed to adapt environmental permitting and financial incentives, such as those initiated in Portugal to combat water scarcity (Portaria no. 54-C/2023, 27 February). Such instruments must recognize that the agricultural grid cell, when linked to its unique upstream catchment, constitutes a micro-hydrologic unit capable of significant autonomous water provision.

To help fill the research gaps outlined above, we engaged in this work. The primary aim of this study is to establish a high-resolution hydrologic baseline for decentralized rainwater harvesting, evaluating the potential and security of these systems under historical and future climate trajectories. The specific objectives are to (a) develop a parcel-centric delineation workflow to identify the unique upstream catchments of all vineyard and olive grove parcels of continental Portugal; (b) analyze the hydrologic ratio between ex-parcel runoff potential and in-parcel precipitation resources across diverse agroclimatic zones defined for the country; (c) define a "Water Security" index based on the hydrologic buffer between harvested volumes and the prescribed biological irrigation requirements for permanent crops; (d) assess the long-term viability of hillslope rainwater harvesting as an adaptive strategy by projecting these hydrologic variables under three CMIP6 socioeconomic pathways.

The novelty of this research lies in the methodological shift from the valley junction to the hillslope grid cell. We propose a framework that links every individual vineyard and olive grove parcel in continental Portugal to its specific upstream contributing area, effectively treating the entire landscape as a mosaic of tens of thousands of individual catchments. We believe these are enough novel insights that justify publishing this study.

2. Materials and Methods

2.1. Study Area

The study area is continental Portugal, namely the space of vineyards and olive groves that existed in this territory in 2023 as per the official cartography of land use and occupation (COS23; https://www.dgterritorio.gov.pt/COSc2023-Carta-de-Ocupacao-do-Solo-Conjuntural-de-2023, Lisbon, Portugal, accessed on 16 October 2025). As illustrated in Figure 1a, vineyards occupied areas all over continental Portugal, with stronger densities in the so-called "wine regions" such as the Douro (northeast), Alentejo (southeast) or Bairrada (central coast) regions. As regards the olive groves (Figure 1b), the occupation was concentrated in the inlands from north to south. In 2023, the area classified by the COS23 as vineyards was 202,620 hectares, distributed by 25,725 parcels. This differs from the area indicated in the latest report of the Vine and Wine Institute for the same period, which was 180,360 hectares (https://www.ivv.gov.pt/np4/estatistica/, accessed on 18 October 2025). The olive groves, on the other hand, occupied 455,434 hectares, distributed by 39,360 parcels. In the past three decades, the area of vineyards has reduced by some 35%, in response to

global trends of declining wine consumption. The olive groves showed a 7% increase from 2002 to 2024, with a substantial relocation from the center of Portugal to the Alentejo region after the establishment of Alqueva's Multi-Purpose Project, which has a capacity to irrigate nearly 120,000 hectares.

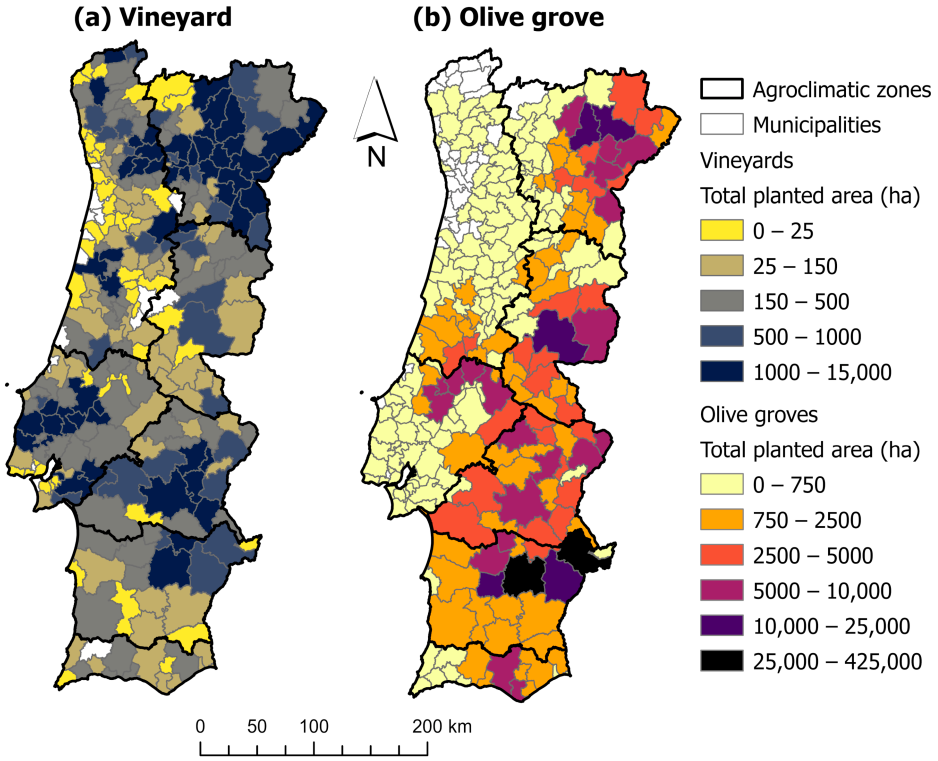


Figure 1. Spatial distribution of (**a**) vineyards and (**b**) olive groves in continental Portugal in 2023. Data source: https://www.dgterritorio.gov.pt/COSc2023-Carta-de-Ocupacao-do-Solo-Conjuntural-de-2023, Lisboa, Portugal, accessed on 16 October 2025.

Traditionally, vineyards and olive groves planted in continental Portugal were rainfed cultures. However, climate change has imposed declines in the annual precipitation, and the need to irrigate these cultures to keep their health and productivity has increased. So, nowadays the irrigation of vineyards and olive groves has become a common practice. Moreover, to support the implementation of irrigation, some public initiatives were launched, mostly related to irrigation efficiency. An important initiative was the Portaria no. 54-C/2023 of 27 February, which established rules for the financial support of interventions targeting adaption to climate change and resilience to water scarcity, namely water savings as a function of climate context. A fundamental rule set in this initiative was to prioritize interventions that would enable the reduction of irrigation water consumption without harming plant health or crop productivity in relation to reference irrigation allocations. The reference irrigation needs of vine and olive trees are indicated in Table 1 for the seven agroclimatic regions of Portugal shown in Figure 2, which generally correspond to drier regions as one moves southward. The needs were determined by the Portuguese Directorate-General for Agriculture and Rural Development [40]. As shown in Table 1, the irrigation needs are higher for olives than for vine trees and, regardless of the culture, are higher for regions where the annual precipitation is lowest. Additionally, they are higher for dry than for semi-humid years. In all cases, the irrigation needs indicated in Table 1 refer to drip irrigation.

Table 1. Irrigation needs of vine and olive plants in dry (I-dry) and semi-humid (I-semi-humid) years and across the agroclimatic regions of Portugal (see location in Figure 2). The needs refer to drip irrigation. The year is defined as "dry" if the annual precipitation is lower than *P*, and "semi-humid" otherwise. Data source: [40].

Zone	*P* (mm/Year)	Occupation (m^2)			I-Dry (m^3/ha)		I-Semi-Humid (m^3/ha)	
		Vineyard	Olive Grove	Total	Vineyard	Olive Grove	Vineyard	Olive Grove
1	905	321	232	553	1511	1808	1388	1661
2	509	854	1046	1901	1616	1173	1485	1078
3	758	69	583	651	1839	2138	1690	1966
4	697	395	436	831	2273	2928	2089	2691
5	609	209	821	1030	2403	3082	2208	2833
6	572	79	1157	1236	2656	3319	2441	3051
7	509	15	223	239	2778	3642	2553	3347

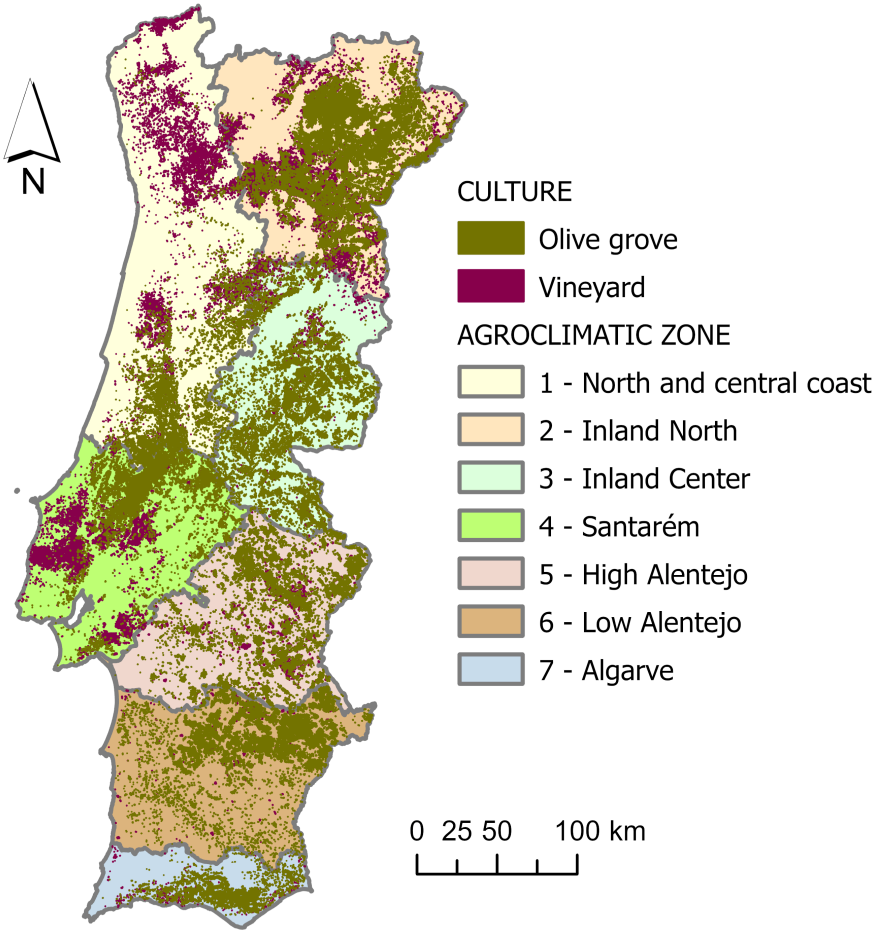


Figure 2. Agroclimatic zones of continental Portugal with indication of vineyard and olive grove parcels. Adapted from [40].

According to the National Institute for Statistics (https://www.ine.pt/, accessed on 15 December 2025), groundwater dominates the sources of irrigation water in continental Portugal, with a share of 74% distributed by dug/drilled wells (59%) and springs (15%), while surface water represents solely 25%, evenly distributed by artificial reservoirs (12.5%) and rivers/lakes (12.5%). Residual water and the public network complete the irrigation water sources with 1% contribution (Table 2; upper panel). A regional assessment of these sources shows that the use of dug/drilled wells increases from 30% in the north to 70–80% in the south of continental Portugal, and a similar trend is observed for the

artificial reservoirs that represent 5% in the north-center but can reach 20–30% in the Alentejo and Algarve regions. On the other hand, the trends for springs and rivers are reversed. In the first case, the use drops from 40% in the north to <5% in the south, in the second case from 20% to <2%. Data from the Portuguese Irrigation Information System (IIS; https://sir.dgadr.gov.pt/, accessed on 15 December 2025) provide deeper insights about volumes of water stored in artificial reservoirs and used to irrigate crops in major hydro-agricultural settlements. In 2025, these regions were irrigated by nearly 60 dam reservoirs with an effective volume of 1965 hm^3, on average. Among them, the Alqueva reservoir stands out at 996 hm^3. Some important information compiled from the IIS is that a large share of reservoirs could not support irrigation to a full extent (100%). The lower panel of Table 2 reveals that, on a long-term average (20 years), the irrigation capacity of 22 reservoirs (nearly 40%) was insufficient at some level.

Table 2. (Upper panel) irrigation sources in the agriculture sector in continental Portugal. The numbers refer to percentage of use per source; (lower panel) volumes of irrigation water and irrigation capacity of monitored artificial reservoirs. The capacities refer to the number of reservoirs that could irrigate the targeted areas with restrictions (capacity < 100%) or without restrictions (capacity > 100%), namely averages observed for the 2005–2025 period. The sources and the capacities are discriminated by agroclimatic zone (Figure 2). Data source: Irrigation Information System (https://sir.dgadr.gov.pt/, accessed on 15 December 2025).

Agroclimatic Zone		**1**	**2**	**3**	**4**	**5**	**6**	**7**
Irrigation source	Surface water							
	Artificial reservoir	4.9	8.1	15.2	5.4	32.7	32.7	19.9
	River and lake	18.5	20.7	13.7	11.9	5.3	5.3	1.9
	Other	0.3	0.8	0.7	1.3	1.7	1.7	0.8
	Groundwater							
	Dug/drilled well	50.2	45.7	60.2	79.2	57.3	57.3	72.7
	Spring	25.7	24.2	9.6	1.2	2.6	2.6	3.5
	Other	0.2	0.2	0.4	0.3	0.1	0.1	0.6
	Other							
	Residual water	0.0	0.1	0.0	0.1	0.0	0.0	0.0
	Public network	0.1	0.2	0.2	0.7	0.2	0.2	0.6
Irrigation from monitored artificial reservoir	Volume of water available for irrigation (hm^3)	144.0	54.6	153.8	202.8	250.9	996.0	163.3
	Irrigation capacity (%)							
	>100	6	11	5	3	4	2	5
	80–100	3	2	1				4
	60–80		1		1	1		1
	30–60		3		1	1		1
	<30	1			2			

Taken together, the numbers about irrigation in continental Portugal reveal a relationship between water scarcity imposed by low levels of precipitation and the use of groundwater sources explored by wells and of reservoirs created by dams and weirs. The share of surface water accumulation in retaining infrastructures is, however, relatively small (12.5% at national scale), and not enough to support full irrigation in nearly 40% of cases. Thus, the construction of more field rainwater harvesting systems is justified to complement the existing infrastructure. Despite covering irrigation sources and capacity in general terms, we believe the information presented above holds for the irrigation of vineyards and olive yards as well.

2.2. Datasets and Sources

The hydrologic framework developed to assess irrigation potential through rainwater harvesting used raster datasets of digital elevation models, of historical and future precipitation, and of curve numbers, provided by the sources listed in Table 3.

Table 3. Datasets used in hydrologic modeling, including web sources.

Data	Description and Purpose	Source
Digital elevation model	Spatial distribution of altitudes across continental Portugal, used to delineate the catchment located upstream of each vineyard and olive grove, and characterize them for area, average slope, and average stream order in keeping with the Strahler classification [41]	https://www.chelsa-climate.org/datasets, accessed on 7 November 2025
Precipitation	Spatial distribution of annual precipitation across continental Portugal, used to estimate (historical data) or forecast (projected data) average precipitation over vine and olive plantations as well as average effective precipitation over the catchment located upstream the same parcels	https://www.chelsa-climate.org/datasets, accessed on 7 November 2025
Curve number	Spatial distribution of curve numbers (average soil moisture conditions) across continental Portugal, used along with the precipitation data to estimate effective precipitation in the catchments located upstream the vineyards and olive groves	https://figshare.com/articles/dataset/GCN250_global_curve_number_datasets_for_hydrologic_modeling_and_design/7756202, accessed on 7 November 2025
Irrigation requirements	Irrigation needs of vine and olive trees set up across the agroclimatic regions of continental Portugal and for dry and semi-humid years, used along with precipitation and runoff potential determined previously to assess the irrigation potential of vineyards and olive groves through rainwater harvesting	[40], see Table 1
Other data	Agroclimatic regions and administrative division (district level) of continental Portugal	[40]; https://www.dgterritorio.gov.pt/cartografia/cartografia-tematica/caop, accessed on 15 December 2025

The climate data were retrieved from the Climatologies at High-resolution for the Earth's Land Surface Areas (CHELSA) dataset, spanning both the recent past and future periods [42,43]. The dataset for each period contained 30-year climatic normals downscaled to a resolution of 30 arc-sec (approximately 1 km) through the CHELSA script following Karger et al. [43]. Furthermore, the dataset was already bias-adjusted [44] using a trend-preserving bias correction methodology [45]. This study used climate normals of total monthly precipitation for the historical period (from 1981 to 2010), and a future period (from 2041 to 2070). Future climate scenarios were derived from the CMIP6 project (Coupled Model Intercomparison Project Phase 6 scenarios) [46] and followed the anthropogenic radiative forcing scenarios—Shared Socioeconomic Pathways [47]: SSP1-2.6; SSP3-7.0 and SSP5-8.5 (Figure 3). In brief, the SSP1 ("Sustainability" pathway) refers to a world that is undergoing a gradual yet profound transition towards a more sustainable future, characterized by the prioritization of inclusive development that respects environmental boundaries that have been predicted. The SSP3 ("Regional Rivalry" pathway) sees the world in re-

gional rivalry, where, among other issues, the prevailing tendency among nations is to prioritize the attainment of energy and food security objectives within their respective regions, often at the cost of pursuing more comprehensive development agendas. Finally, the SSP5 ("Fossil-fueled Development" pathway) projects the planet to be a place where the prevailing sentiment is that the most effective route to sustainable development is to place faith in the efficacy of competitive markets, innovation and participatory societies to produce rapid technological progress and the development of human capital. For each emission scenario, future projections correspond to 5-member ensemble means simulations of global circulation model experiments.

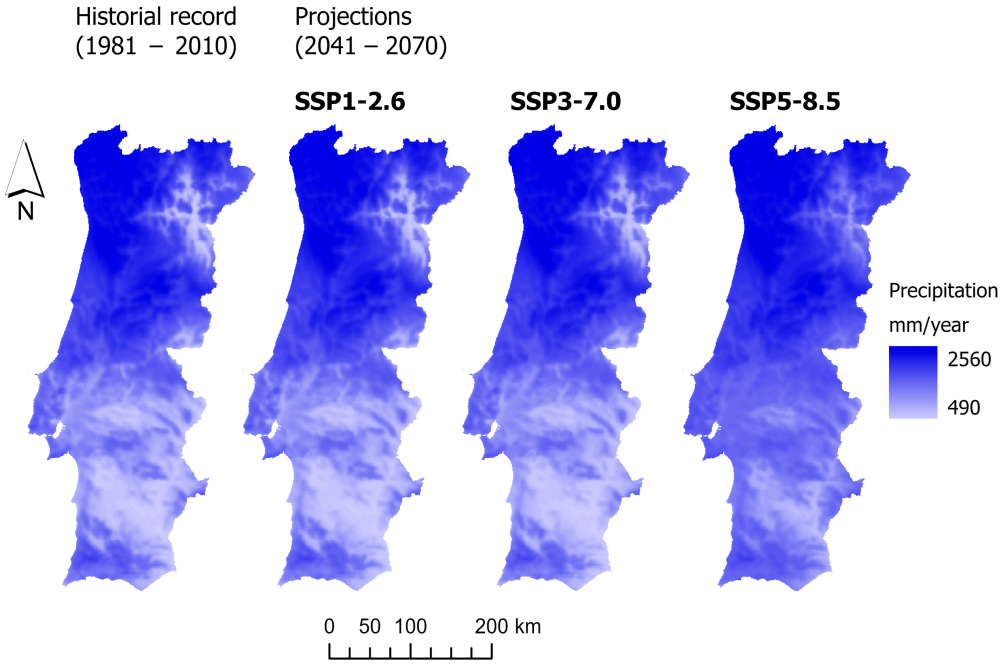


Figure 3. Precipitation data used in the hydrologic framework model.

The curve numbers were recovered from the GCN250 [48], which is a globally consistent gridded dataset defining Curve Numbers (*CNs*) at the 250 m spatial resolution from new global land cover (300 m) and soil (250 m) data. The GCN250 is representative of runoff for a combination of the European Space Agency's Global Land Cover Dataset for 2015 (ESA CCI-LC; https://www.esa-landcover-cci.org/, accessed on 7 November 2025), resampled to 250 m, and geo-registered with the Hydrologic Soil Group's Global Data Product (HYSOGs250m; https://www.earthdata.nasa.gov/data/catalog/ornl-cloud-global-hydrologic-soil-group-1566-1, accessed on 7 November 2025), released in 2018. The *CN* values are contingent on antecedent runoff conditions (ARC), which are influenced by factors such as rainfall intensity and duration, total rainfall, soil moisture conditions, cover density, stage of growth, and temperature. The hydrologic framework used the ARCII (average) conditions.

The irrigation requirements of vine and olive plants were compiled from the Portuguese Directorate-General for Agriculture and Rural Development [40]. To calculate the irrigation needs (see Table 1), the authors used the methodology of the FAO—Food and Agriculture Organization (https://www.fao.org/land-water/resources/tools/software/cropwat/en, accessed on 15 December 2025)—and the available information on reference evapotranspiration; culture coefficients in keeping with the initial, development, intermediary and final phases of plant growth; culture evapotranspiration; effective precipitation; and climate scenario (dry or semi-humid year) set up on the basis of climatological norms (1971–2000 and 1991–2020). The transition between "dry" and "semi-humid" years was set

differently for the seven agroclimatic regions of Portugal (Figure 2), where the precipitation thresholds are indicated in Table 1.

2.3. Hydrologic Framework

The hydrologic framework is portrayed as a workflow in Figure 4. The methodology comprises four steps: 1. Data handling, 2. Hydrologic modeling, 3. Rainwater harvesting planning, and 4. Irrigation potential assessment. The details of each step are presented in the next subsections. In brief, the data handling comprises preparing the datasets to work in the ArcGIS Pro (version 3.4.0) geographic information system (ESRI, Redlands, CA, USA, https://www.esri.com/, accessed on 7 November 2024), namely clipping them to the study area (continental Portugal) and organizing all the information required for the next steps in geopackage and Excel file formats. The hydrologic modeling includes cross-tabulating precipitation records with parcels of target irrigable cultures (in the current study, vineyards and olive groves) to estimate the rainwater falling in the parcels. Moreover, as unique and novel feature, hydrologic modeling includes a module to estimate the surface flow reaching each parcel from the upstream catchment. The planning of rainwater harvesting balances the storage potential of vineyards and olive groves, if small dams are built to retain the precipitation over the parcel (called in-parcel resources) or the runoff entering the parcel from upstream (ex-parcel resources). Finally, the assessment of irrigation potential compares the storage potential with the irrigation requirements of vine and olive plantations, on an annual basis, in average and low precipitation conditions. The steps outlined above run for historical and projected precipitation records, considering various shared socioeconomic pathways, as indicated above (Section 2.2).

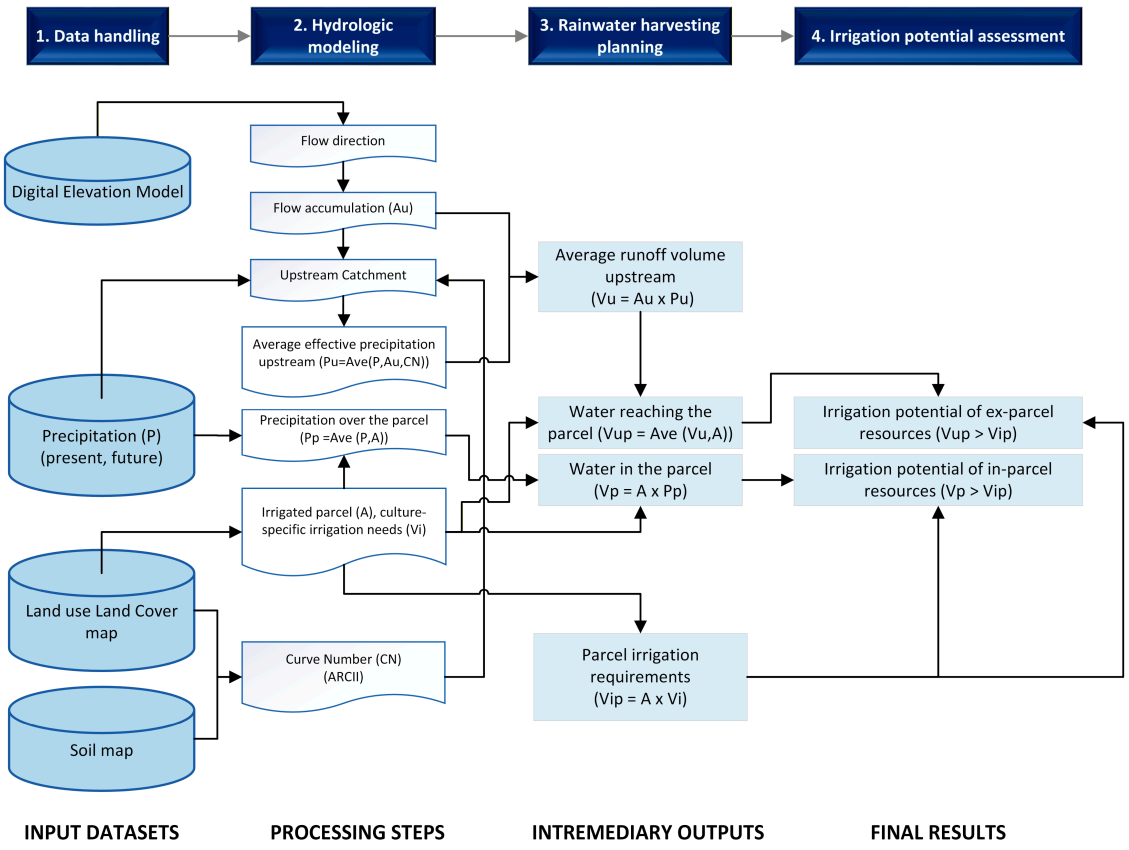


Figure 4. Hydrologic framework showing the steps and tasks involved in the assessment of irrigation potential derived from in-parcel and ex-parcel harvested rainwater resources. The arrows designate the flow from input datasets to intermediary outputs and final results.

The unique feature of our hydrologic framework is therefore the module whereby all pixels of the DEM—digital elevation model (e.g., of continental Portugal)—are linked to an upstream catchment. This differs from all previous hydrologic models because the common approach is to process the DEM in order to delineate catchments located upstream of drainage network junctions, while our approach is to delineate catchments located upstream of parcels (e.g., of vineyards or olive groves) regardless of whether they are drainage network junctions or not. Put another way, our framework moves the hydrologic focus from the stream valleys where the junctions are located to the hillslopes where the parcels of permanent cultures are typically situated.

2.3.1. Data Handling

The geographical datasets were organized in the ArcGIS Pro project's geodatabase as features in raster and vectorial formats. They are provided as geopackage format in the Supplementary Materials (Geographic Information). The raster files comprise the digital elevation model, the precipitation data and the curve numbers derived from soil and land use maps. The terrain and precipitation data downloaded from the above-indicated sources (Table 2) covered the territory of Iberian Peninsula while the curve numbers had a global coverage. This coverage was necessary to determine average values for those parameters in the catchment located upstream of each vineyard or olive grove (called ex-parcel parameters) because Portuguese hydrographic basins can extend to the Spanish territory. Following those calculations, the raster files with the in-parcel and ex-parcel parameters were clipped to the area of continental Portugal and saved as raster files with 100 m $\times$ 100 m resolution. The vectorial files comprised the land use map of continental Portugal, from which 25,725 parcels of vineyards and 39,360 parcels of olive groves were extracted, for a total of 65,085 pieces of land. In addition to the land use map, vectorial features with the delineation of municipalities and agroclimatic regions were also included in the geodatabase. The municipal boundaries were used later to summarize and represent data and results at that level of detail. The vectorial feature representing the agroclimatic regions embedded the irrigation requirements of vine and olive plants, specifically from the region and annual precipitation levels (i.e., semi-humid and dry years), in the respective attribute table. In Step 4, these data were cross tabulated with the vineyard and olive grove parcels and coupled with the harvested rainwater resources estimated in Step 3 to assess the irrigation potential. The vectorial database with the vineyard and olive grove parcels, complemented with the information about municipality, agroclimatic zone, irrigation requirements, harvested rainwater resources, and irrigation potential, among other relevant data (e.g., terrain slope, Strahler's order of streams located upstream the parcel), was exported as Excel file to be used in further data processing (e.g., preparation of summary tables). That file is provided as Supplementary Materials (Alphanumeric Data).

2.3.2. Hydrologic Modeling

The hydrologic modeling (Step 2 in Figure 4) started with the delineation of catchments located upstream of each pixel that composes the DEM of continental Portugal. To complete this task, a Centroid Point Shapefile (CPS) was first created at the location of each pixel, using the Fiona (https://pypi.org/project/fiona/, accessed on 7 November 2025) and Rasterio (https://pypi.org/project/rasterio/, accessed on 7 November 2025) libraries of Python's (version 3.1.4) open-source programming language (Python Science Foundation, Beaverton, OR, USA). Then, the flow direction and flow accumulation were calculated from the DEM of Iberian Peninsula (Figure 5a) using the Whitebox library (https://pypi.org/project/whitebox, accessed on 7 November 2025) [49] of Python, resulting in the FD and FA raster files, respectively (see the FA in Figure 5b). Using these CPS and FA files

in the watershed function of Whitebox library, the drainage area (*DA*) above each CPS was delineated (Figure 5b, blue lines). Having finished this step, the average values of annual precipitation (*P*, historical and projected; Figure 3) and curve numbers (*CNs*) were determined within the drainage areas. This implied implementing an iterative process in the Python platform, whereby, for every *DA*, the average of *P* and *CN* were calculated using the zonal statistics function of the Whitebox library. Subsequently, the table resulting from that iterative process, containing the average *P* and *CN* of each *DA*, was joined to the CPS file, and finally, the *P* and *CN* values were exported as raster files for further processing. The maps representing the original variables and those resulting from the upstream analysis are illustrated in Figure 5c,d for *P* and Figure 5e,f for *CN*.

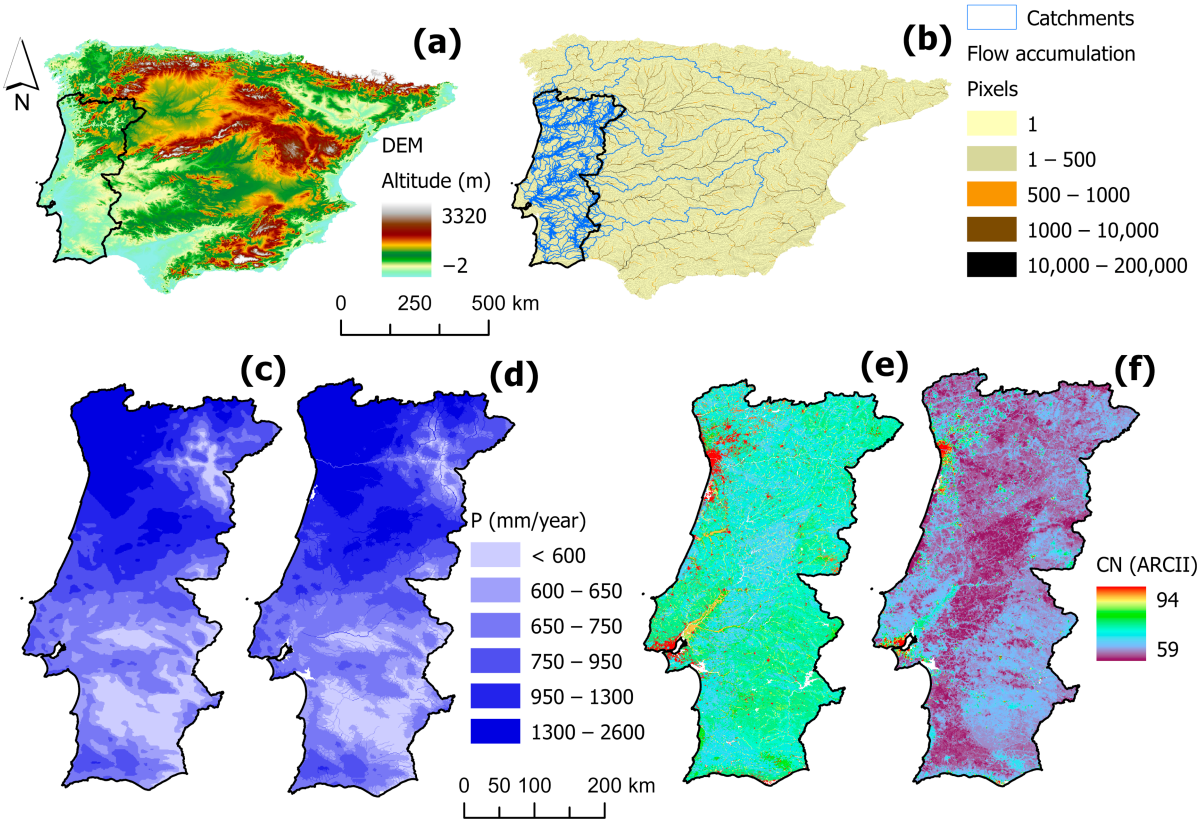


Figure 5. Hydrologic framework implemented to obtain raster files of *P* and *CN* representative of catchments located upstream of each 100 × 100 m pixel located in continental Portugal. (**a**) Digital elevation model of Iberian Peninsula; (**b**) flow accumulation across the Iberian Peninsula indicating the catchments located upstream of the aforementioned pixels; (**c**,**d**) annual precipitation falling over each pixel and average precipitation falling in the catchment located upstream of the pixel, respectively; (**e**,**f**) the same as for precipitation but applied to the curve number (*CN* (ARCII)).

The python codes used to implement the hydrologic module are provided as Supplementary Materials (Python Codes, version 3.1.4). To execute the codes, it is necessary to feed them with the following files: (F1) TIF file with a digital elevation model (DEM). This file must cover all the area draining to the target region. For example, if continental Portugal is the target region, the DEM needs to span the entire Iberian Peninsula; (F2) TIF file with the target region (continental Portugal), obtained from shapefile conversion to raster image. The grid values do not matter in this file, but the cell size and centroid locations must be the same as those from the F1 DEM; (F3) *P* and *CN* data spanning the area of F1 DEM, also provided in TIF format with the same grid size and centroid locations as the F1 DEM.

The first algorithm in the Python code, "1_create_points.py" (P1), generates a point shapefile (CPS) containing the centroid of each grid cell from the F2 DEM. The second algorithm, "2_iterate_points_and_rasters.py" (P2), comprises 2 parts. The first part (P2.1) replicates the F1 DEM, but with filled sinks, to be used in the creation of flow accumulation and flow direction files. The second part (P2.2) uses the flow accumulation file in a cycle that runs through all the centroid points to delineate the respective upstream drainage area (*DA*). During this cycle, the mean of *P* and *CN* of each *DA* is calculated using zonal statistics tools and attributed to the respective centroid. At the end of P2.2 cycle, the CPS shapefile's attribute table is updated with the mean of *P* and *CN* values of all centroids. Finally, the third algorithm in the Python code, "3_create_rasters.py "(P3), creates a couple of raster files by converting the CPS shapefile into TIF files of *P* and *CN*. Figure 6 illustrates the workflow described above using the *P* variable as an example.

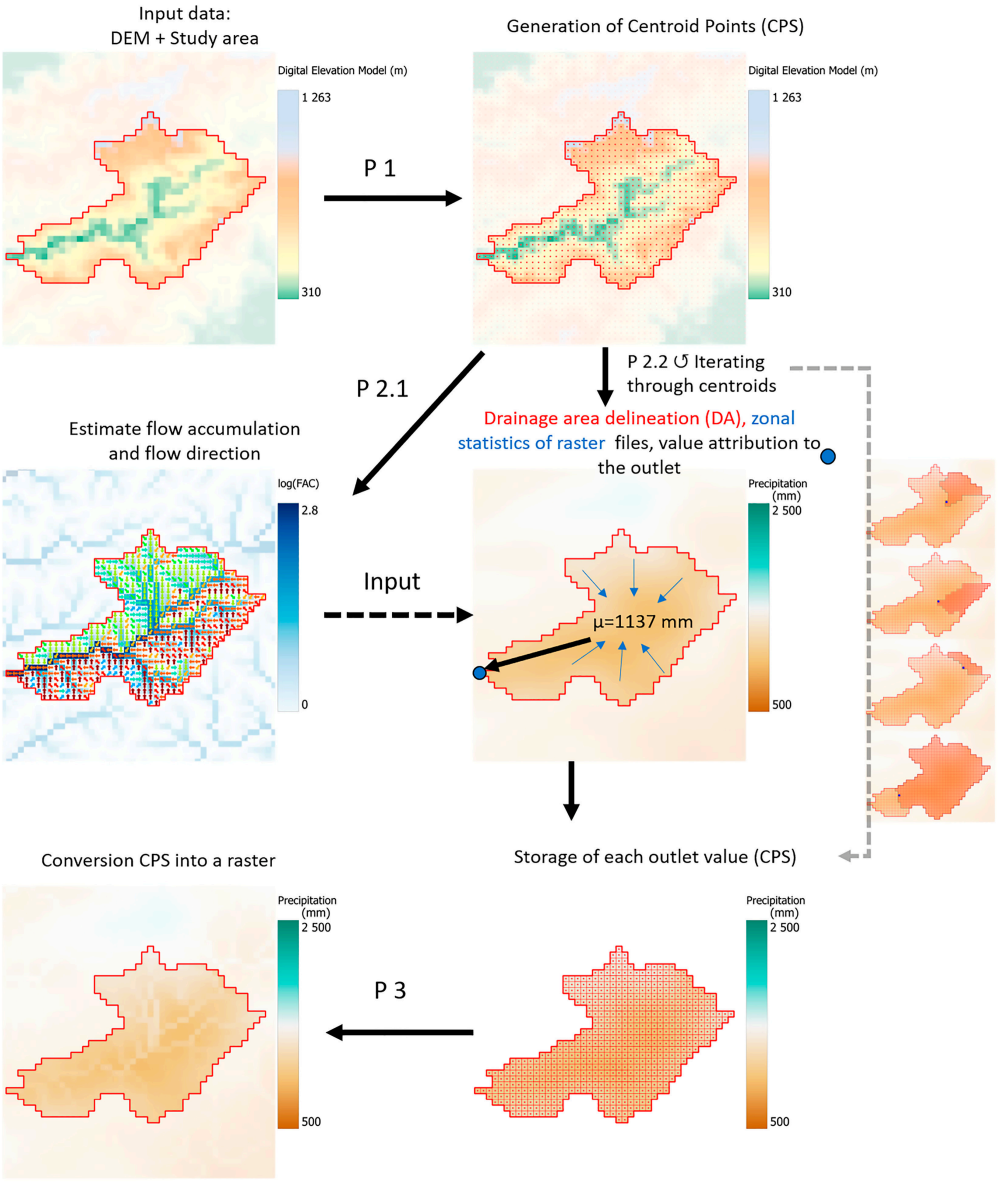


Figure 6. Creation of raster files describing the mean *P* of drainage areas located upstream of a grid cell. In this study, the procedure was replicated for the curve number (*CN*) but has been designed to hold for any variable. The Python codes used to implement the procedure are provided as Supplementary Materials (Python Codes). The arrows designate the step (P) flow from P1 to P3.

2.3.3. Rainwater Harvesting Planning

The planning of rainwater harvesting comprises two scenarios. (S1) Collecting rainwater that falls in the irrigated parcel (Pp), composed of a vineyard or olive grove in the current study: in this case, the available resource is precipitation falling in the parcel that can be collected at the lowest altitude point to maximize the accumulated volume.

The value of Pp is given by:

$$Pp = mean(P, A) \quad (1)$$

where P is the annual precipitation ($L/m^2 * year$) falling in the parcel of area A (m^2). In the GIS environment, the value of Pp can be estimated through zonal statistics of annual precipitation within that parcel. The runoff accumulated in the parcel in one year and harvested in the lower altitude point is Vp (m^3), estimated as

$$Vp = Pp * A \quad (2)$$

In scenario S2, the parcel can receive and collect runoff from hillslopes located upstream. In this case, the runoff reaching a grid cell in the parcel (Vu, m^3) is given by

$$Vu = Pu * Au \quad (3a)$$

where Pu ($L/m^2 * year$) is the effective precipitation over the upstream catchment linked to the parcel, estimated by the Soil Conservation Service method [50]:

$$Pu = \frac{(P - Ia)^2}{P - Ia + S} \quad (3b)$$

$$Ia = 0.2 * S \quad (3c)$$

$$S = 25.5 * \left(\frac{1000}{CN} - 10\right) \quad (3d)$$

with P ($L/m^2 * year$), I ($L/m^2 * year$), S ($L/m^2 * year$) and CN (dimensionless) representing the annual precipitation, initial abstraction, maximum infiltration and curve number, respectively. Equation (3b) is subject to the following boundary condition: if $P - Ia < 0$, $Pu = 0$. The P, Ia, S and CN parameters are estimated within the drainage basin of area Au (m^2) located upstream of the cell, using the Python codes described in Section 2.3.2. The available resource in this scenario can be equated to the average Vu (Vup, m^3) considering all the grid cells that intersect the parcel.

$$Vup = mean(Vu, A) \quad (4)$$

Additionally, the collecting site can be set to the highest altitude point within the parcel to maximize the efficacy of gravity irrigation.

2.3.4. Security Analysis of Irrigation Potential

The irrigation requirements (drip irrigation) of vineyards and olive groves are indicated in Table 1 for "dry" and "semi-humid" years and across the agroclimatic regions of continental Portugal (Figure 2). Other irrigation requirements could be acknowledged, concerning other forms of irrigation (e.g., sprinkler). However, in continental Portugal drip irrigation is the preferred option because of its high water use efficiency, which is essential for a crop often grown in dry areas or regions with limited water availability. Thus, for testing our hydrologic framework, we decided to use the requirements of drip irrigation. To assess the irrigation potential of rainwater harvested sources, the drip irriga-

tion requirements (Vi, $m^3/ha * year$, values in Table 1) were compared with the in-parcel (Vp, $m^3/year$) and ex-parcel (Vup, $m^3/year$) resources defined in Section 2.3.3. Firstly, the irrigation requirements were estimated for each parcel (Vip, $m^3/year$) as follows:

$$Vip = Vi * A \quad (5)$$

Secondly, the Vip values were compared with the Vp and Vup counterparts:

$$Vp > Vip, \text{ in-parcel rainwater harvesting is secure for irrigation} \quad (6a)$$

$$Vup > Vip, \text{ ex-parcel rainwater harvesting is secure for irrigation} \quad (6b)$$

A detailed assessment of security, built-up on Equations (6a) and (6b), is proposed that classifies the level of security. In that context, the following classes are defined for values of $(Vp - Vip)/Vip$): (1) < 0—insecure; (2) 0–0.5—moderately insecure; (3) 0.5–1—secure; (4) 1–5—considerably secure; (5) > 5 allow expansion of irrigated area. For values of $(Vup - Vip)/Vip$, the following security classes were defined: (1) < 0—insecure; (2) 0–1—moderately insecure; (3) 1–10—secure; (4) 10–100—considerably secure; (5) 100–1000—allowed expansion; (6) allowed diversion.

The security classifications based on *Vp* and *Vup* both comprise a "moderately insecure" level for security values $(V - Vip)/Vip$) larger than 0, which may be counter intuitive, but is intentional. When the security index equals 0, the available water volume exactly equals the crop irrigation requirement ($V = Vip$). While this represents a perfect equilibrium in a static scenario, it represents an operationally insecure state in real-world agriculture due to climatic stochasticity. To account for this, the "moderately insecure" class captures a safety buffer above the breakeven point (> 0).

The safety thresholds defining the irrigation security classes were designed to be asymmetric between in-parcel (*Vp*) and ex-parcel (*Vup*) frameworks to reflect the distinct hydrologic and operational risks of micro- *versus* macro-catchment harvesting (https://www.fao.org/4/i1861e/i1861e06.pdf, accessed on 15 July 2026). While a safety buffer of 0 to 0.5 (up to 50% surplus above crop demand) defines the "moderately insecure" class for *Vp*, this boundary was extended to 0 to 1.0 (100% surplus) for *Vup*. This more conservative threshold for ex-parcel resources is mathematically required to buffer against the non-linear volatility of catchment runoff generation, severe transmission losses (gully infiltration and evaporation) over long hillslope transit paths, and regulatory or physical extraction inefficiencies inherent to routing shared upstream surface waters.

3. Results

3.1. Topographic, Hydrologic and Agroclimatic Context of Hillslope Rainwater Harvesting Simulations

The vineyards and olive groves of continental Portugal are mostly located in flat to sloppy hillslopes of small water courses. Table 4a,b summarize the distribution of vineyard and olive grove parcels per slope class and watercourse's Strahler order. In the case of vineyards (Table 4a), 46% of all parcels were planted in flat (0–5%) to smoothly undulated (5–10%) hillslopes, while a considerable portion (14%) were planted in craggier (slope 20–40%) terrains. For olive groves (Table 4b), a larger proportion of parcels were planted in the flat to smoothly undulated hillslopes (58%), while the craggy terrains are much less represented (<5%). In both cultures, the watercourses were mostly of Strahler order 1 (frequently ephemeral), namely 83% in the case of vineyards and 76% in the case of olive groves. This confirms the placement environment of most vineyards and olive groves away from rivers, as referred above.

Table 4. (**a**) Location of vineyard parcels of continental Portugal distributed across slope classes and Strahler order of neighbor water courses. (**b**) Location of olive grove parcels of continental Portugal distributed across slope classes and Strahler order of neighbor water courses.

(**a**)						
Strahler Order	**Slope Class (%)**					**Total**
	Flat	**Smoothly Undulated**	**Undulated**	**Sloped**	**Scarped**	
	0–5	**5–10**	**10–20**	**20–40**	**>40**	
1	28	18	17	14	5	83
2	5	4	3	1	0	13
3	2	1	1	0	0	3
4	1	0	0	0	0	1
Total	36	23	20	14	6	100
(**b**)						
Strahler Order	**Slope Class (%)**					**Total**
	Flat	**Smoothly Undulated**	**Undulated**	**Sloped**	**Scarped**	
	0–5	**5–10**	**10–20**	**20–40**	**>40**	
1	36	22	12	4	2	76
2	9	3	2	1	0	15
3	3	1	1	0	0	5
4	1	1	0	0	0	2
5	1	1	0	0	0	2
Total	50	27	16	5	2	100

The agroclimatic context of rainwater harvesting simulations is summarized in Table 5. The columns labeled 1 to 7 in the first row indicate the agroclimatic zones represented in Figure 2. The threshold of annual precipitation that splits "dry" from "semi-humid" years is listed in the second row. The next rows depict average annual precipitations in the seven agroclimatic regions, as measured in the historical period (from 1981 to 2010) and anticipated for the 2041–2070 period, considering the three shared socioeconomic development pathways. Finally, the last set of rows describe the difference between measured/anticipated precipitation values and the references indicated in row 2. Whenever the difference is positive, the year is considered semi-humid in the region, and the simulation uses the irrigation requirements listed under the "I-semi-humid" column of Table 1; otherwise, it uses the values listed under the "I-dry" column. As per the results, most simulations used the "semi-humid" scenario, while the "dry" scenario was foreseen for agroclimatic regions 4, 5 and 6 (Santarém and Alentejo) under the most fossil fueled-oriented pathways (SSP3-7.0 and SSP5-8.5).

Table 5. Agroclimatic context of irrigation potential simulations. The cells filled with italic numbers represent simulations where the irrigation potential of rainwater harvesting assumed irrigation requirements of semi-humid years (values under the "I-semi-humid" column of Table 1), while the cells filled with bold face numbers assumed requirements of dry years (column "I-dry").

Agroclimatic Zone	**1**	**2**	**3**	**4**	**5**	**6**	**7**
Reference precipitation dividing dry from semi-humid conditions (mm/year)	905	509	758	697	609	572	509
Average precipitation per zone (mm/year)							

Table 5. *Cont.*

Agroclimatic Zone	1	2	3	4	5	6	7
Historical	1069	883	968	732	649	608	687
SSP1-2.6	1067	887	964	722	641	594	662
SSP3-7.0	1017	844	915	685	600	548	610
SSP5-8.5	1002	833	901	669	585	531	585
Difference between historical/projected and reference precipitation (mm/year)							
Historical	164	374	210	35	40	36	178
SSP1-2.6	162	378	206	25	32	22	153
SSP3-7.0	112	335	157	**−12**	**−9**	**−24**	101
SSP5-8.5	97	324	143	**−28**	**−24**	**−41**	76

3.2. Rainwater Harvesting Resources

The spatial distribution of in-parcel (*Vp*) and ex-parcel (*Vup*) irrigation potential of rainwater harvesting sources is illustrated in Figure 7a for vineyards and Figure 7b for olive groves. In both figures, the *Vp* and *Vup* resources are represented by the green and purple ramp of colors, respectively. The panels (i) to (iv) show the *Vp* and *Vup* resources as estimated for the current agroclimatic condition (panel (i)) and forecasted for the three shared socioeconomic development pathways (panels ii–iv). For the vineyards (Figure 7a), the current irrigation potential from in-parcel resources varies from a minimum of 2000 m^3/year to a maximum that can exceed 70,000 m^3/year, while from ex-parcel resources the range is from 5000 m^3/year (i.e., *Vup* is 2.5-fold larger than the *Vp*) to >2,500,000 m^3/year (35-fold larger). This result shows unequivocally how beneficial planning rainwater harvesting can be with a focus on runoff supplied from upstream areas, notwithstanding the location of vineyard parcels away from large water courses (Table 4a). Figure 7a also reveals more current in-parcel rainwater harvesting resources in agroclimatic zone 5 (high Alentejo) and fewer in agroclimatic zones 1 (north and central coast), 3 (inland center) and 7 (Algarve). Additionally, the ex-parcel resources are highlighted in agroclimatic zone 2 (inland north). The results for olive groves (Figure 7b) also expose the current larger contribution of ex-parcel resources for irrigation potential, relative to in-parcel resources, and a spatial variability of *Vp* and *Vup*. Now, the larger *Vp* values seem to be concentrated in the inland regions of continental Portugal, while the *Vup* values are smaller in agroclimatic region 1. When the results for the shared socioeconomic pathways are compared with the current condition, no clear differences are detected, neither for the vineyards nor the olive groves.

A complimentary assessment of in-parcel and ex-parcel resources was based on parcel area-normalized *Vp* and *Vup* values. The results are presented in Table 6. For both cultures, this new look discloses a clear decrease in *Vp* and *Vup* from north to south, which is a noticeable influence of precipitation that drops in the same direction. Thus, the combined analysis of Figure 7a,b and Table 6 makes it evident that *Vp* and *Vup* simultaneously depend on climate variability and parcel area. As regards this later influence, Table 6 shows markedly larger areas in the Alentejo region (agroclimatic zones 5 and 6) relative to the other regions. In the Alentejo region, the vineyard parcels cover 13.7–21.3 ha, on average, and the olive groves cover 20.8–31.1 ha. In the other regions, the ranges are 3.6–9.1 ha (vineyards) and 4.3–15.3 ha (olive groves). Table 6 also confirms the relationship *Vup* >> *Vp* revealed in Figure 7a,b. In the vineyards, they are lower in the Alentejo region (*Vup*/*Vp* = 4–11) and higher in Santarém (*Vup*/*Vp* = 67–125). In the olive groves, the lowest ratios occur in the low Alentejo and Algarve regions (*Vup*/*Vp* = 8–11) and the highest values in the Santarém and north/central coast (*Vup*/*Vp* = 57–139). Besides confirming the *Vup*/*Vp* ratios, the analysis based on parcel-normalized values suggests a ratio decay in the

future, in the vineyards, and a rise (or no variation) in the olive groves. For example, the *Vup*/*Vp* of vineyards from Santarém region (agroclimatic zone 4) is projected to drop from 125 to 67, while the *Vup*/*Vp* of olive groves from the same region are anticipated to rise from 69 to 123.

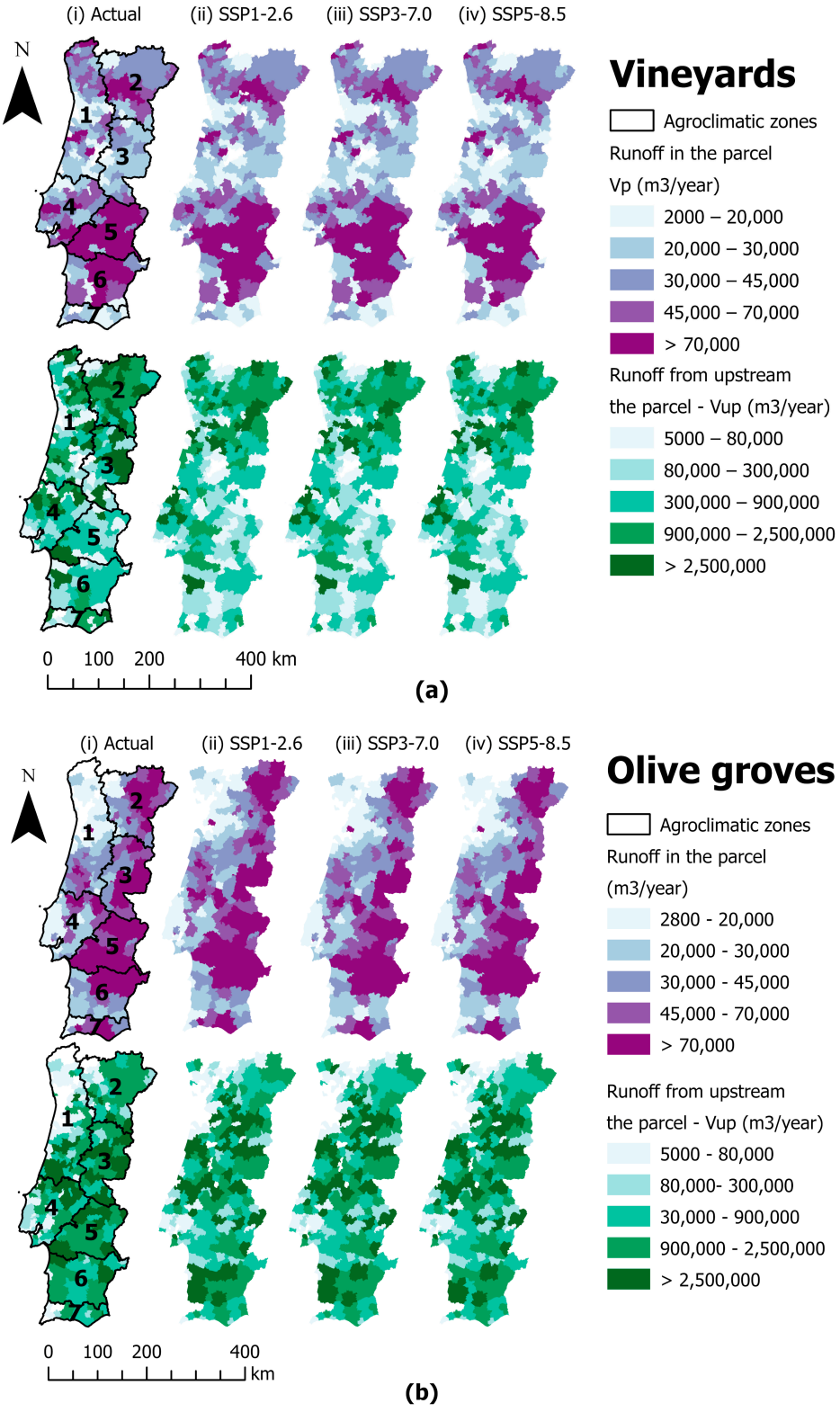


Figure 7. (**a**) Spatial distribution of *Vp* and *Vup* in vineyard parcels under the current and future agroclimatic conditions. (**b**) Spatial distribution of *Vp* and *Vup* in olive grove parcels under the current and future agroclimatic conditions. Labels 1 to 7 represent the agroclimatic regions (Figure 1).

Table 6. Analysis of parcel area-normalized *Vp* (Equation (1)) and *Vup* (Equation (2)), and the corresponding *Vup*/*Vp* ratios, in the vineyard and olive grove parcels of continental Portugal, averaged across agroclimatic zones and estimation periods (historical and SSP projections.

Zone	Average Parcel Area (ha)	Potential In-Parcel (*Vp*) Water Resources (m^3/ha.year)			
		Historical	**SSP1-2.6**	**SSP3-7.0**	**SSP5-8.5**
Vineyards					
1	5.3	9095	9099	8691	8711
2	9.1	9885	9925	9460	9877
3	3.6	9823	9785	9302	9313
4	8.1	6928	6810	6467	6332
5	21.3	6565	6479	6060	5882
6	13.7	5966	5856	5404	5326
7	3.7	7049	6784	6266	6008
Olive groves					
1	4.3	9669	9624	9132	9019
2	9.5	7843	7877	7491	7330
3	7.1	9290	9234	8761	8668
4	8.2	7570	7495	7098	7027
5	20.8	6133	6067	5678	5511
6	31.1	5890	5774	5340	5301
7	15.3	7002	6744	6218	5821
		Potential ex-parcel (*Vup*) water resources (m^3/ha.year)			
Vineyards					
1	5.3	464,565	400,903	386,602	380,791
2	9.1	244,616	199,833	192,080	189,194
3	3.6	651,464	287,736	276,631	272,244
4	8.1	869,171	454,667	438,319	426,413
5	21.3	25,531	23,918	22,948	22,195
6	13.7	67,048	34,000	32,397	31,214
7	3.7	274,644	131,376	125,487	119,531
Olive groves					
1	4.3	549,078	1,325,512	1,275,904	1,254,685
2	9.5	149,593	123,435	118,213	116,516
3	7.1	396,744	430,897	414,645	407,732
4	8.2	523,575	913,464	880,279	862,488
5	20.8	135,098	173,907	166,552	161,544
6	31.1	57,500	60,639	57,726	55,318
7	15.3	53,447	61,025	58,486	55,697
		Ratio of ex-parcel over in-parcel resources (*Vup*/*Vp*)			
Vineyards					
1	5.3	51	44	44	44
2	9.1	25	20	20	19
3	3.6	66	29	30	29
4	8.1	125	67	68	67
5	21.3	4	4	4	4
6	13.7	11	6	6	6
7	3.7	39	19	20	20
Olive groves					
1	4.3	57	138	140	139
2	9.5	19	16	16	16
3	7.1	43	47	47	47
4	8.2	69	122	124	123
5	20.8	22	29	29	29
6	31.1	10	11	11	10
7	15.3	8	9	9	10

3.3. Security of Harvested Rainwater Irrigation Potential

The relationship between irrigation potential (*Vp*, *Vup*) and irrigation requirements (*Vip*), as set by Equations (6a) and (6b) and the related security classification (Section 2.3.4), was assessed at the municipal level and is represented in Figure 8a for in-parcel resources and Figure 8b for ex-parcel resources. As per Figure 8a, the in-parcel resources considerably secure vineyard irrigation countrywide, with few exceptions. In many municipalities of agroclimatic regions 1 (north and central coast) and 2 (inland north), the resources ensure irrigation potential with a safety buffer so high ($(Vp - Vip)/Vip > 5$) that diversion to other places can be recommended. These results hold for the actual socioeconomic development as well as for the projected CMIP6 pathways. The scenario differs from the olive groves, where the in-parcel resources considerably secure ($1 < (Vp - Vip)/Vip < 5$) irrigation northwards of agroclimatic region 4 (Santarém) but just secure ($0.5 < (Vp - Vip)/Vip < 1$) irrigation southwards for the current socioeconomic status. Additionally, the future conditions change the scenario drastically because the "considerably secure" status of agroclimatic regions 1 to 4 degrades to "secure", and the "secure" status of regions 5 to 7 degrades to "moderately insecure" ($0.0 < (Vp - Vip)/Vip < 0.5$). Some municipalities even drop their status to "insecure" ($(Vp - Vip)/Vip < 0$). When the analysis is aggregated at the agroclimatic region scale (Table 7), the above cited scenarios are confirmed and can be summarized in the following numbers: (1) In the vineyards, the regional security of irrigation potential sourced from in-parcel harvested rainwater reaches the highest level of 6.4–5.9 in the north and central coast of continental Portugal and drops smoothly towards the Algarve where it reaches 1.4–1.3. This pattern holds for present and future socioeconomic development. (2) In the olive groves, the previous pattern is generally replicated for the current socioeconomic status, where the north part of Portugal has a regional security around 5 and the south around 0,75. However, when the future shared socioeconomic pathways are considered, the agroclimatic regions 5 and 6 (Alentejo) become (highly) "insecure" ($-33.2 < (Vp - Vip)/Vip < -18.6$).

Table 7. Regional security of irrigation potential of vineyards and olive groves in continental Portugal, sourced from in-parcel and ex-parcel harvested rainwater. Positive values represent secure and negative values insecure agroclimatic regions under current and future socioeconomic development conditions.

Zone	Security of In-Parcel Water Resources ($Vp - Vip$)/Vip				Security of Ex-Parcel Water Resources ($Vup - Vip$)/Vip			
	Historical	**SSP1-2.6**	**SSP3-7.0**	**SSP5-8.5**	**Historical**	**SSP1-2.6**	**SSP3-7.0**	**SSP5-8.5**
Vineyards								
1	6.4	5.7	6.0	5.9	904.3	667.2	642.4	633.0
2	5.2	5.2	5.4	5.3	728.0	601.8	579.0	570.0
3	4.4	4.4	4.6	4.5	702.9	280.7	269.9	265.4
4	2.0	1.9	1.9	1.8	1428.3	740.5	756.3	736.4
5	1.6	1.6	1.5	1.4	80.3	85.6	75.3	72.8
6	1.2	1.1	1.1	1.0	248.2	32.6	28.5	27.4
7	1.4	1.3	1.4	1.3	256.0	98.8	94.3	89.8
Olive groves								
1	4.5	0.4	0.4	0.4	811.6	426.9	410.8	426.3
2	5.4	0.7	0.7	0.7	571.3	70.1	66.8	69.4
3	3.4	0.6	0.6	0.6	615.0	149.0	144.1	149.1
4	1.5	–2.1	–2.1	–2.3	746.3	195.0	189.4	195.9
5	1.0	–18.6	–19.0	–20.4	365.5	139.2	134.4	138.2
6	0.7	–30.1	–30.7	–33.2	218.6	111.4	107.9	110.1
7	0.8	0.3	0.3	0.2	83.0	68.5	68.0	70.5

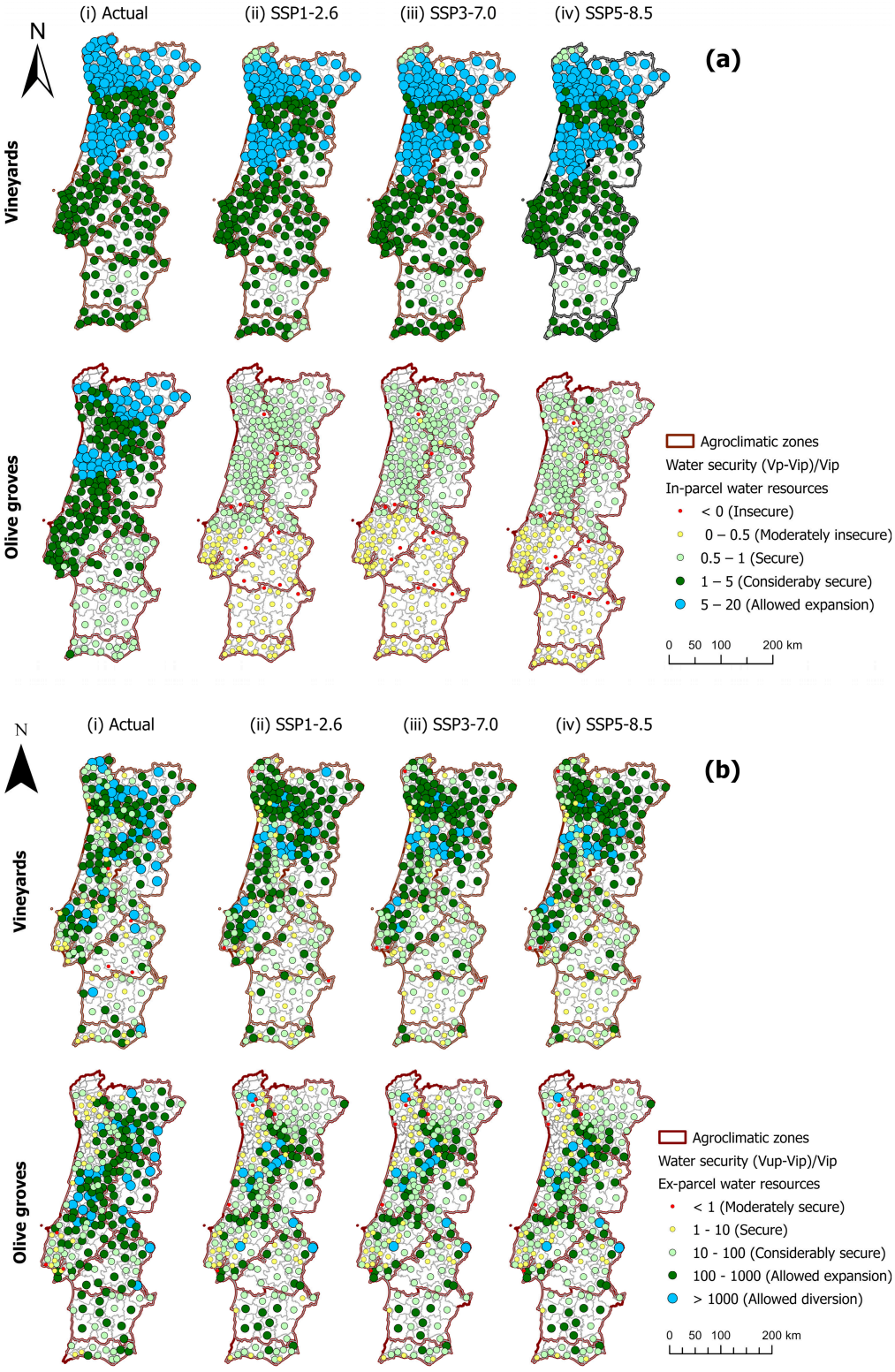


Figure 8. (**a**) Municipal security of irrigation potential sourced from in-parcel harvested rainwater. The upper and lower panels refer to vineyard and olive grove irrigation potential, respectively. The maps labeled (i) refer to irrigation potential in the current socioeconomic development, whereas maps labeled (ii) to (iv) project future scenarios. (**b**) Municipal security of irrigation potential sourced from ex-parcel harvested rainwater. As in (**a**), the upper and lower panels refer to vineyard and olive yard irrigation potential, respectively. The maps labeled (i) refer to irrigation potential in the current socioeconomic development, whereas maps labeled (ii) to (iv) project future scenarios.

The municipal security of irrigation potential sourced by ex-parcel harvested rainwater, illustrated in Figure 8b, is more reassuring than the security linked to in-parcel harvested rainwater, either for vineyards (upper panel) or olive groves (lower panel). This is because all security classes (colored circles) are abundantly represented in the maps of both cultures. But there are spatial differences to acknowledge. In the vineyards, the smooth decline from north to south persists, with a major deviation from this pattern located in agroclimatic region 4 (Santarém) that unexpectedly presents the highest security of all regions. This exception is more evident in the current socioeconomic condition but is still visible in the future shared socioeconomic pathways. The pattern in the olive groves is like the vineyard pattern, but solely for the current socioeconomic status. For the shared pathways, only region 1 keeps a very high security status ("allowed expansion" or "allowed diversion"), while region 2 drops considerably, its security level becoming the least secure. The regional analysis (Table 7) confirms these patterns, providing numbers to be used as references.

4. Discussion

4.1. The Dominance of Ex-Parcel Resources

A primary finding of this study is that ex-parcel resources, i.e., runoff from upstream catchments, are significantly more substantial than in-parcel resources, meaning direct precipitation on the parcel. This finding is supported by previous literature [51,52]. For vineyards, ex-parcel potential is between 2.5- and 35-times larger than in-parcel potential. In specific regions like Santarém, the ratio of ex-parcel over in-parcel resources can reach as high as 125 to 1. This suggests that planning rainwater harvesting with a focus on upstream runoff—even for parcels located away from major watercourses—offers a far more robust solution for irrigation than relying solely on precipitation within the parcel boundaries. In general, upstream runoff harvesting systems can collect substantial supplemental water volumes, with studies reporting up to 3008 m^3/ha per season in semi-arid regions. Furthermore, these systems significantly enhance groundwater recharge, with increases of 2.6–6.9 m observed in Indian semi-arid tropics [24]. However, modeling shows that increasing the area devoted to runoff harvesting improves groundwater stores and irrigation sustainability up to a threshold, beyond which further expansion reduces streamflow without added benefit [53]. This is why using low-order catchments like those depicted in Table 4a,b are not a limitation of rainwater harvesting from upstream runoff; it is an asset. In this case, we get the benefits of collecting expressive water resources from the upper hillslopes without the trade-off of reducing the flow of downstream water courses. In-parcel harvesting systems, on the other hand, are limited to the rainfall directly falling on the parcel, the reason why water savings are typically modest in these cases, with studies reporting solely 45.54 m^3/ha additional water for maize [54]. Techniques such as mulching and micro-catchments can improve soil water storage but are less effective than upstream runoff collection for supplemental irrigation [55,56].

4.2. Low Strahler Orders as Hurdles Mitigators

When evaluating the practical implementation of ex-parcel rainwater harvesting (*Vup*), a distinction must be made between macro-scale river engineering and the decentralized hillslope framework proposed herein. While capturing ex-parcel volumes that range from 2.5- to 35-times larger than in-parcel precipitation sounds operationally daunting, the geomorphological data presented in Section 3.1 provides a strong justification for its real-world viability. The spatial analysis reveals that the studied olive groves and vineyards are predominantly anchored within catchments of low Strahler stream orders (1st and 2nd order), representing immediate hillslopes, ephemeral gullies, and primary headwater channels. This micro-catchment focus fundamentally shifts the socioeconomic, legal, and

ecological dynamics of water harvesting, mitigating the barriers typically associated with macro-scale surface water diversion:

Property and Boundary Simplification: At the 1st- and 2nd-Strahler-order scale, the upstream drainage areas (*Au*) are small and compact. In the Portuguese agricultural landscape, these micro-catchments are frequently contained entirely within the boundary of a single estate or shared between a minimum number of adjacent landowners. This high spatial localization drastically reduces the property friction and land-acquisition disputes that stall larger regional infrastructure projects.

Low-Cost, Decentralized Infrastructure: Capturing runoff from headwater channels does not require capital-intensive, high-risk concrete dams. Instead, it relies on small-scale, decentralized engineering interventions such as excavated earthen micro-reservoirs, small check-dams, contour swales, and vegetative filter strips. These structures carry minimal capital expenditure and can be progressively implemented and maintained by individual smallholders or local agricultural cooperatives.

Streamlined Regulatory and Water-Rights Pathways: While diverting perennial, high-order rivers in Portugal requires exhaustive, multi-year licensing and environmental impact assessments through the Portuguese Environment Agency (APA), the retention of diffuse hillslope runoff and seasonal, non-perennial flows in headwaters is subject to a significantly lighter regulatory burden. Small-scale water retention structures under specific volumetric thresholds face faster approval pathways, aligning with national strategic goals for decentralized climate adaptation.

Localized and Positive Ecological Footprint: Far from causing major ecological disruptions, intercepting torrential winter runoff in 1st- and 2nd-order ephemeral streams can yield net positive environmental externalities. By capturing peak seasonal flows at the source, these micro-reservoirs mitigate downstream valley flooding, reduce gully erosion, and trap sediments before they enter larger river networks, all while preserving the fundamental baseline flow of the wider basin. Consequently, because our framework targets micro-ex-parcel resources rather than macro-river systems, the substantial *Vup* volumes identified remain an accessible and highly practical buffer against future aridity.

4.3. Spatial Variability and the North-South Gradient

The effectiveness of rainwater harvesting is strongly influenced by Portugal's latitudinal precipitation gradient. Municipalities in the north and central coast (agroclimatic zone 1) and inland north (zone 2) exhibit high irrigation security. In many cases, the safety buffer is so large that surplus water could potentially be diverted for other uses or places. Resources decrease noticeably from north to south. In the Alentejo and Algarve (zones 5, 6 and 7), in-parcel resources are only "secure" (rather than "considerably secure") under the current socioeconomic development status. Interestingly, the Alentejo region has significantly larger average parcel areas (up to 31.1 ha for olive groves) compared to the north (3.6–5.3 ha), which partially offsets the lower per-hectare precipitation by providing a larger collection surface. Precipitation variability has been considered the single most important climatic factor influencing rainwater harvesting system efficiency, with system reliability highly sensitive to both the magnitude and timing of rainfall events [57,58]. Thus, the contrasting security among north and south rainwater harvesting systems of continental Portugal is not surprising. The scientific literature also highlights the direct implication of security on system storage. Systems must be designed to local rainfall patterns, including frequency, seasonality, and the duration of antecedent dry periods. For example, in semi-arid Kenya, a 50 m^3 farm pond can meet supplemental irrigation needs for a 300–600 m^2 garden, but only if dry spells and rainfall timing are adequately considered [57]. Conversely, regions with well-distributed rainfall require smaller storage volumes and achieve higher reliability

than areas with pronounced wet and dry seasons [59,60]. Thus, harvested rainwater for vineyard and olive yard irrigation probable requires larger infrastructure in the south than in the north of Portugal to ensure the same level of security. Some regionalization approaches that account for spatial variability in rainfall and demand have optimized tank sizing and system reliability [59,61], which may help adapting storage capacity for vineyard and olive yard irrigation in continental Portugal, especially under the less secure scenarios. Furthermore, projected shifts in spatial precipitation patterns necessitate adaptive designs that can accommodate future uncertainties [62,63]. This is crucial because climate change is expected to increase rainfall variability and alter seasonal patterns, generally reducing security in drier regions and increasing uncertainty in wetter regions [64].

Spatial variability and the north–south gradient of irrigation security for vineyards and olive groves of continental Portugal are primarily driven by climatic factors (e.g., precipitation and evapotranspiration), but parcel characteristics as well as the hydrologic potential of catchments also play an important role. Annual precipitation significantly decreases from north to south in continental Portugal. Northern regions (zones 1 and 2) receive much higher rainfall than the Alentejo and Algarve (zones 5, 6, and 7). As precipitation drops southwards, irrigation needs increase to maintain crop health. Southern regions have higher reference irrigation requirements due to drier conditions. Historical data (1981–2010) show a clear surplus in the north, while future projections (2041–2070) under CMIP6 scenarios indicate a narrowing gap between available water and crop needs, particularly in the south. As regards parcel size, the contrast in agricultural land management between regions is unambiguous. In the Alentejo (zones 5 and 6), vineyard parcels average 13.7–21.3 ha and olive groves 20.8–31.1 ha. In contrast, other regions (north and center) have smaller parcels ranging from 3.6–9.1 ha for vineyards to 4.3–15.3 ha for olive groves. Larger parcels in the south provide a bigger collection area for in-parcel rainwater harvesting (*Vp*), which partially mitigates the lower per-square-meter rainfall. Finally, the hydrologic influence is relevant because runoff from upstream catchments (ex-parcel resources) is far more abundant than direct in-parcel precipitation, and varies across the country. The ratio of ex-parcel to in-parcel resources (*Vup*/*Vp*) is generally higher in the north and center, (e.g., reaching up to 125:1 in Santarém for vineyards) compared to the south, where it can drop to 4:1 in the high Alentejo.

4.4. Contrasting Spatio-Temporal Trends

4.4.1. The *Vup*/*Vp* Trends

The climate projections reported contrasting gradients of *Vup*/*Vp* ratios in the vineyards and olive groves (Table 6). The ratio was projected to decrease in the vineyards and increase in the olive groves. The *Vup*/*Vp* ratio depends on the Topographic Ratio (*Au*/*A*) as well as on the Runoff Efficiency (*Pu*/*Pp*), which derives from combining Equations (2) and (3a). In the hydrologic modeling, the Topographic Ratio remained constant overtime, while the Runoff Efficiency changed because the annual precipitation in continental Portugal was projected to decrease in the shared socioeconomic pathways. Under these circumstances, the *Vup*/*Vp* is generally expected to decrease in a future drier climate. The reason is that a lower precipitation in the future may fail to meet the initial abstraction (*Ia*) threshold more often (Equation (3b)), causing *Pu* to decrease faster than *Pp*, which implies a decrease in the *Vup*/*Vp*. This has likely occurred in the vineyards. The increase in *Vup*/*Vp* in the olive groves requires a deeper assessment. Under a drying climate, the only way the *Vup*/*Vp* ratio can increase is if precipitation at the parcel (*Pp*) decreases at a significantly faster rate than the average precipitation across the upstream catchment (*Pu*). Figure 9a,b show how the annual precipitation changed over the territory of continental Portugal between the historical period and the projection for 2041–2070 under the

SSP5-8.5 pathway (used as example). Figure 9a shows the precipitation change over the parcels (*Pp*) and Figure 9b over the upslope catchments (*Pu*), revealing an expressive spatial variability. Figure 9c illustrates the spatial variation of *Vup*/*Vp* during the same time frames ($\Delta Vup/Vp$ = *Vup*/*Vp* (SSP5-8.5) − *Vup*/*Vp* (Historical)). It shows $\Delta Vup/Vp > 0$ occurring where the parcels are linked to higher order streams (the purple and red colors in the figure represent pixels where $\Delta Vup/Vp > 0$ and coincide with the larger rivers of mainland Portugal). Table 4a,b confirm that olive grove parcels are indeed linked to hillslopes of larger Strahler order (9% linked to hillslopes of orders 3 to 5) than the vineyards (4% linked to hillslopes of orders 3 and 4). Thus, in mainland Portugal the *Vup*/*Vp* is projected to increase in the olive groves probably because large catchments have the capacity to buffer the effect of precipitation decrease on runoff (Figure 9c), while *Pp* is more locally controlled and may decrease sharply (e.g., zones 1 and 7, Figure 9a). Table 8 provides additional insights to understand the contrasting patterns of *Vup*/*Vp* in the vineyards and olive groves. Among other things, it links a major portion of *Vup* (nearly 80.6% in the olive groves and 74.9% in the vineyards) to a minor number of large catchments (top 1% in *Au*). Thus, while 56.3% of vineyard and 56.7% of olive grove parcels are expected to show a decline in the *Vup*/*Vp* ratio in the future, the large parcels linked to high Strahler-order streams counterbalance this trend. Apparently, in the vineyards the counterbalance was not enough to produce an increase in *Vup*/*Vp* at the macro scale (Table 6), but in the olive groves the buffering effect of "mega-catchments" was enough to offset the declining trend of most small hillslopes.

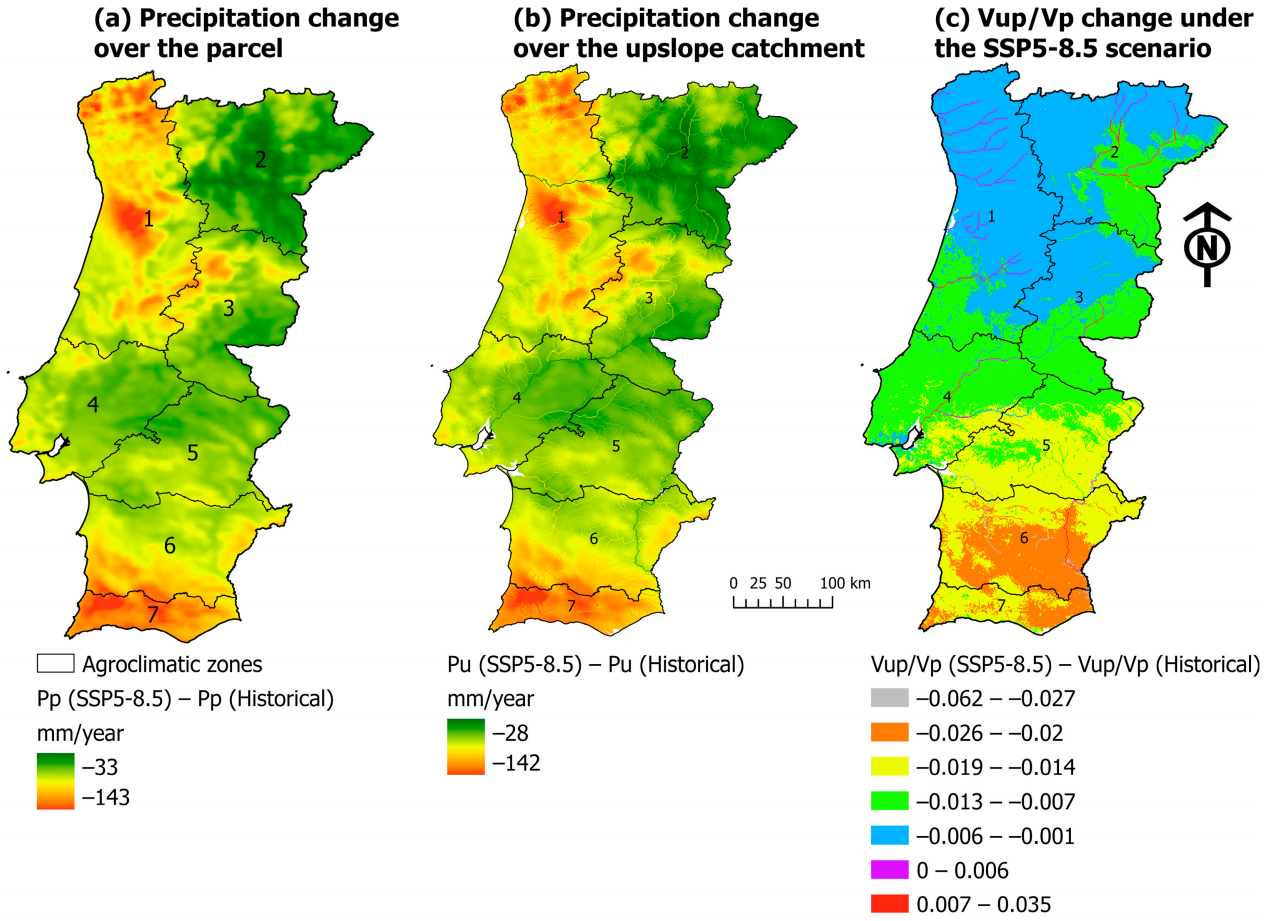


Figure 9. Precipitation changes from the historical period (1981–2010) to the climate change projection (2041–2070), at parcel (panel (**a**)) and upslope catchment (panel (**b**)) scales. Corresponding variation of *Vup*/*Vp* (panel (**c**)). The labels 1 to 7 indicate the agroclimatic zone numbers.

Table 8. Discrimination of parcel (*A*) and upslope catchment (*Au*) areas as function of percentile (top 1% and bottom 99%). Percentage of vineyards and olive groves contributing to *Vup* decline in the future and contribution of top 1% larger parcels to the *Vup*.

Parameter		Olive Grove	Vineyard
Number of parcels		39,360	25,725
Average *A* (ha)	Bottom 99%	2.9	2.9
	Top 1%	11.3	5.4
Average *Au* (ha)	Bottom 99%	4.2	4.1
	Top 1%	4620.5	2588.6
Parcels declining *Vup* (%)		56.3	56.7
Top 1% *Vup* share (%)		80.6	74.9

The divergent future trends in *Vup*/*Vp* likely arise from scale-dependent hydrological connectivity. In olive groves connected to upslope catchments of Strahler orders 3 to 5, larger contributing areas and more continuous flow paths can sustain or amplify run-on delivery relative to locally generated runoff, especially when runoff source areas are spatially connected [65–67]. By contrast, smaller vineyard hillslopes are more strongly controlled by local infiltration capacity, soil management, and inter-row structure, so a drier future climate can reduce parcel-generated runoff more than upslope inputs, or vice versa depending on local connectivity and storage conditions [68–71]. This interpretation is consistent with Mediterranean studies showing that runoff generation depends on the interactions among vegetation cover, soil crusting/compaction, microtopography, and antecedent moisture, and that scale effects can reverse apparent runoff–transfer relationships [72–76]. Accordingly, changes in *Vup*/*Vp* should be viewed as an emergent property of hydrological connectivity and landscape organization rather than a direct effect of crop type alone [77–80].

4.4.2. Irrigation Security

The contrasting results between vineyard and olive grove irrigation security (Figure 8a and Table 7) are likely explained by a combination of biological requirement disparity, spatial concentration in vulnerable zones, and the "dry year" threshold effect. A primary modeling assumption of our framework is that irrigation needs are inherently higher for olive trees than for vines (Table 1). Because the security metric is defined as $((Vp - Vip)/Vip)$, the larger *Vip* (the need) for olive groves naturally depresses the security value compared to vineyards, even if the available rainwater (*Vp*) was identical. Even in the historical period, olive groves in the southern agroclimatic zones (zones 6 and 7) show significantly lower security (0.7–0.8) than vineyards in the same regions (1.2–1.4). From a different standpoint, vineyards are distributed all over continental Portugal, with significant presence in the wetter northern and central-coast regions (zones 1 and 2). This geographic spread buffers their regional average security. Conversely, a large area of olive groves is concentrated in the Alentejo region (specifically zone 6—Low Alentejo). Since this region has the lowest annual precipitation and the highest irrigation requirements, the bulk of the olive yard data points are clustered in the most hydrologically stressed environment. The hydrologic model also assumes that irrigation needs (*Vip*) increase significantly when a year is classified as dry (the *P* threshold of Table 1). Future climate projections (the SSP scenarios) indicate that many areas in the south will cross this precipitation threshold more frequently. For olive groves in zone 6, the transition to future climate normals triggers the switch to "I-dry" requirements. Because these requirements for olive trees in the Alentejo are exceptionally high relative to the projected annual precipitation, the security ratio collapses

from a marginal historical positive (0.7) to a massive deficit (<−30). In contrast, because vineyard requirements ("I-dry") are lower and their spatial distribution is more favorable, their regional security remains positive countrywide (averaging > 1.0 even in the south). In summary, the divergent results of vineyards and olive groves are not an error of runoff logic but a reflection of crop-specific vulnerability embedded in the official irrigation norms and the geographical reality of where these crops are currently situated in continental Portugal.

It is important to distinguish between the physiological drought tolerance of vine and olive crops and the "dry year threshold effect" (I_{dry}) applied in our modeling framework. While the olive tree is highly drought-resilient and capable of surviving extreme water deficits, the I_{dry} threshold represents the boundary for maintaining commercially viable yields. The sharp decline in the security index for southern olive groves under extreme climate projections reflects a transition from productive rainfed agriculture to severe yield suppression. Although vineyards exhibit less vulnerability in our model, this is consistent with their lower total seasonal water requirements and the agronomical reality that mild to moderate water stress in vines can often be tolerated or even desired for quality purposes [81–86]. In contrast, severe water deficits in olive groves during critical stages (such as pit hardening and oil accumulation) result in steep, near-linear declines in oil yield [87–90]. Consequently, the large negative index values for southern olive groves highlight a severe future risk to economic viability, even if the trees themselves physiologically survive [91–94].

4.5. Climate Resilience and Future Vulnerability

A central discussion in this study focuses on the contrasting resilience of vineyards and olive groves under future climate scenarios (SSP1-2.6, SSP3-7.0, and SSP5-8.5), with advantage for vineyards. The improved water use efficiency of vineyards over olive groves has been reported in other studies [95]. In continental Portugal, one explanation is that vineyards demonstrate a high degree of climate-proofing. Countrywide, in-parcel resources (Vp) remain considerably secure for vineyards, even under the most severe SSP5-8.5 scenario. This is due to their comparatively lower irrigation requirements. Olive groves are significantly more vulnerable. Their higher reference irrigation needs, combined with a massive relocation of these crops to the drier Alentejo region, create a precarious balance. Under future projections, the security of in-parcel resources for olive groves in the south (zones 5, 6, and 7) degrades from "secure" to (highly) "insecure". The hydrologic framework uses a safety buffer metric ($(Vp - Vip)/Vip$) to quantify resilience. In agroclimatic zones 1 (north/central coast) and 2 (inland north), the safety buffer for vineyards is extremely high (scores of 5.7 to 6.4). Thus, these regions not only have enough water for their own needs but could potentially divert surplus harvested water to other agricultural uses. In the south, this buffer shrinks. For olive groves, the security score for in-parcel resources drops to negative values in future scenarios (e.g., SSP3-7.0 and SSP5-8.5), signaling that direct precipitation on the parcel will no longer suffice to meet irrigation demands [39,96]. Ex-parcel potential is consistently 2.5- to 35-times larger than in-parcel potential. Even in the most water-stressed scenarios for the south, the ex-parcel resources generally remain "secure". For example, while a vineyard's in-parcel security might be 1.3 in the Algarve, its ex-parcel security remains robust because the upstream drainage area provides a much larger collection volume to buffer against declining precipitation. In future scenarios (especially SSP3-7.0 and SSP5-8.5), the difference between projected precipitation and the reference "dry year" threshold becomes negative in several zones. This shift forces the use of "dry year" irrigation requirements more frequently, which are substantially higher than semi-humid needs, further stressing the rainwater infrastructure. Thus, ex-parcel

harvesting would be an adaption strategy for irrigation of vineyards and olive groves in continental Portugal [97,98].

4.6. Beyond Hydrologic Buffering: Integrative Agronomic and Technological Adaptation Pathways

While the construction of ex-parcel rainwater harvesting (RWH) networks provides a critical biophysical buffer, the projected transition of southern olive groves to "insecure" states under extreme scenarios like SSP5-8.5 demonstrates that supply-side interventions cannot act in isolation. To build genuine climate resilience in highly stressed agro-climatic zones like the Alentejo, hydrologic buffering must be integrated into a broader, multi-layered framework of agronomic adaptation and advanced irrigation technologies.

Agronomic Diversification and Phenological Selection: For long-lived permanent crops like grapevines and olive trees, traditional annual crop rotation is structurally unfeasible. Instead, long-term agronomic adaptation must rely on varietal diversification and genetic selection. Future orchard restructuring in water-limited Portuguese systems should prioritize locally adapted olive cultivars such as Cobrançosa and Galega vulgaris, and drought-resilient grapevine rootstocks such as 110R and 140Ru, because the evidence is strongest for drought tolerance and water-use performance; heat tolerance is well supported for Cobrançosa, but not clearly established for 110R or 140Ru [99–102]. Furthermore, understory management in these parcels can be adapted through diverse cover-cropping. Maintaining an appropriate ground cover can reduce soil erosion, increase organic matter, improve soil structure and infiltration, and often enhance soil moisture and water retention, although the net effect depends on species choice, climate, and management intensity because cover crops can also compete with the main crop for water if poorly timed or excessive [103–109].

Advanced Deficit Irrigation Paradigms: On the demand side, adapting to a drier future requires moving away from full-evapotranspiration crop watering toward managed water-stress strategies. Implementing regulated deficit irrigation (RDI) allows producers to reduce water applications during phenologically less sensitive periods, such as post-veraison/post-harvest in grapevines and pit hardening in olives, while maintaining adequate irrigation during highly sensitive stages such as flowering and fruit set [89,110–114]. Similarly, partial root-zone drying (PRD) alternates irrigation between halves of the root system, so that roots in the drying zone generate chemical signals—especially ABA—that promote partial stomatal closure and reduce transpiration, while the irrigated side helps sustain plant water status under appropriate conditions [115–118]. However, the strength of the ABA signal and the resulting stomatal response vary with soil drying severity and PRD design, and in some cases PRD does not clearly maintain water status better than deficit irrigation or may even reduce yield [119,120]. Taken together, RDI and PRD can reduce seasonal irrigation demand by about 20% to 40% in some crop and site conditions, but yield and oil/wine quality are not always fully preserved, especially under severe deficits or when timing and soil conditions are suboptimal [87,121–123]. Nevertheless, they directly alter the *Vip* denominator used in our security metrics.

Precision Agrotechnology and Digital Twin Modeling: Maximizing the efficiency of both harvested rainwater and restricted allocations requires transitioning from empirical, calendar-based scheduling to automated precision agriculture. The deployment of Internet of Things (IoT) architectures that integrate wireless soil-moisture probes, sap-flow sensors, and microclimate stations enables real-time monitoring of crop water status and water-stress indicators, supporting timely irrigation decisions and early stress detection [124–128]. When paired with high-resolution remote sensing data such as Sentinel-2 or drone-based thermal imagery, farmers can estimate spatially variable crop coefficients and evapotranspiration maps at field scale, supporting more precise irrigation management [129–132].

This digital integration ensures that water harvested from upstream catchments (*Vu*) is applied with sub-parcel precision via subsurface drip networks, minimizing evaporative losses and optimizing every cubic meter of captured runoff. Ultimately, combining macro-scale RWH infrastructure with farm-level agrotechnological and genetic innovations offers the most viable defense against the severe desertification pressures predicted for the mid-21st century.

4.7. Policy Integration, Legislative Reform, and Financial Frameworks for Decentralized Rainwater Harvesting

To translate the biophysical potential of micro ex-parcel rainwater harvesting into a scalable climate-adaptation strategy, governance structures must adapt to a decentralized paradigm. Because Section 3.1 demonstrates that the studied olive groves and vineyards are anchored within 1st- and 2nd-Strahler-order catchments, policy framework interventions do not require massive public works. Instead, policy must focus on mobilizing and regulating thousands of small-scale, private, on-farm interventions. Integrating this micro-scale parcel hydrology into existing environmental and agricultural governance requires a roadmap spanning targeted legislative simplification, localized financial incentives, and spatial planning tools.

Strahler-Based Legislative Streamlining and Prior Notification Regimes: The Portuguese Water Law (Lei da Água, Lei no. 58/2005) and its associated licensing framework (Decreto-Lei no. 226-A/2007) treat surface water capture under a rigid, centralized framework designed for perennial river basins. This creates disproportionate bureaucratic hurdles for micro-scale interventions. To resolve this, the Portuguese Environment Agency (APA) should introduce a tiered regulatory framework explicitly based on stream order and permanence. For non-perennial 1st- and 2nd-Strahler-order channels, where runoff consists of diffuse, episodic winter surges, the complex, multi-year water concession process should be replaced by a simplified "Prior Notification with Standardized Technical Norms" regime. Under this system, constructing a micro-reservoir (e.g., <5000 m^3) or installing a series of headwater check-dams would receive automatic authorization within a short timespan (e.g., 30 days), provided the design meets basic regional criteria for sediment trapping and localized safety. This shifts the state's regulatory burden from heavy prohibition to the rapid, widespread deployment of decentralized upstream retention.

PEPAC Financial Integration for Nature-Based Solutions (NBSes): Because micro ex-parcel harvesting relies on low-cost, decentralized engineering (contour swales, earthen check-dams, small excavated retention basins), funding mechanisms should target high-density, farm-level distribution rather than multi-million-euro infrastructure grants. Within Portugal's Strategic Plan for the Common Agricultural Policy (PEPAC), a distinct funding axis should be carved out under "On-Farm Eco-Efficiency." This measure should provide streamlined, flat-rate grants covering a large share (e.g., up to 85%) of the costs for individual smallholders implementing nature-based hillslope interventions. Furthermore, because these 1st- and 2nd-order headwater structures perform critical environmental services, such as trapping agricultural sediments before they reach major river basins and mitigating valley floor erosion, farmers should receive annual "Eco-Scheme" payments to offset the operational costs of periodic desilting and channel maintenance, turning hillslope runoff management into a recognized public good.

Fiscal Incentives for Micro-Scale Water Neutrality: National and municipal governments can deploy targeted fiscal drivers to accelerate the adoption of headwater harvesting. At the national level, green tax reforms should offer corporate tax (IRC) deductions for agricultural estates investing in precision agrotechnology paired with micro-RWH. A reduced VAT rate (shifting from 23% to 6%) should apply to materials essential for small-scale hillslope management, such as clay or geomembrane pond liners, geotextiles for erosion

control, and IoT soil-moisture probes. At the municipal level, councils should grant exemptions on the Municipal Property Tax (IMI) for rural parcels that achieve a verified state of "Micro-Catchment Water Autonomy." This status is achieved when a farm's small-scale headwater storage capacity is spatially proven to offset its modeled dry-year deficit (*Vip*) without relying on over-allocated regional aquifers or public supply systems.

Municipal Planning (PDM) and Micro-Catchment Spatial Zoning: The physical scaling of these systems requires embedding micro-catchment hydrology directly into Municipal Master Plans (Plano Diretor Municipal—PDM). Rather than managing land use via broad administrative zones, municipal planners should utilize high-resolution digital elevation models to map 1st- and 2nd-Strahler-order drainage networks. PDMs could then link agricultural expansion permissions directly to local topographic ratios (Au/A). For instance, in "critically insecure" southern zones, the expansion of intensive permanent crops would be legally conditioned on the installation of a proportionate number of headwater retention swales or micro-ponds. By linking municipal land-use rights to the natural carrying capacity of the immediate hillslope, local governance can foster long-term climate resilience without disrupting the wider regional water balance.

4.8. Methodological Innovation

The framework's primary novelty lies in its module that links every pixel of a digital elevation model (DEM) to its own specific upstream catchment. This is a departure from conventional hydrologic models, which typically delineate catchments only upstream of major drainage network junctions (where streams meet). Put another way, the traditional approach focuses on stream valleys and the accumulation of water at fixed nodes in a drainage network, whereas the current approach delineates catchments located upstream of individual agricultural parcels, regardless of whether those parcels are near a drainage network junction or not. This effectively moves the hydrologic focus from the valley floor to the hillslopes, where vineyards and olive groves are typically situated. To achieve this parcel-level precision, the framework employs a high-resolution spatial analysis using Python's programming language and the Whitebox data library. Using these tools, a Centroid Point Shapefile (CPS) is created for every single pixel in the 100 m $\times$ 100 m grid covering continental Portugal. For every one of these points, the framework calculates the flow direction and flow accumulation from the DEM to delineate the exact drainage area (DA) located above that specific point. Once the drainage area is identified, the model uses zonal statistics to calculate average annual precipitation (P) and Curve Numbers (CNs) specifically for that upstream catchment. These values are then used to estimate the ex-parcel resources (Vu)—the surface flow that would reach the parcel from its unique upstream hillslope. This innovation is a breakthrough in the assessment of ex-parcel resources. Being independent from water courses, the model can quantify the irrigation potential for thousands of parcels located in headwater areas or on slopes that were previously "invisible" to standard catchment models. It allows for the identification of ideal locations for small-scale on-farm storage, such as small dams or weirs, even if the parcel is not directly on a river. The hillslope-focused model revealed that ex-parcel potential is often 2.5- to 35-times larger than the water captured purely from direct precipitation within the parcel (Vp). In some regions like Santarém, this ratio can be as high as 125 to 1. This high-resolution approach ensures that every agricultural parcel in Portugal—over 65,000 in this study—is evaluated based on its unique topographic and hydrologic surroundings.

4.9. Limitations and Future Research

4.9.1. Limitations

Agroclimatic and Temporal Simplifications: A primary limitation lies in the reliance on a fixed annual precipitation threshold to categorize years as "dry" or "semi-humid." While establishing a standardized macro-regional baseline, this approach oversimplifies intra-annual climate variability and introduces a climatological averaging bias. Under CMIP6 projections, Mediterranean ecosystems like continental Portugal face a profound seasonal shift toward torrential winter rain and prolonged summer droughts. This temporal decoupling has critical implications for crop phenology and irrigation timing that an annual model cannot capture. For instance, high winter runoff might mathematically classify a year as "semi-humid," yet a subsequent dry spring would trigger the irrigation window weeks ahead of schedule. Furthermore, from a micro ex-parcel rainwater harvesting (RWH) perspective, seasonal distribution dictates operational security; concentrated winter surpluses must be stored in small, decentralized farm structures over extended dry seasons. Because these micro-reservoirs have limited individual volumes, accelerated summer evaporation or localized capacity thresholds can cause a system to fail long before the annual water balance reflects a deficit.

Spatial and Operational Scale Constraints: As a macro-regional assessment evaluating over 65,000 parcels, the framework operates under simplified parameterizations. The 100 m grid resolution and the assumption of uniform soil hydraulic properties are particularly restrictive for a micro-harvesting paradigm. They omit the precise micro-topographical drainage paths of 1st- and 2nd-Strahler-order channels, micro-scale soil heterogeneity (e.g., compaction, preferential flow), and localized land management practices (e.g., cover crops, terracing). Because these micro-features directly dictate whether a specific hillside footprint generates or absorbs localized headwater runoff, keeping them static limits the model's sub-grid precision for site-specific planning.

Technical and Structural Assumptions: On the demand side, the model assumes the exclusive use of highly efficient drip irrigation. Consequently, the results do not account for the higher water requirements of traditional sprinkler or surface methods. On the supply side, the framework estimates potential biophysical volume but does not factor in variable micro-conveyance efficiencies, transmission losses along ephemeral gullies, or the specific site-by-site economic cost–benefit ratio of deploying and maintaining thousands of decentralized, small-scale harvesting structures across highly fragmented properties.

Methodological Constraints Regarding Extreme Antecedent Moisture Conditions: Although climate change is projected to increase the frequency of extreme, flood-inducing rainfall and severe drought events, our hydrological modeling was conducted under average antecedent runoff conditions (ARC II). While evaluating dry (ARC I) and wet (ARC III) states is critical for event-based hydrological forecasting and localized risk assessment, uniformly applying these extreme conditions across multi-decadal simulations would permanently skew the cumulative soil water balance. Such an approach would artificially inflate or suppress long-term run-on aggregates, obscuring the primary climate change signals—shifting precipitation and evapotranspiration regimes—projected by the SSP scenarios. Dynamically alternating between ARC states across tens of thousands of parcels would require a high-resolution, continuous daily soil-moisture accounting module, which falls outside the scope of this regional, index-based assessment. Consequently, maintaining ARC II provides the most statistically robust baseline for comparing relative, long-term shifts in crop viability. However, we acknowledge that this approach limits the model's ability to capture the acute impacts of individual extreme weather anomalies, an area that future localized studies should address using dynamic antecedent moisture modeling.

4.9.2. Directions for Future Research

Downscaling and Field Validation: Future work must transition to monthly or daily balance models to capture the compounding impacts of shifting seasonality on micro-storage depletion. Incorporating high-resolution LiDAR data will allow researchers to map exact micro-depressions and hillslope geometries suitable for low Strahler-order interventions, such as contour swales, check-dams, or small excavated retention basins. Future work must therefore bridge the gap between regional vulnerability mapping and localized hydrological engineering. We propose a two-tiered validation approach as the immediate next step: (a) High-resolution topographic modeling—utilizing the current national study as a screening tool, future efforts will select representative, high-vulnerability "hotspot" parcels for case-study analysis. These sites will be modeled using high-resolution Light Detection and Ranging (LiDAR) data (e.g., 1 m to 5 m resolution) to accurately capture micro-basin routing and true volumetric storage potential. (b) Empirical field validation—the high-resolution models will be coupled with on-the-ground monitoring—such as the installation of localized stream gauges, runoff plots, and soil moisture sensors—to empirically validate the Curve Number runoff estimates under varying seasonal conditions. Conducting this micro-scale field validation is a strict prerequisite before presenting specific, localized engineering guidelines or subsidy frameworks to policymakers, ensuring that proposed water harvesting infrastructures are both economically viable and hydrologically sound under future climate extremes.

Hydro-Structural Refinements: Additionally, running simulations under ARCI (extreme dry) and ARCIII (extreme wet) antecedent runoff conditions will make it possible to stress-test these decentralized systems against the mid-21st century's predicted climatic anomalies. Future models should also evaluate runoff water quality, specifically focusing on sediment transport and organic clogging in headwater channels, which can quickly compromise micro-scale drip filters if left untreated.

Systemic and Resource Integration: Rather than modeling on-farm RWH in isolation, future studies should simulate the dynamic, conjunctive integration of decentralized headwater resources with existing groundwater networks and large-scale public infrastructure (such as the Alqueva reservoir system). This will determine how micro-scale, localized retention can act as a distributed input to build multi-source irrigation resilience.

Socioeconomic, Regulatory, and Crop Expansion: The hillslope-focused framework should be expanded to other permanent crops in central-southern Portugal facing similar water threats, such as cherries, almonds, and citrus. Finally, a critical next step involves analyzing how decentralized, low Strahler-order RWH strategies align with current Portuguese water regulations regarding simplified licensing or prior notification for small-scale on-farm ponds, while evaluating the microeconomic viability and maintenance costs of these networks for smallholder farmers.

5. Conclusions

This study establishes a comprehensive hydrologic framework for the decentralized assessment of rainwater harvesting potential, shifting the focus from traditional valley-bottom drainage junctions to agricultural hillslopes. By delineating catchments for 65,085 individual vineyard and olive yard parcels across continental Portugal, we provide a high-resolution quantification of "in-parcel" versus "ex-parcel" water resources under historical and CMIP6 climate scenarios.

The most significant hydrologic finding is the overwhelming dominance of ex-parcel runoff, which provides a volumetric potential between 2.5- and 35-times greater than direct in-parcel precipitation. In specific regions like Santarém, these ratios reach as high as 125:1, demonstrating that hillslope runoff is a massive, underutilized resource for supplemental

irrigation. This dominance remains robust even in low-order catchments, which offers the unique hydrologic advantage of capturing water on upper hillslopes without significantly depleting downstream river flows.

The analysis reveals an evident north–south gradient in irrigation security. While vineyards currently maintain high security countrywide, southern olive groves—particularly in the Alentejo region—face a substantial degradation of security status by 2070. Under the SSP5-8.5 pathway, security indices for olive groves drop to –33.2, indicating that current direct-precipitation harvesting will be fundamentally insufficient to meet future biological water requirements. This highlights an urgent need for infrastructure that prioritizes ex-parcel collection to buffer against the projected 20–30% reduction in southern surface water availability.

Methodologically, this work demonstrates the power of integrating open-source spatial libraries (Fiona, Rasterio, Whitebox) with parcel-centric delineation to provide actionable data for decentralized water management. From a policy perspective, our findings provide the quantitative basis for initiatives like Portaria no. 54-C/2023, proving that rainwater harvesting can complement Portugal's over-exploited groundwater (74% of current use).

In conclusion, the proposed framework offers a scalable solution for Mediterranean regions facing similar water-security challenges. We demonstrate that while climate change will inevitably shrink the hydrologic "safety buffer", the strategic capture of ex-parcel hillslope runoff provides a resilient alternative to centralized systems, which currently fail to meet full irrigation demands in 40% of Portuguese reservoirs. Future water management must therefore move beyond large-scale damming to embrace parcel-level hillslope hydrology as a cornerstone of agricultural adaptation.

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