

Article

Nature-Based Solutions for Flood Mitigation and Soil Conservation in a Steep-Slope Olive-Orchard Catchment (Arquillos, SE Spain)

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Abstract: The frequency and magnitude of flash floods in the olive orchards of southern Spain have increased because of climate change and unsustainable olive-growing techniques. Affected surfaces occupy > 85% of the rural regions of the Upper Guadalquivir Basin. Dangerous geomorphic processes record the increase of runoff, soil loss and streamflow through time. We report on ripple/dune growth over a plane bed on overland flows, deep incision of ephemeral gullies in olive groves and rock-bed erosion in streams, showing an extraordinary sediment transport capacity of sub-daily pluvial floods. We develop a novel method to design optimal solutions for natural flood management and erosion risk mitigation. We adopt physical-based equations and build a whole-system model that accurately reproduces the named processes. The approach yields the optimal targeted locations of nature-based solutions (NbSs) for active flow-control by choosing the physical-model parameters that minimise the peak discharge and the erosion-prone area, maximising the soil infiltration capacity. The sub-metric spatial resolution used to resolve microtopographic features of terrains/NbS yields a computational mesh with millions of cells, requiring a Graphics Processing Unit (GPU) to run massive numerical simulations. Our study could contribute to developing principles and standards for agricultural-management initiatives using NbSs in Mediterranean olive and vineyard orchards.

Keywords: nature-based solutions; distributed hydrological model; IBER+; Guadalquivir basin; European Union Directive 2007/60; flash flood; gully erosion; olive and vineyard orchards



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1. Introduction

The frequency and intensity of sub-daily floods have increased in the Upper Guadalquivir Basin (southern Spain) during the last twenty years due to the actual scenario of climate change [1]. This kind of extreme hydrological event has become more and more relevant in many Mediterranean areas of Europe [2], corroborating the predictions of the Intergovernmental Panel on Climate Change (IPCC) [3] and the European Environmental Agency (EEA) [4]. High precipitation rates combined with anthropogenic effects of soil use and management have provoked unsustainable soil-loss rates and large-scale gully erosion in some European agricultural catchments [5]. Simultaneously, floods have developed at the catchment scale because of deep runoff [6]. Both problems are linked because they depend, in leading order, on the dynamics of overland flows [7]. The Mediterranean Experts on Climate and Environmental Change (MedECC) [8] recommend the implementation of NbS and adaptive practices of sustainable land management because climate change is expected to increase soil erosion in a complex, non-linear way. Mitigating flood risk and preventing soil erosion at large scales cannot be achieved with isolated civil engineering actions; the economic costs and environmental impacts would be prohibitive. Alternatively,

we adopt Nature-Based Solutions (NbSs) [9–11] that seek to delay the flooding, reduce the peak water discharge and erosion capacity of overland flows, and promote infiltration at the basin scale.

We considered a pilot study site of the Upper Guadalquivir Basin where the current land management practice and the increase in extreme rainfall rates (up to approximately $30 \text{ mm} \cdot \text{h}^{-1}$) have caused soil loss rates of $20\text{--}50 \text{ t ha}^{-1} \text{ yr}^{-1}$ (see Figure 2 in [12]). Such values are nearly a maximum in Europe, so the Guadalquivir watershed has attracted the scientific community's interest in gully erosion processes [13,14]. More than 80% of the catchment is dedicated to traditional olive groves (i.e., the vegetation surrounding the crops was removed), a practice extended across the entire Mediterranean basin [15]. In such environments, we have shown the potential of the two-dimensional Saint-Venant Equations (2D-SVEs) to map the extent of the inundations and describe fluvial geomorphological processes at the river-stretch scale [16,17]. High-spatial resolution numerical simulations using 2D-SVE-distributed hydrological models yield further details of the rainfall-runoff-inundation processes at the watershed [6]. The output products for a given rainfall event are the flow depth and velocity not only in the main river but also in smaller spatial-scale elements of the whole drainage network. If the intensity of the precipitation is high enough to provoke water discharges above the drainage capacity of the streams and rivers, the 2D-SVE-distributed numerical simulation gives all the flooded areas across the whole watershed. Furthermore, the interpretation of the flow-velocity map serves to predict the locations where fine sediments transported as wash load settle and provoke slackwater deposits [1].

The main objective of this article is to find the optimal NbS (including its location) which provides the most benefits in terms of hydraulic effectiveness to prevent flooding and soil erosion in steep-slope olive groves. We address both problems at the same time instead of independently. Subsidiary—but no less important—objectives are the increase in the retention capacity of overland flows and the soil infiltration capacity to avoid the undesirable phenomenon of soil-water repellence and higher surface runoff volumes in olive groves [18]. All of them contribute to mitigating street-scale urban floods in the site study. So, this work extends the capabilities and applicability of our former model, initially calibrated and planned only for flood-risk mapping in ungauged olive-orchard basins [1,6].

The developed methodology has two stages: (i) first, the diagnosis of the causes leading to inundation and soil erosion using the highly resolved Computational Fluid Dynamics (CFD) simulation of the current situation; (ii) second, the quantification of the hydraulic effects of the possible measures for natural flood management (NFM) and soil loss mitigation by simulating parameter variation in future scenarios. The output products identify the optimal model parameters across the catchment (i.e., controlled variables) that minimise the objective functions, namely: the peak water discharge at the basin outlet and the shear stresses responsible for soil erosion. The approach is standard in Active Flow-Control (AFC), a “multidisciplinary science and technology thrust aimed at altering a natural flow state into a more desired state” [19]. The last step is the selection of a realistic NbS that produces the optimal values of the controlled physical variables at the targeted placement. We consider NbSs compatible with sustainable production techniques in olive growing [20] and complementary innovations developed worldwide, as described below. Isolated NbSs cannot fix all the problems alone, and the ideal future scenario should exploit several actions' synergetic benefits.

To this end, we apply standard techniques in AFC [19] and CFD [21], which consist of parameter variation and geometric modelling with sub-metric spatial resolution, uncommon yet in evaluating the effectiveness of an NbS [10]. There is presently no standard approach to determining how many NbSs to use and where to locate them in NFM [22]. A limited number of studies applied the typical engineering protocol with spatially-resolved, physically-based 2D-SVE simulations [23]. A frequent limitation of the existing design routines is the coarse resolution of the computational grid because of two reasons: first, the coarse mesh impedes the detailed geometrical modelling and

hydraulic simulation of an individual NbS at a given location; second, the grid size affects the simulation results of rainfall/runoff events in a magnitude as large as physical factors [24]. We overcome such drawbacks using the latest advances in distributed hydrological modelling that allow simulating catchment-scale problems at extremely high spatial resolution in the Graphics Processing Unit (GPU) [25]. We adopt the software IBER+ [26], among alternatives as SERGHEI-SWE [27], TRITON [28], and LISFLOOD-FP [29]. Here we show that IBER+ allows the development of a whole system model incorporating the agricultural areas, the drainage network, urban areas, and civil engineering infrastructures by a multiple-scale grid resolution and proper mapping of physical parameters. Hence, the following issues are addressed at once: simulating rainfall-runoff processes [30]; urban flood mapping [31,32]; soil-erosion risk [14]; and the effectiveness of nature-based mitigation measures [33–35]. However, the current limitation of single GPU computations in IBER+ restricts the catchment area to 20 km² for extremely high spatial resolutions of 1 m². Scaling up the analysis to larger draining basins (<1000 km²) is now possible with SERGHEI-SWE through exascale High-Performance Computing (HPC) technology and multi-GPU [27]. The proposed approach permits fully exploiting the available Digital Elevation Model (DEM), resolving many microtopographic features controlling surface flow, soil erosion and sediment transport connectivity.

To the best of the authors' knowledge, the design of nature-based interventions and the quantification of their hydraulic benefits in reducing flood and soil loss hazards in catchments with soil uses dominated by olive growing have not been undertaken beforehand. Such objectives lie in the scope of NbSs, which are "actions to protect, sustainably manage, and restore natural or modified ecosystems, that address societal challenges effectively and adaptively, simultaneously providing human well-being and biodiversity benefits" [36]. Plausible NbSs for our targeted physical goals are the creation of an online wetland [37–39] or a naturalised irrigation pond [40], gullies infilling with dry bush or small boulders [20,41], gravels seeding in streambeds [23,42], flexible submerged vegetation planting in streams [43], and the restoration of the river floodplains [44]. Additionally, we suggest adopting cultivation systems in olive orchards based on plant residue mulches [45] and live plant covers along the middle of the orchard lanes [46]. Such tools are suitable for water conservation and erosion control in Mediterranean olive tree cropping [47] and are also compatible with water collection pits [20]. The outputs of our study contribute to developing principles and standards for agricultural-management initiatives using NbSs [48,49] and could be applied in other Mediterranean areas of Europe with similar problems under the current climate change scenario [8].

2. Materials and Methods

2.1. Study Site

The selected study area is located in the southwest of Europe within the upper Guadalquivir Basin (Spain). The basin has a small size of $A_{\text{drain}} = 6.9 \text{ km}^2$, a mean slope of 19% and a maximum (minimum) height greater (lower) than 750 m MSL (360); see Figure 1. The catchment mimics an ideal laboratory with a homogeneous surface but at a much larger, real scale. Olive groves dominate the soil use, occupying 93.4% of the drainage area. There are approximately 46,500 olive trees (green dots in Figure 1a), with a density of 70 trees·hectare^{−1}. The combination of steep slopes (Figure 1b) and land use of olive groves under conventional tillage prevent infiltration [18]. Additionally, the lack of natural cover exposes sediment to erosion and causes a high development of laminar and gully processes.

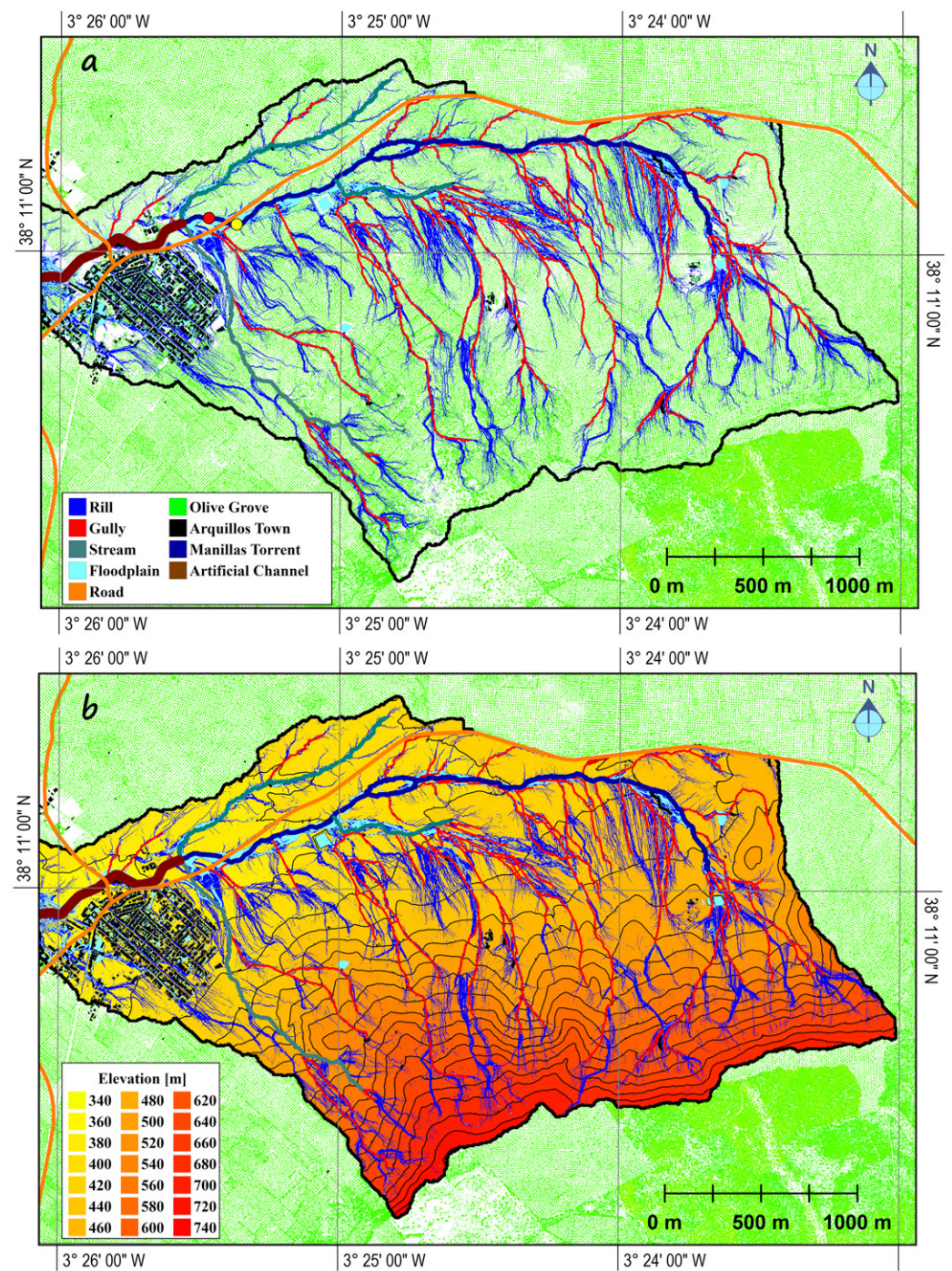


Figure 1. General characteristics of the Manillas basin in Arquillos (Jaén, Southeast Spain). (a) Catchment overview (perimeter highlighted with the black solid line) with three regions of interest: the urban areas (black), the man-made channel that should protect the town from inundation (thick line in brown), and olive trees (green dots). The drainage network is composed of rills, gullies, and streams. (b) Hypsometric map and drainage network. For completeness, main traffic roads are coloured in orange. Maps created from scratch with Matlab and GlobalMapper based on a Light Detection and Ranging (LiDAR) dataset acquired on May 2021 with 1.5 points per square meter (<https://www.ign.es/>, accessed on 1 July 2022). Rills, gullies, and streams were obtained from the distributed hydrological simulations presented in this paper.

We identified the following sediment sources according to the classification by Charlton [50], see Figure 1: rill (light blue), gully (red), and stream (dark blue and greenish blue). Rills are small micro-channels where overland flow exerts a shear stress on the soil close to the threshold value for erosion with flow depths of up to 30 mm. Gullies are relatively permanent ephemeral channels in semi-arid environments without vegetation cover, eroded during highly seasonal precipitation. The gully channel is narrow, with a steep bed slope and a characteristic flow depth larger than 0.5 m. Smaller features, intermediate in size between gullies and rills, are referred to as ephemeral gullies in Soil Science Society of America [51]. Stream channels collect and transfer the sediment budget produced in rills and gullies [52]. In the Manillas basin, streams develop in regions with much smaller bottom slopes than for ephemeral gullies. All these elements of the drainage network are connected to the primary river system, referred to as the Manillas stream. In general, the channel form of the streams can adapt to altered environmental conditions [53].

The absence of civil infrastructure in most of the watershed ensures that runoff responds naturally to torrential rainfall. Hence, overland flows erode many gullies and shallow streams that drain transverse to the Manillas stream. The Manillas stream catches overland flows from the gullies and shallow streams along 4.6 km with a mean slope of 4.2% and two nick points. The stepper reach is located in the headwater (i.e., first 500 m with a 6.7% slope). Later, the bed slope decreases to 3.3% for 1000 m. Further downstream, it reaches a constant value of 1.8%, which remains for 3 km. During its fluvial course, the main channel exhibits non-uniform bankfull dimensions. On occasion, the water has sculpted a much wider and deeper channel than other river stretches. Therefore, the channel-reach morphology may correspond to a single confined flow or a floodplain channel, depending on the river stretch [52]. The wash load is the dominant transport process due to the small sediment size and straight planform [54]. The fine granulometry of available sediments favours transport processes dominated by wash load that settle slackwater deposits with low flow velocity [55].

The Mediterranean climate, characterised by seasonal and irregular rainfall distribution, dominates the Upper Guadalquivir Basin, including the Manillas sub-basin. The complex topography of the landscapes and the geographical position favour two climate influences coming from the Mediterranean Sea and the Atlantic Ocean. So, two kinds of precipitation events usually develop. First, low intensity and continuous rainfalls longer than one week, which are not dangerous in small basins [16,17]. Second, sub-daily rainfalls, which are produced by reduced area storms and cause local short-rain floods at small basins [1,6]. The increase in frequency and magnitude of short-pluvial floods reported in the present study case further corroborates the predictions of the IPCC [3] and the EEA [4]. Nowadays, short rains are becoming more frequent and more severe in the Manillas basin and other basins of the Guadalquivir headwaters.

Because of orographic constraints, since 1970, Arquillos town has grown, occupying the meanders floodplain that exists at the basin outlet. A regular train of two meanders surrounds the urban area, with a linear wavelength and amplitude of 500 m and 100 m, respectively. In the last decades, storms with an accumulated precipitation depth of 90 mm provoked flash floods for a few hours nearly once a year. To protect the town from inundations, an artificial channel with a uniform rectangular section of 1.4 m depth and 3 m width was built in the 1980s (Figure 2). Presently, the reinforced-concrete base of the channel is eroded, which illustrates the high-speed flows that develop along the flume during extreme rains. This point implies that the flow velocity is above the threshold of erosion for a concrete pavement (i.e., $6 \text{ m}\cdot\text{s}^{-1}$), which would be corroborated with the numerical simulations conducted in this study. Furthermore, there is considerable evidence of channel overtopping because several inundations occurred in the paved road crossing the town shown in Figure 2b.

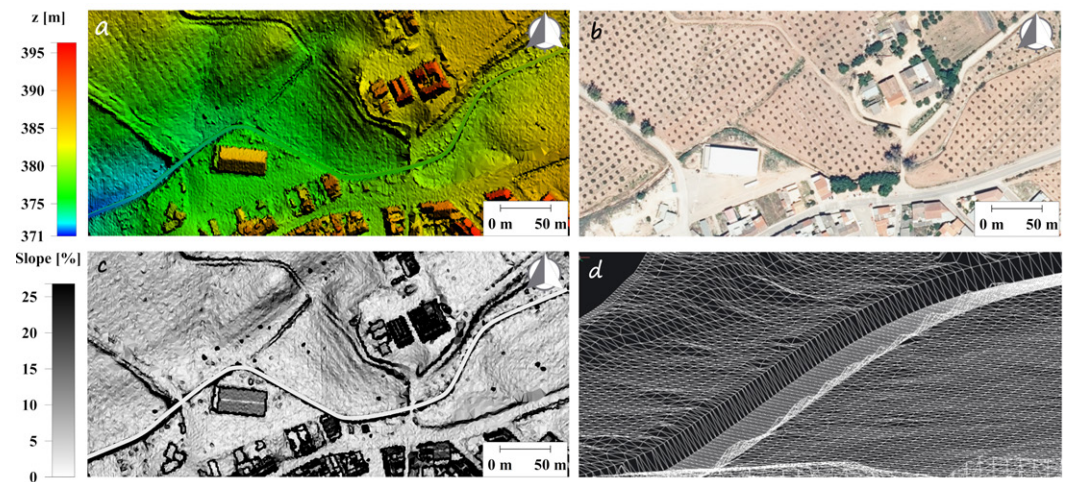


Figure 2. (a) DEM, (b) orthophoto, and (c) DEM slope in a small area surrounding the Arquillos town. We built the DEM from scratch using filtered LiDAR data and in-situ measurements with Leica Zeno 20 Global Positioning System (GPS). (d) Zoom of the computational mesh for the artificial channel and the floodplains. Note the hybrid topology of the cells with rectangular elements in the channel and triangles otherwise.

2.2. Distributed Hydrological-Hydraulic Modelling

The two-dimensional shallow-water equations, better known as the Saint-Venant equations, were adopted to describe the motion of surface waters. To this end, we configured the hydrological module of IBER+ [26]. It solves numerically the depth-averaged inviscid conservation laws of mass and momentum for clear water in a two-dimensional, Cartesian system of coordinates, given in compact form by

$$\frac{\partial h}{\partial t} + \nabla \cdot (h \mathbf{u}) = P - I, \quad (1)$$

$$\frac{\partial h \mathbf{u}}{\partial t} + \nabla \cdot (h \mathbf{u} \mathbf{u}) + \nabla \left(\frac{g h^2}{2} \right) = -g h \nabla z - \frac{\tau_b}{\rho}, \quad (2)$$

where t is the time, h is the depth of the water measured along the vertical coordinate, $\mathbf{u}$ is the depth-averaged velocity vector, z is the bed altitude, and g is the acceleration due to gravity. The source terms in the continuity Equation (1) represent the rainfall intensity, P , and the soil infiltration rate, I . In the momentum balance Equation (2), the source terms are the bed slope ∇z and the bottom shear stress τ_b/ρ , in which ρ is the water density. Manning's friction law was used for evaluating the hydraulic resistance in (2) by setting

$$\frac{\tau_b}{\rho} = \frac{g n^2}{h^{1/3}} \mathbf{u} |\mathbf{u}|, \quad (3)$$

where n represents Manning's roughness coefficient.

The assumption of small bottom slopes is the basic hypothesis of the two-dimensional shallow-water Equations (1)–(2), which imply that the pressure distribution on the vertical is hydrostatic. Although such a constraint is not formally satisfied in all the situations, as in mountain areas, the most sophisticated GPU numerical codes for distributed hydrological simulations solve standard Equations (1)–(2) [26–29]. Nowadays, there is no consensus on the theoretical formulations for steep slopes, and several theories have been proposed (see the review by Maranzoni and Tomirotti [56]). So, on the numerical side, the existing numerical codes are in-house and still based on CPU instead of GPU [57,58], preventing their use for the current purpose.

The two-dimensional shallow water model (1)–(3), together with homogeneous initial conditions for h and u , were discretised using a finite volume method based on the DHD solver [59] implemented in the free-software IBER+ [26]. The Reynolds stresses were neglected as suggested by Cea and Bladé [59] for overland flow applications. We ran all the simulations using single-precision calculations in a Quadro RTX5000 GPU. In so doing, we achieved a reasonable computational time of three days per simulation. We set the Courant-Friedrich-Lewy number of 0.45 to satisfy the stability constraint of the DHD scheme.

In the following subsections, we describe the configuration of the physical parameters of the hydrological model. We give details on the computational grid, and the DEM in Section 2.2.1. Then, in Section 2.2.2, we used historical data of extreme hydrological events to characterise the design storm parametrised with P in (1). Lastly, we configured the Manning roughness n (2) and the infiltration rate I (1) in Section 2.2.3 and Section 2.2.4, respectively, borrowing existing results from well-established studies. The analysis of the possible values of I and n for the present-day situation and the future with NbSs served to vary them systematically and configure a set of fifteen numerical simulations.

2.2.1. Computational Mesh

We built a computational mesh across the whole drainage area of 7 km² subdividing it into three regions. The whole system model requires a high spatial resolution to capture with accuracy the topographic flow control exerted across the catchment pathways and urban areas. First, we discretised the man-made channel of 1 km length and 3 m width (brown line in Figure 1) with 60,000 structured elements of 0.1 m × 0.5 m size. Elevations of the channel thalweg and lateral walls were measured in situ with a Leica Zeno 20 Global Positioning System (GPS) combined with laser Leica DISTO™ and AS11 multi-frequency Global Navigation Satellite System (GNSS) antenna. Subsequently, a digital elevation model of the channel area was constructed, and the elevations were assigned to the computational grid. Second, the urban area (black squares in Figure 1) was discretized with triangular cells with a characteristic size of 1 m. The nodes elevation were obtained from a home-made DEM based on Light Detection and Ranging elevations acquired on May 2021 by the Spanish Geographical Institute (<https://www.ign.es/>, accessed on 1 July 2022). The average distance of a point from its neighbours in the LiDAR dataset is 0.82 m (corresponding to the point density of 1.5 points per square meter) with a root mean squared error between the ground reference and estimated position of 0.3 m and 0.15 m in the horizontal and vertical coordinates, respectively. Third, the computational grid is coarser in the greatest rural area of the Manillas catchment (green region in Figure 1) because the unstructured grid has a characteristic edge length of 1.5 m. Elevations were also obtained from the LiDAR data that had to be filtered to delete the vegetation and olive trees, keeping only the ground points. The elevations of the gullies and streams are accurately represented in the LiDAR data thanks to the seasonal behaviour of the precipitation. The computational mesh amounts to 7 million cells and replicates real topography in the simulated region.

Figure 2 shows details of the geometrical model in a zoomed area that includes the channel, buildings and olive groves. The elevations (Figure 2a) accurately represent the civil infrastructures visible in the orthophoto (Figure 2b). The man-made channel that surrounds the town can be better observed in the shadowgraph (Figure 2c). Lastly, Figure 2d shows a zoom of the computation grid near the channel. We ensured that the surface in the olive-grove floodplains was smooth by removing the olive trees when constructing the DEM from LiDAR, as described above.

2.2.2. Design Storm

To represent the distribution of rainfall intensity over time, parametrised by $P(t)$ in (1), we analysed the extreme values of available rainfall data since 1950. The main objective was to calibrate the rainfall rate $\bar{P}$ and duration D of the step hyetograph:

$$P(t) = \begin{cases} \bar{P} & \text{if } 0 \leq t \leq D \\ 0 & \text{if } t > D \end{cases} \quad (4)$$

Figure 3a shows the accumulated precipitation for 24 h (referred to as daily rainfall depth from now on) measured by a rain gauge located in the Guadalén Reservoir at a distance of 4 km downstream of the town of Arquillos. The maximum value was 95 mm on 15 August 1996 due to a sudden storm in the night. It caused the most catastrophic flood reported in the town of Arquillos. Real-time hydrologic monitoring has provided hourly average values since 2010. Figure 3b depicts the accumulated precipitation for 1 h (referred to as hourly rainfall depth), with a peak value of $30 \text{ mm}\cdot\text{h}^{-1}$ on 8 June 2011 at 7:00 a.m. There are other extreme events with hourly rainfall depths close to the peak value, for instance, $27.9 \text{ mm}\cdot\text{h}^{-1}$ on 21 October 2012 at 4:00 a.m. and $28.9 \text{ mm}\cdot\text{h}^{-1}$ on 7 September 2016 at 8:00 a.m. Usually, the storm lasts for three hours and leads to daily rainfall depths of 80–95 mm (Figure 3a). Subsequently, we set the design storm parameters given by $\bar{P} = 30 \text{ mm}\cdot\text{h}^{-1}$ and $D = 3 \text{ h}$ that lead to daily/hourly rainfall depths similar to the highest values measured since 1950.

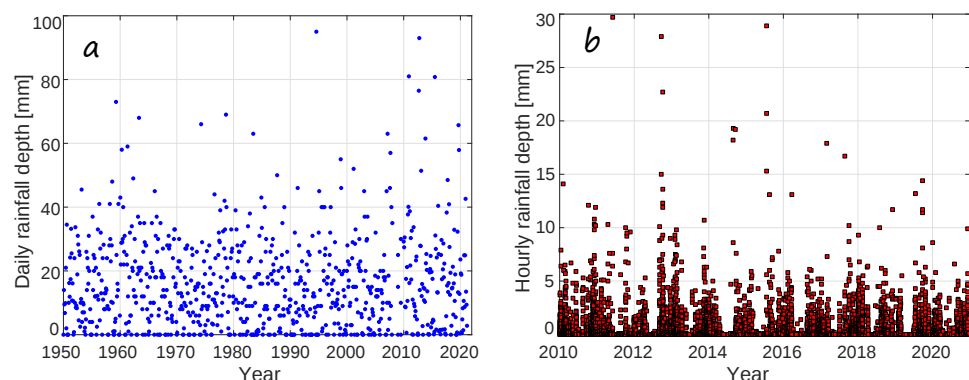


Figure 3. Maximum values of daily (a) and hourly (b) precipitation depth recorded 1950–2022 and 2010–2022, respectively. Data source: <http://www.chguadalquivir.es/saih/>, accessed on 1 July 2022.

The dangerous nature of short-rain floods in small-area catchments is related to the short period of concentration T required to achieve the peak streamflow Q_{ss} , given in the absence of infiltration by Brutsaert [60]:

$$Q_{ss} = A_{\text{drain}} \bar{P}, \quad (5)$$

$$T = \frac{L}{U_{\bar{P}}}, \quad (6)$$

with the runoff velocity $U_{\bar{P}}$:

$$U_{\bar{P}} = (\bar{P} L)^{\frac{2}{5}} \cdot S_0^{\frac{3}{10}} n^{-\frac{3}{5}}. \quad (7)$$

In (6)–(7), L is the characteristic length of the catchment (e.g., $L = A_{\text{drain}}^{1/2}$ in a nearly square basin), S_0 is the mean basin slope and n corresponds to Manning's roughness coefficient. Setting $n = 0.02 \text{ s}\cdot\text{m}^{-1/3}$ as for similar basins [1,6], we get $U_{\bar{P}} = 1.3 \text{ m}\cdot\text{s}^{-1}$, $T = 33 \text{ min}$ and $Q_{ss} = 57.4 \text{ m}^3\cdot\text{s}^{-1}$. The theoretical value of T can be interpreted as the minimum duration of the rain event T needed to provoke Q_{ss} .

Such an extreme value of the peak water discharge was not observed before 1996. Conversely, it has become usual in the last decade because of sudden storms with a duration shorter than one day and longer than the concentration time T , referred to as a short-rain flood [61]. Short-rain floods have acquired relevancy in small catchments under the actual climate change scenario not only in the Upper Guadalquivir River [1,6] but also in the Mediterranean [2,62]. Furthermore, the reported increase in the frequency and the magnitude of short-rain inundations corroborates the predictions of the IPCC [3] in the current study site.

2.2.3. Surface Roughness

Manning's equation has been used intensively in riverine hydraulics since its formulation in 1889. Extensive tables of the roughness coefficient n are available for different channel characteristics [63,64], natural channels, and flood plains [65]. More recently, distributed hydrological simulations have shown that Manning's resistance law is also plausible to predict the runoff dynamics in roads, urban floods and agriculture areas [32,66–68].

We classified the catchment area into six types of soils, as shown in Figure 4a, and assigned the Manning coefficient described below. Urban areas (dark green), roads (orange), and existing irrigation ponds (brown) were delimited from the most recent orthophoto. They occupy about 7% of the drainage area. The analysis of the water distribution for paved roads [69] and the urban regions [70] showed that the coefficient $n = 0.015 \text{ s} \cdot \text{m}^{-1/3}$ is appropriate in both of them. For irrigation ponds finished in plastic materials, the accepted values is $n = 0.012 \text{ s} \cdot \text{m}^{-1/3}$ [64].

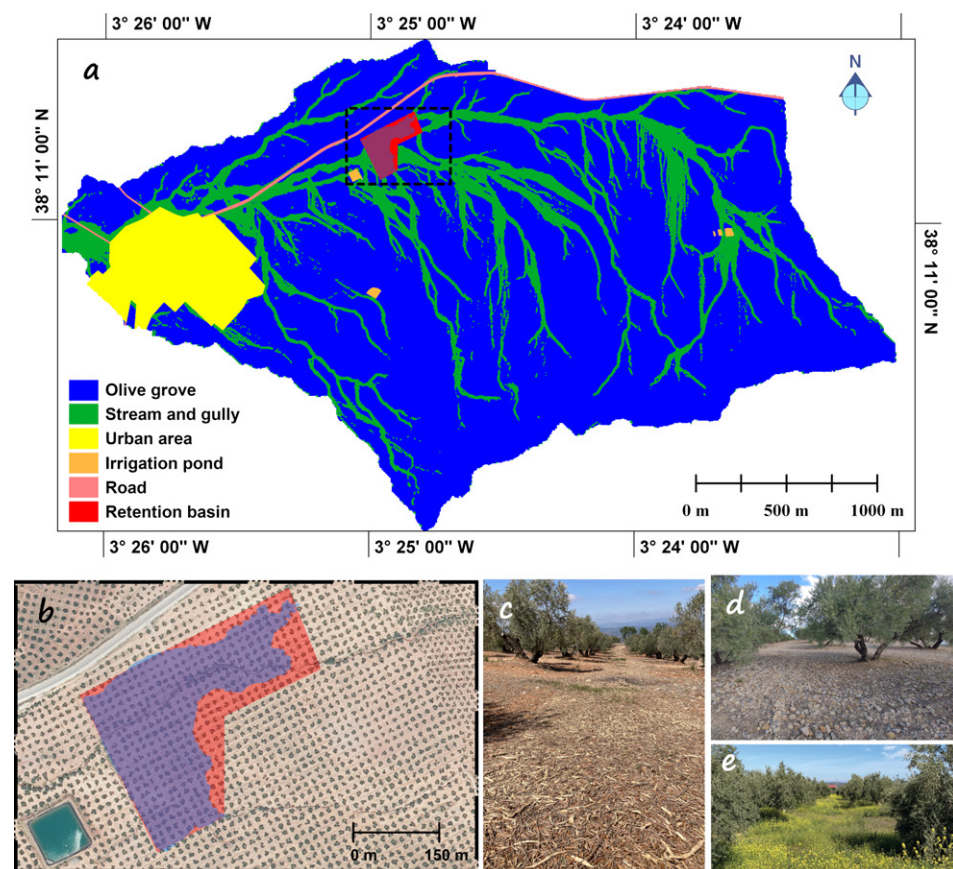


Figure 4. (a) Regions defined in Section 2.2.3 to assign the Manning roughness. (b) Orthophoto in the dashed rectangular area of panel a showing sandy clay loam on the surface outside the olive tree canopy projection and inside streams because of the herbicide uses. The blue and red polygons are possible retention basins based on an artificial wetland or a large irrigation pond. (c–e) Possible NbS using ground branches, gravels and natural full-cover crop.

The largest region occupied by olive grove (81%), see the blue area in Figure 4a, has a density of 70 trees·hectare⁻¹ and the soil management is nearly homogeneous. The traditional use implies that the vegetation surrounding the crops was removed, as observed in the orthophoto of Figure 4b. To simulate hydrological processes in the present day, we set the value $n = 0.02 \text{ s} \cdot \text{m}^{-1/3}$ corresponding to fine sand (colloidal) as calibrated in our previous work [6]. We will see that the ensuing runoff velocities are high, so we would consider a possible NbS for soil erosion mitigation that seeks rising resistance to the flow. Some examples are: integrating the ground branches back into the soil after the pruning process (Figure 4c), redistributing gravels to form coarse surface structures (Figure 4d), and temporary spontaneous cover crops (Figure 4e). Following Crompton and Thompson [71], we set $n \approx 0.2 \text{ s} \cdot \text{m}^{-1/3}$ to imitate an NbS that provokes macro-roughness effects in possible future scenarios.

The absence of natural cover has exposed sediment to erosion and caused a high incision of gullies and streams (green area in Figure 4a). Such regions were unknown a priori. To delimit them, we run a preliminary simulation with a constant Manning value of $n = 0.02 \text{ s} \cdot \text{m}^{-1/3}$. Subsequently, we selected the regions with flood depths of $h > 0.01 \text{ m}$ to extract the water mask depicted in green in Figure 4a. It occupies 12% of the basin area and lacks riparian vegetation; note the sandy colour in the streams of Figure 4b. To simulate hydrological processes in the present day, we set $n = 0.025 \text{ s} \cdot \text{m}^{-1/3}$ as calibrated in a catchment with similar geographical characteristics and precipitation regime [1]. Further, we would consider possible NbSs for increasing the floodplains retention area, delaying the concentration time and attenuating the peak water discharge for short rainfalls [37]. Plausible NbSs for increasing the in-channel roughness are riparian buffer installation, rock armour, willow in-ditch barriers, and timbers in a cross formation, among others. So, we simulated scenarios with the large (and realistic as well) value of $n = 0.2 \text{ s} \cdot \text{m}^{-1/3}$ [65].

Lastly, the red region in Figure 4a represents a possible flood retention basin that (does not exist in present days but) would store overland waters, preventing the inundation of downstream urban areas. The present day simulation helps find the optimal siting and sizing of the flood barrier [38]. Figure 4b shows a zoom of the location and shapes of two possible solutions: the light blue corresponds to an artificial wetland that uses a 406 m height flood barrier to store the water; the light red represents a larger 6 m depth irrigation pond. The Manning coefficient $n = 0.012 \text{ s} \cdot \text{m}^{-1/3}$ [64] was used for the impermeable retention area when the simulated scenario included it.

2.2.4. Infiltration

We adopted the Soil Conservation Service (SCS) Curve Number (CN) approach for evaluating the infiltration parameter I (1) in the distributed hydrological simulation of the Manillas agricultural watershed. In particular, we used a continuous version of the curve number methodology [72]. The theoretical foundations of the SCS-CN are well described in the book by Hawkins et al. [73]. Details on the numerical implementation in the distributed-hydrological model IBER+ can be found in the software manual [74]. For brevity, we describe the parametrisation of the model for our simulations concisely.

The model relies on a single parameter—called a Curve Number (CN)—that depends on the hydrologic soil group and the soil use and management. In the urban area, irrigation ponds and roads of Figure 4, we set the impermeable condition $I = 0$ corresponding with $CN = 100$. Based on the surface texture of the olive grove region, gullies, and streams, the hydrologic soil group is sandy clay loam (group C [73]). Such soils have low infiltration rates when thoroughly wetted. Indeed, Burguet et al. [18] reported soil water repellence, i.e., $I = 0$, under conventional tillage in olive-orchard catchments. Here we borrow values for the CN parameter in olive orchards from Romero et al. [75], who calibrated it under different soil management in the Upper Guadalquivir watershed. Currently, the soil use and management correspond with no-tillage (Figure 4c), i.e., the soil is weed-free using herbicide. Hence, we set $CN = 89$ (see CNII in Table 6 in [75]). Such a scenario is denoted by CN89 from now on.

The risk of high runoff depths (associated with values of CN close to 100) could be mitigated using an NbS that rises the soil surface roughness for a possible future scenario (Figure 4e). The surface outside the olive tree canopy projection could be covered by a well-implanted cover crop providing 30–70% ground cover. Hence, the CN would decrease from 89 to 64 [75]. We denote the future scenario as CN64.

In addition, we consider a third scenario (CN100) for impermeable soils, i.e., $I = 0$ or $CN = 100$, to check the assumption that simplified the numerical modelling in our previous work [1,6].

To evaluate the infiltration capacity of overland flows, we accounted for the local basin slope S_0 . We corrected the CN values for scenarios CN89 and CN64 with the algebraical formula per Ajmal et al. [76]:

$$CN \leftarrow CN \left[1 + \frac{50 - 0.5 CN}{CN + 75.43} \left(1 - e^{-7.125(S_0 - 0.05)} \right) \right]. \quad (8)$$

Figure 5 shows the CN map in the Manillas stream's watershed. For completeness, we also included the computed histograms. In the present day (CN89), CN varies in the narrow range of 88–92, and in the future (CN64), CN could change to a broader interval of 60–72. In both scenarios, the most probable value tends to be the highest boundary, i.e., 92 for CN89 and 72 for CN64, highlighting the effect of the steep slopes. Indeed, the comparison between the CN maps (Figure 5a,c) with the hypsometric map (Figure 1b) indicates a good correlation between the highest values of CN and the steepest slopes.

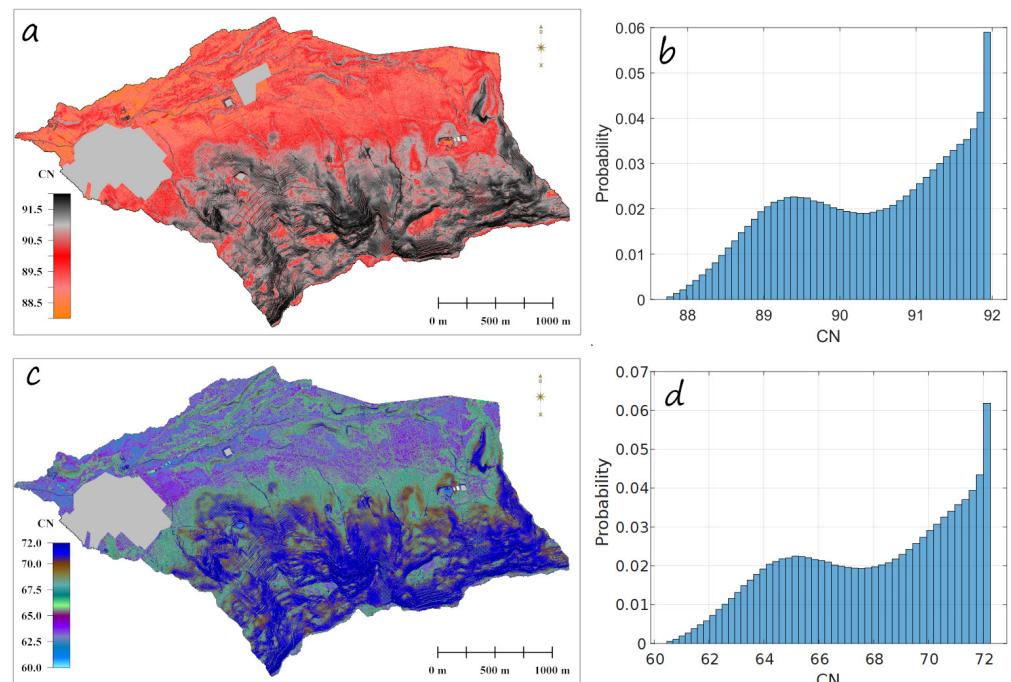


Figure 5. Map and histogram of the local values of the Curve Number (CN) for the simulation setups CN64 (a,b) and CN89 (c,d) in the Arquillos Basin, computed and drawn by the authors using the Methods detailed in Section 2.2.4.

3. Results

We simulated the hydraulic response of overland flows for six hours for the design storm given in Section 2.2.2, i.e., for a spatially-uniform rainfall $\bar{P} = 30 \text{ mm} \cdot \text{h}^{-1}$ of three-hours duration. We ran fifteen simulations corresponding to the combinations of the three CNs {64, 89, 100} in the olive-grove area and the A-to-E scenarios that varied the Manning roughness or altered the digital elevation model in the retention basin as follows:

- (A) Without NbS, i.e., as in the present day with the Manning roughness mapping described in Section 2.2.3;
- (B) Macro-roughness effects in the olive-grove region and the drainage network, i.e., $n = 0.2$ in the blue and green areas of Figure 4a;
- (C) Macro-roughness effects only in the olive-grove region (i.e. $n = 0.2$), keeping the drainage network as in the present day (i.e. $n = 0.025$);
- (D) The artificial wetland, see the blue area in Figure 4b, by constructing a barrier at the level of 406 m with a maximum local height of 6 m, which yields an inundated area of 0.044 km^2 with a storage capacity of $V_w = 0.097 \text{ hm}^3$. The optimal location (dashed square in Figure 4a) catches three streams that drain 3.9 km^2 (56% of the total basin area);
- (E) A reservoir pond with a uniform depth of 6 m to store storm runoff. The trapezoidal shape of the reservoir (red area in Figures 4a,b), surrounding the ground line at 406 m, has a perimeter of 1.5 km, a surface of 0.065 km^2 , the bottom carved at 397 m, and a pond capacity of $V_p = 0.39 \text{ hm}^3$.

The following subsections summarise the results for the fifteen scenarios simulated numerically. In Section 3.1, we start describing the dynamics of overland flows for the actual situation of the draining basin. Regarding the flood risk analysis, we shall verify the outputs of the computational model with available paleohydrological information on the simulated flood event. Further, we discuss the effects of surface waters on soil erosion risk at the catchment scale. Subsequently, in Section 3.2, we identify the most beneficial physical parameters concerning the mitigation of urban floods. Additionally, in Section 3.3, we analyse the simulated shear stresses to select the optimal model parameters for mitigating soil erosion.

Lastly, in Section 3.4, we site and select the optimal nature-based solutions that provide the most benefits for minimising the peak streamflow, the runoff depth, and the erosion-prone area, which is the desired state. The fifteen scenarios simulated previously serve to delimit the specific locations where a change of the model's physical parameters is required to achieve the optimal values. Next, the particular NbS for the targeted placement is selected according to the simulation results.

3.1. Distributed Hydrological Simulation of the Catchment in the Present Day

Figure 6 shows the maps of the flow depth h (Figure 6a) and the magnitude of the velocity vector $|\mathbf{u}|$ (Figure 6b) simulated at the time of the peak flow $t = 3 \text{ h}$ for the scenario CN89-A. The flow depth in the tributary streams that drain to the main Manillas stream (green area in Figure 4) reaches values close to 1 m in agreement with the bankfull depth of the actual channels. There, the flow velocity is higher than $1 \text{ m}\cdot\text{s}^{-1}$, see the orange region in Figure 6b, which is fast. Deeper and even faster flows develop in the downstream reach of the Manillas stream with flow depths and velocities of approximately $h_{\max} = 2.5 \text{ m}$ and $|\mathbf{u}_{\max}| = 5 \text{ m}\cdot\text{s}^{-1}$. The flow regime becomes critical with the Froude number $Fr = |\mathbf{u}_{\max}| / \sqrt{g h_{\max}} = 1.01$. Regarding the runoff depth, characteristic values are around 2.5 mm (purple colour in Figure 6a) in the southern region draining to the Manillas stream, with high velocities in the range of $0.1 - 0.4 \text{ m}\cdot\text{s}^{-1}$ (Figure 6b). Conversely, in the northern area, where the basin slope decreases and the terrain is flatter than in the southern region, the runoff depth is much shallower, and the velocity is slower. Hence, we observe a clear topographic control between the runoff dynamics correlated well with the terrain elevation and slope (Figure 1b). Then, we evaluated the shear-stress vector τ_b from (3) using the simulated hydraulic variables h and $\mathbf{u}$, and drew the map of its magnitude in Figure 6c. The shear stress varies in the wide range of the order of magnitudes from 10^{-4} to $10^4 \text{ N}\cdot\text{m}^{-2}$.

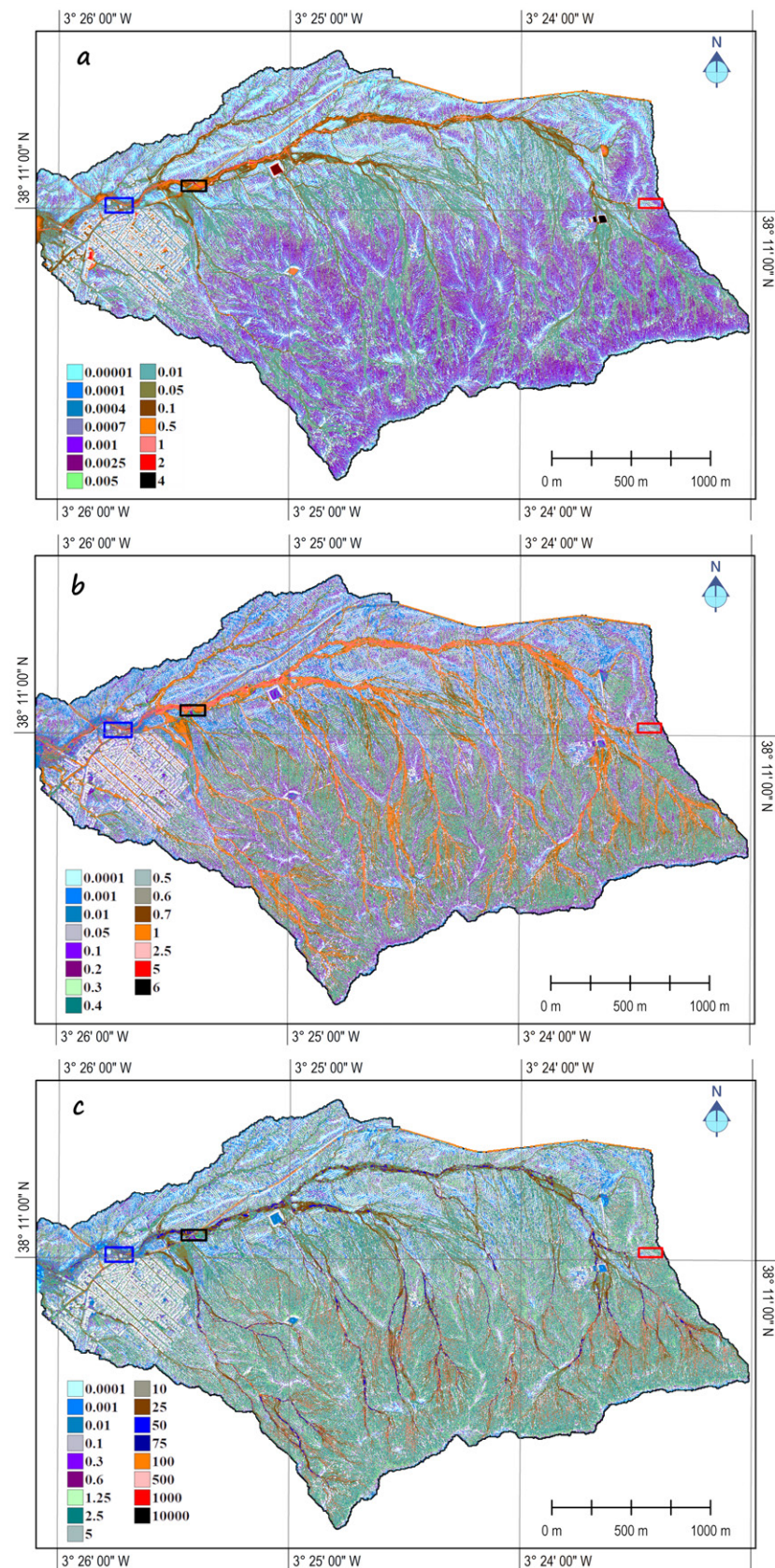


Figure 6. Map of the maximum values of the (a) flow depth h [m], (b) magnitude of the velocity vector $|u|$ [m·s⁻¹], and (c) magnitude of the shear stress vector $|\tau_b|$ [N·m⁻²] at peak flow (i.e., $t = 3$ h) for the present-day soil use and management (simulation CN89-A).

In agreement with the simulated flow velocities, the runoff exerts high stresses in the southern region to the Manillas stream because of the steep slopes. The values are more significant than the critical threshold $\tau_c = 0.083 \text{ N}\cdot\text{m}^{-2}$ [77] for silt motion in most watersheds. The highest values occur in the headwater streams, $|\tau_b| \sim O(10^2)$, decreasing progressively downstream and keeping high values of $O(10)$ until the tributary streams reach the main Manillas stream. In the olive-grove region of the southern watershed, erosional processes are also dominant because the shear stress is above the critical value for erosion. The high shear stress and the fine granulometry of available sediments favour transport processes dominated by wash load. Slackwater sediments may settle in the inundated floodplains with a low flow velocity of the Manillas stream where $|\tau_b| < \tau_c$ [55]. The high spatial resolution of the numerical simulation allows the identification of multiple-scale geomorphological processes, see Figure 7, illustrating such sediment transport regimes.

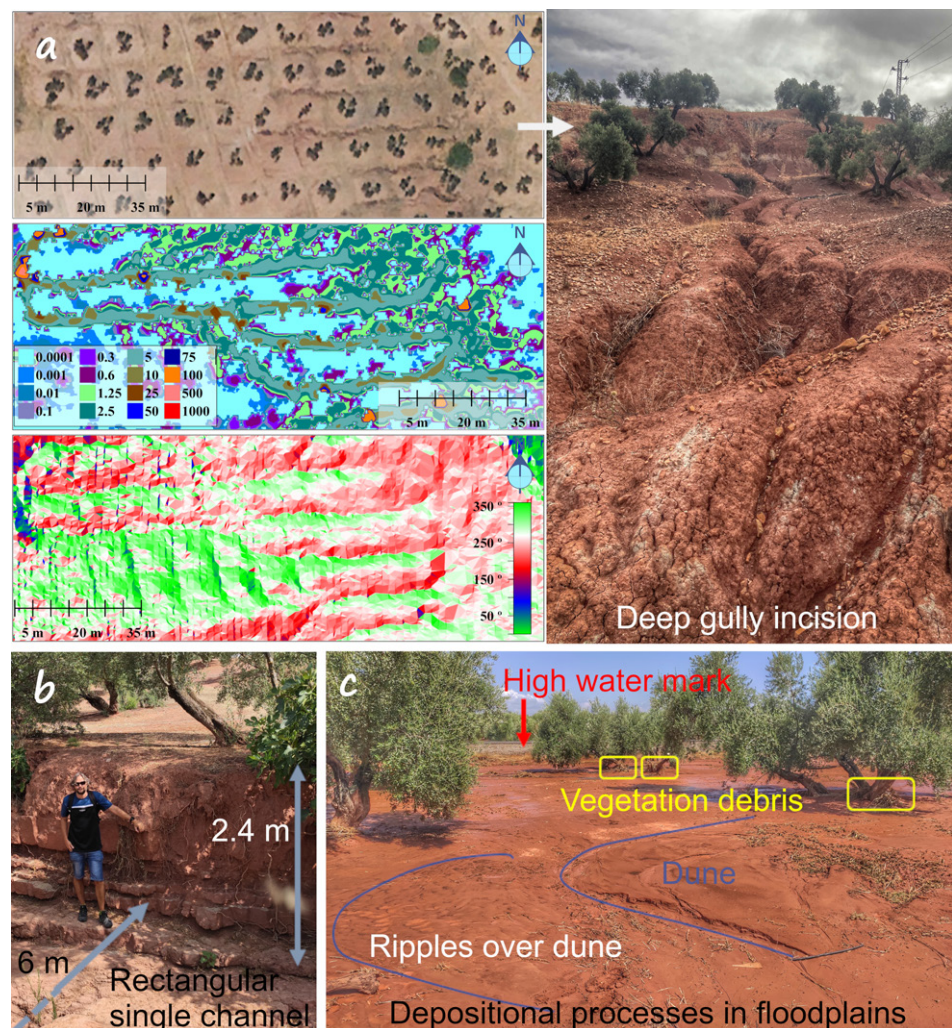


Figure 7. Examples of fluvial geomorphological features in the Manillas watershed that serve to verify the accuracy of the simulation CN89-A. (a) Gully network in the eastern headwater (red rectangle in Figure 6c): the left column shows a zoom of the shear-stress map, an orthophoto and the slope direction map for the DEM; the photo in the right-hand-side depicts an upstream view of the existing gullies. (b) Confined single-thread channel eroded in a rocky bed due to high shear stresses. (c) Paleostage indicators of flood levels and bedforms developing in unconfined flow on a floodplain. Photographs b and c were taken in the locations marked with the red and yellow dots in Figure 1a few meters downstream and upstream of the cross between the Manillas stream and the road, respectively.

For instance, extreme erosion or gullies can be located from the simulated map of shear stress (Figure 6c). In the small rectangular area in red of Figure 6c, there is a train of gullies. They are visible in the orthophoto of this region (see the panel at the top of Figure 7a). The five gullies are in-parallel outside the olive tree canopy projection. The simulated shear stress inside the gullies is approximately $5 \text{ N}\cdot\text{m}^{-2}$, as shown in the shear-stress map in the middle of Figure 7a. Thus, the contour level $|\tau_b| = 5 \text{ N}\cdot\text{m}^{-2}$ yields the extension and the path of the gully. The predicted trajectory of the gully is indeed well-correlated with the breaks in the slope of the terrain depicted in the panel at the bottom of Figure 7a. After locating the gullies on the map, we visited the place. We found the deeply incised gullies visible in the in situ photo of Figure 7a, proving the accuracy of the numerical simulation.

Another example illustrating the erosional power of the high-speed flow is the rock-bed incision depicted in Figure 7b. The precise location corresponds with the red square in Figure 1a (also, with the left-upper corner of the black rectangle in Figure 6). A few meters downstream of the first cross between the Manillas stream and the road, where the shear stress was as high as $100 \text{ N}\cdot\text{m}^{-2}$ (Figure 6c), the water flow sculpted a single confined channel. The flow eroded a first layer (i.e., 0.7 m) of poorly consolidated sediments (mostly silt and clay) and a second rocky bed (i.e., 1.7 m), leading to the rectangular cross-section of depth $H = 2.4 \text{ m}$ and with $B = 6 \text{ m}$. The authors of [78] showed that the bankfull dimensions B and H of straight rivers adapt to the regime-based bankfull capacity Q_{1D} and satisfies the classical Manning equation for a uniform flow in a rectangular channel [63]:

$$Q_{1D} = \frac{B H}{n_{1D}} R_h^{2/3} \sqrt{S_0} \quad \text{with} \quad R_h = \frac{B H}{2 H + B}. \quad (9)$$

For dimensionally-similar channel planforms, Bohorquez [16] calibrated the one-dimensional roughness parameter $n_{1D} = 0.055 \text{ s}\cdot\text{m}^{-1/3}$, which accounts not only for the hydraulic resistance of the walls and the bed but also for the presence of sparse riparian vegetation and secondary head losses. We measured the thalweg elevation using Leica Zeno 20 GPS and obtained the local slope value $S_0 = 0.0196$. Substituting these values into (9), yields the peak water discharge $Q_{1D} = 44.4 \text{ m}^3\cdot\text{s}^{-1}$. Taking into account that the draining area to this cross-section is $A_{\text{drain}} = 4.76 \text{ km}^2$, the theoretical value of the streamflow given by (5) is $Q_{ss} = 39.7 \text{ m}^3\cdot\text{s}^{-1}$ for the rainfall intensity $\bar{P} = 30 \text{ mm}\cdot\text{h}^{-1}$, which differs only by 11%.

Upstream of the single channel described above and before the cross between the Manillas stream and the road, see the specific location marked with a yellow dot in Figure 1a, a singular sedimentary process was identified during fieldworks on 25 August 2021. We found ripples over parabolic dunes and ripples above the plane bed, see Figure 7c, provoked by the previous day's flood. The growth of ripples over dunes, see the review on dunes by Bohorquez et al. [79], is usual in deep river flow and reflects a severe inundation in the floodplains of the Manillas stream. Indeed, the high-water marks on the road ditch and the top level of the vegetation debris on the olive-tree trunk yield flow depths of 0.4–0.5 m. Such values are in agreement with the simulated flow depth in Figure 6b, which provides further validation of the model input data and the simulation results. Additionally, the formation of a plane-bed occurs only at high shear stresses [77], which implies a notable sediment transport capacity of overland flows in olive groves. The transport-stage parameter $\Gamma \equiv |\tau_b|/\tau_c - 1$ achieved the value of 29 in the simulation, which lies in the interval of the upper-regime plane bed $20 < \Gamma < 40$ for silt [54,77]. So, dunes ($2 < \Gamma < 10$) and ripples ($\Gamma < 4$) grew during the recession stage of the flood.

3.2. Mitigation of Urban Flooding through Basin-Scale NbSs

The distributed hydrological simulation also provides the inundation map in the urban area near the catchment outlet. First, we use the simulated values of flow depth to verify the accuracy of the numerical simulation regarding historical information on flood

levels. Later, we describe the benefits of NbSs for flood risk mitigation by analysing the outputs of the simulated future scenarios.

Figure 8a depicts a zoom of the flow depth map for the present-day hydrological simulation introduced in Section 3.1. The flooded urban area corresponds with the blue rectangle in Figure 6a. The flow depth was more profound than the 1.4 m channel height in most of the reach shown on the map. Overtopping of the right bank provoked the inundation of the olive-grove floodplains. In the 45-degree channel bend upstream of the area of Figure 8a, the water flow abandoned the channel over the left bank and inundated the road and main street of the town of Arquillos. The numerical simulation predicts the flow accumulation on a corner (highlighted with a black rectangle in Figure 8a), leading to a maximum depth of about 0.5 m. The pictures taken in 1996 and 2013 in that place corroborates the numerical simulation result. Note the brown marks left by the slurry flow on the walls (Figure 8b) or the deep water flow reaching the windows (Figure 8c). Lastly, the flood left the town through the level ground surrounding the sports hall and returned to the channel.

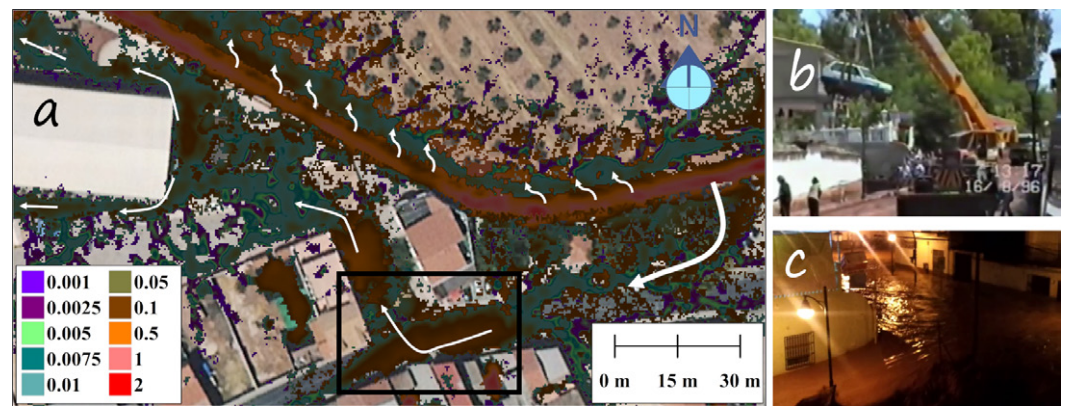


Figure 8. (a) Map of the simulated flow depth (h in meter), for the present-day scenario CN89-A at the time of peak flow (i.e., $t = 3$ h), in the urban area inundated downstream of the overtopped artificial channel. Flow from right to left. The region in panel a occupies the blue rectangle in the flow-depth map shown in Figure 6a. The pictures on the right-hand side correspond to the inundations on (b) 15 August 1996 and (c) 8 March 2013 in the boxed area of panel a when the artificial channel was unable to protect the town from flooding.

To draw an overview of the benefits of possible future scenarios that implement an NbS for flood management, we compared the simulated hydrographs $Q(t)$ in a cross-section of the Manillas stream at the town inlet. The hydrograph was computed from the hydraulic variables $h(\mathbf{x}, t)$ and $\mathbf{u}(\mathbf{x}, t)$ during the transient numerical simulation:

$$Q(t) = \int_{\mathbf{x}_i}^{\mathbf{x}_e} h(\mathbf{x}, t) \mathbf{u}(\mathbf{x}, t) \cdot \mathbf{n} d\mathbf{l}, \quad (10)$$

where $\mathbf{x}_i$ and $\mathbf{x}_e$ denotes the initial and end points of the cross-section, respectively, and $\mathbf{n}$ is the unit vector pointing in the direction perpendicular to the cross-section.

Figure 9 shows the hydrographs for the fifteen simulations. The water discharge grew monotonously during the rising limb and attained a steady state at the end of the rainfall, i.e., $t = 3$ h, when the water discharge was at a maximum. The key variables used to evaluate the benefits of the NbS are the values of the peak water discharge and the time to peak flow, also known as the time of concentration or the duration of the rising limb. In the simulation, we defined the time of concentration T_{sim} as the instant of time when the simulated discharge $Q(t)$ reached the 90% of the maximum value (i.e. $Q = 0.9 \times Q_{\text{max}}$ at $t = T_{\text{sim}}$) [60]. Table 1 gives both the peak water discharge Q_{max} and the concentration-time T_{sim} for all the simulated scenarios.

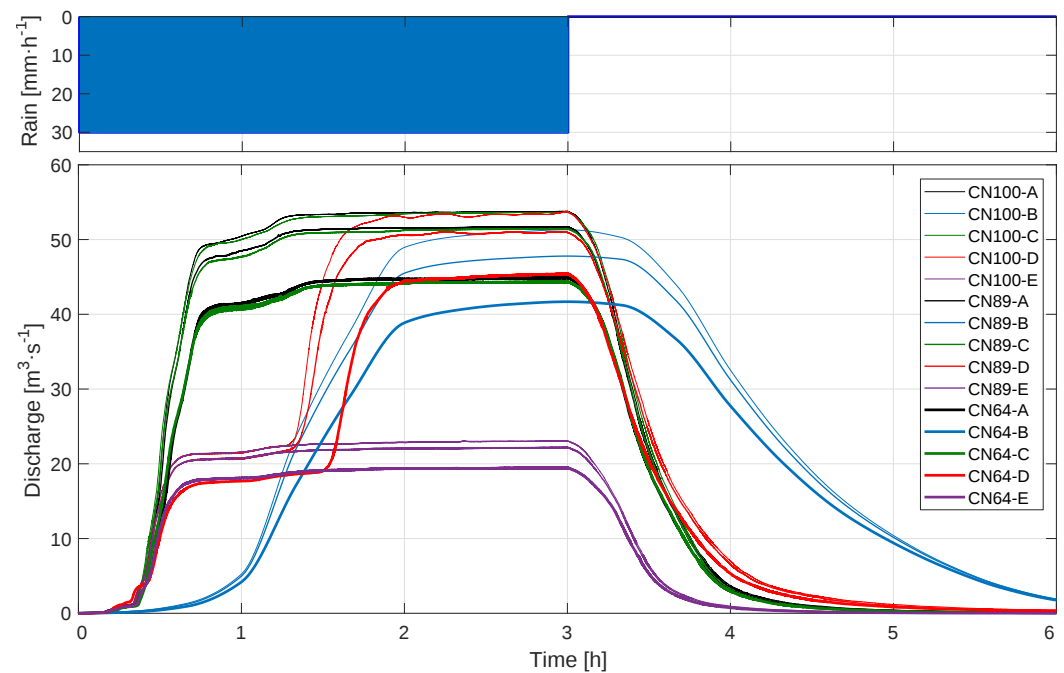


Figure 9. Hydrograph at the basin outlet for the fifteen physical scenarios.

Table 1. Peak water discharge $Q_{\max}$ and time of concentration T_{sim} for the simulated hydrographs in Figure 9. The attenuation of the peak discharge regarding the maximum value of scenario CN100-A and the delay factor of the time to peak flow are also given.

	A	B	C	D	E	A	B	C	D	E
	$Q_{\max}$ [$\text{m}^3 \cdot \text{s}^{-1}$]					T_{sim} [min]				
CN100	53.8	51.3	53.7	53.7	23.1	44	120	45	94	37
CN89	51.7	47.8	51.5	51.0	22.2	45	120	46	96	38
CN64	44.9	41.7	44.3	45.4	19.5	46	120	47	108	41
	Attenuation (%)					Delay ($\times$)				
CN100		4.6	0.3	0.2	57.1		2.7	1.0	2.1	4.1
CN89	3.9	11.2	4.3	5.1	58.7	1.0	2.7	1.0	2.2	4.1
CN64	16.6	22.5	17.6	15.5	63.8	1.1	2.7	1.1	2.5	4.1

The peak streamflow in the absence of infiltration (i.e., $53.8 \text{ m}^3 \cdot \text{s}^{-1}$ for CN100-A) lies very close to the theoretical value predicted using the rational method for the whole basin, i.e., $Q_{\text{ss}} = 57.4 \text{ m}^3 \cdot \text{s}^{-1}$ (5), due to the proximity of the town of Arquillos to the basin outlet. The time of concentration $T_{\text{sim}} = 44 \text{ min}$ is also close to the theoretical prediction $T = 33 \text{ min}$ (6). Interestingly, in the current scenario with the actual soil uses and management (i.e., simulation CN89-A), the infiltration was negligible and attenuated the peak discharge only by 3.9%. Even for the lowest curve number (simulation CN64-A), we found that $Q_{\max}$ decreased slightly from 53.8 to $44.9 \text{ m}^3 \cdot \text{s}^{-1}$, which represents a small relative factor of 16.6%. Furthermore, hydrographs A (black lines in Figure 9) nearly overlap those of the simulations type C (green lines in Figure 9). Subsequently, acting on the olive-grove area to improve the infiltration (i.e., decreasing the curve number) and raise the surface roughness (i.e., increasing the Manning parameter), as shown in Figures 4c–e, does not help to attenuate the peak discharge substantially nor delay the inundation in the urban area. In the best case, the streamflow was attenuated by 17.6% (CN64-C) and reached $Q_{\max} = 44.3 \text{ m}^3 \cdot \text{s}^{-1}$ with the same concentration time as for scenario A. The increase in the Manning roughness in the olive-tree area (coloured in blue in Figure 4) did not delay

the inundation because the water drops had to travel a short distance to reach elements of the drainage network. Such a distance was much shorter than the characteristic lengths of the gullies and streams (green area in Figure 4) that remained unaltered in scenario C concerning A.

Promising results were obtained for NbS type B that alters the roughness of the drainage network through riparian buffer installation, boulders, and willow in-ditch barriers, among others. The most noticeable result was the delay of the rising limb, which can be appreciated in the hydrographs of Figure 9 coloured in blue. The concentration-time increased from about 45 min to 120 min, i.e., by a factor of 2.7. On the one hand, the benefits of NbS type B are great during the first hour of the rainfall independently of the CN value because $4.2 \leq Q \leq 5.3 \text{ m}^3 \cdot \text{s}^{-1}$ at $t = 1 \text{ h}$ for $64 \leq \text{CN} \leq 100$. Such streamflow values are much lower than for scenarios A and C at the same instant of time, which ranges in the interval $40.9 \leq Q \leq 50.5 \text{ m}^3 \cdot \text{s}^{-1}$. On the other hand, for rainfall durations of 2–3 h, the peak discharge is about $38.9 \leq Q \leq 51.3 \text{ m}^3 \cdot \text{s}^{-1}$, which is closer to the peak values for scenarios A and C. Hence, NbS type B is practical for mitigating the risk of flooding in the town for extreme rains shorter than one hour, but longer events require other NbSs.

The installation of a flood barrier to create an artificial wetland (NbS D) and the construction of a large reservoir pond (NbS E), recall Figure 4a,b, stopped the growth of the streamflow at $t \approx 30 \text{ min}$ as shown by the hydrographs in red and purple (Figure 9), respectively. The discharge reached a constant value of $Q = 17.7 \text{ m}^3 \cdot \text{s}^{-1}$ (21.5) for $\text{CN} = 64$ (100) up to $t = 1 \text{ h}$. The reservoir pond was able to store stormwater for the three-hour rainfalls, keeping the peak discharge in the town as low as $Q_{\max} = 19.5 \text{ m}^3 \cdot \text{s}^{-1}$ (CN64-E). The wetland was filled in 90 min (77 min) in scenario CN64-D (CN100-D), and the hydrograph shows a second stage of the rising limb achieving the same peak discharges as for present scenario A (Table 1). Hence, the wetland could delay the flood and protect the town from inundation for about 1 h and 30 min, whilst the reservoir pond would be a solution for rainfalls of 3 h.

3.3. Benefits of NbS to Mitigate Soil Erosion Risk

We seek to find the NbS that decreases the component of the shear stress responsible for soil erosion τ_{bs} below the critical threshold τ_c . The main objective is to impede that $\tau_{bs} > \tau_c$ as occurs actually in most of the olive-grove area (simulation CN89-A described in Section 3.1 and Figure 6c). Otherwise, the significant shear stresses provoke unsustainable soil losses and the formation of deep gullies in most of the catchment (e.g., Figure 7a). If we achieve the goal $\tau_{bs} < \tau_c$, we stop the actual erosion processes and reduce the catchment sediment budget. Furthermore, we prevent the silting of the Guadalén Reservoir, where the Manillas stream drains at a distance of 4 km from the basin outlet. Sediments exposed to erosion over the Manillas basin are mostly coarse silt, with a uniform grain size in the range of $[0.031, 0.0625] \text{ mm}$. The critical shear stress for the onset of sediment motion was determined from Table 7.1 in Julien [77], which yields $\tau_c = 0.083 \text{ N} \cdot \text{m}^{-2}$ in water at 20°C . For evaluating the local shear stress responsible for erosion τ_{bs} , we used the classical shear-stress partitioning that decomposes the effective boundary shear stress $|\tau_b| = \tau_{bf} + \tau_{bs}$ into the form drag τ_{bf} and the skin friction τ_{bs} (see details in § 2.8.1 by García [54]).

A simple and compact way to visualise the benefits of NbS in the whole watershed is to analyse the changes in the probability of the flow depth (Figure 10a), velocity magnitude (Figure 10b), and shear stress (Figure 10c) regarding the current situation. To compute the probabilities, we accounted only for the regions of interest: the olive groves and the drainage network (blue and red areas in Figure 4a, respectively). Hence, we excluded the non-erodible urban areas and civil infrastructure from the analysis.

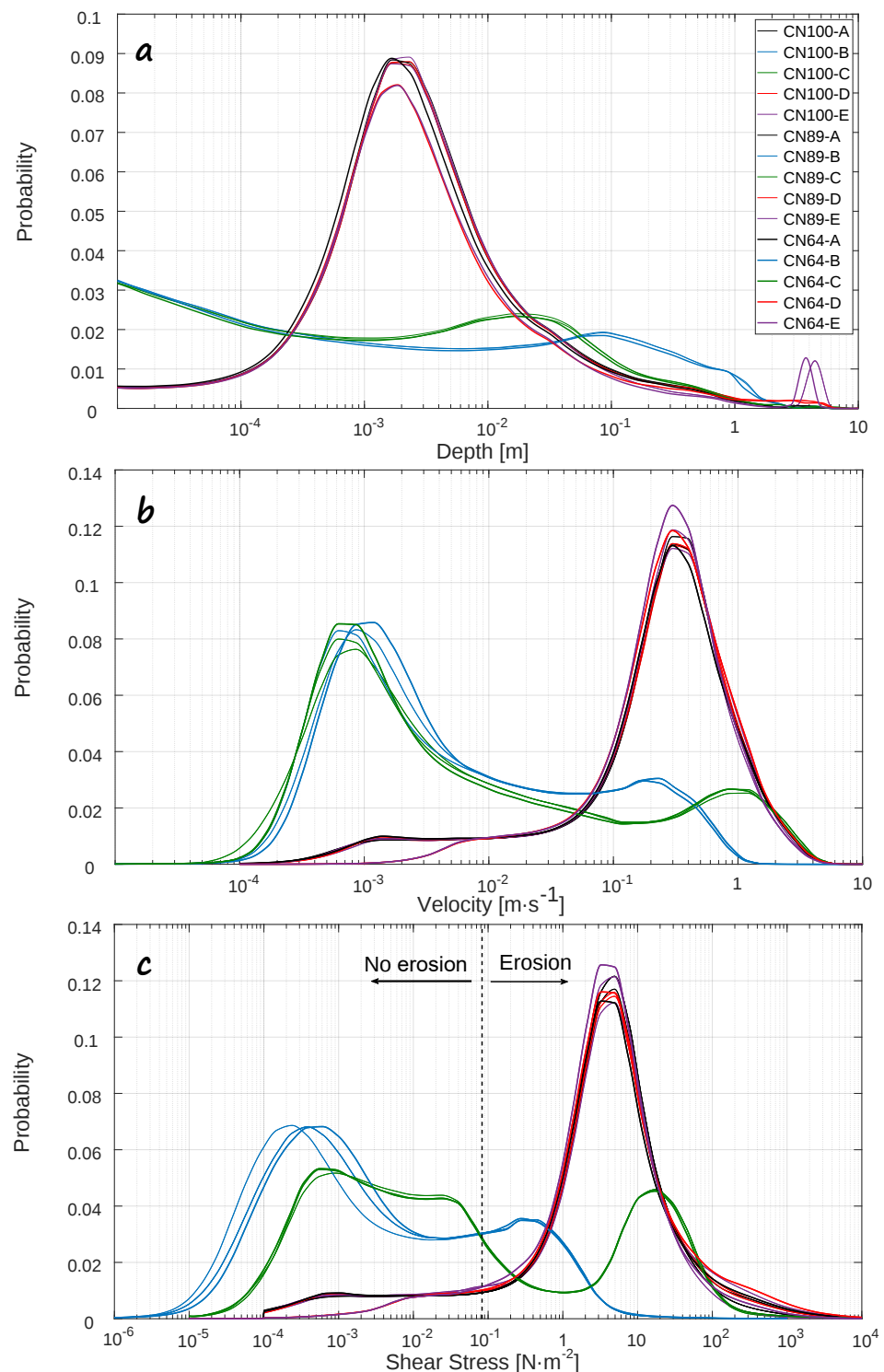


Figure 10. Histograms of the simulated (a) flow depth h , (b) magnitude of the velocity vector $|u|$, and (c) the skin friction τ_{bs} for the fifteen scenarios explained in Section 3.3.

In the absence of an NbS (solid black lines in Figure 10), the most probable values of the flow depth, velocity, and shear stress vary in the narrow intervals $[1.6, 2.4]$ mm, $[0.3, 0.4]$ m·s^{−1}, and $[3, 5]$ N·m^{−2} for all the infiltration rates (simulations CN100-A, CN89-A, and CN64-A). Indeed, the three curves in black nearly overlap. The wetland (NbS D in purple) and the reservoir pond (NbS E in red) do not provoke a substantial modification of

the probability curves that are similar to the actual ones (scenario A in black). A significant part of the shear-stress curves for the simulations type A, D, and E lie out of the target region $\tau_{bs} < \tau_c$. Table 2 shows the cumulative probability for the catchment area where erosion occurs due to $\tau_{bs} > \tau_c$. Independently of the infiltration rate, erosion develops in more than 86.4% in scenarios A, D, and E. The values in Table 2 show that the infiltration does not play a role in controlling erosion because of the same reasons that did not substantially attenuate the streamflows (Figure 9a). The steep slopes of the watershed and the high precipitation intensity favour runoff formation to the detriment of infiltration processes.

Table 2. Relative area (%) where the dangerous threshold for erosion $\tau_{bs} > \tau_c$ holds.

	A	B	C	D	E
CN100	87.8	25.4	39.9	86.9	86.7
CN89	87.2	25.1	40.1	86.9	87.3
CN64	86.4	25.3	39.4	91.7	93.1

The interventions on the agricultural area (NbS C, green lines in Figure 10c), including the channels of the drainage network (NbS B, blue lines in Figure 10c), changed the shear-stress distribution by a great extent. The distribution switched to a multimodal distribution. The major mode decreased from $[3, 5] \text{ N}\cdot\text{m}^{-2}$ (present-day) to $[2.4, 6.5] \times 10^{-4}$ (NbS B) and $[5.1, 9.2] \times 10^{-4}$ (NbS C) when the mean curve number varied in the range of $[64, 100]$. The most probable values of the shear stress developed in the agricultural area of the watershed. This fact highlights the soil-loss mitigating effect of NbS B and NbS B C because the major modes are lower than the threshold for erosion. The minor mode for NbS B, about $[0.27, 0.44] \text{ N}\cdot\text{m}^{-2}$, is also one order of magnitude lower than presently. Consequently, the relative area where the dangerous threshold for erosion $\tau_{bs} > \tau_c$ occurred decreased from about 86% to 25% in NbS B. In the case of NbS C, the potential area for erosion also falls to 39%. The minor peak arising in the probability of the shear stress at $\tau_{bs} \sim 15 \text{ N}\cdot\text{m}^{-2}$ for NbS C corresponds to the high velocities, of the order of $1 \text{ m}\cdot\text{s}^{-1}$ (Figure 10b), in the unaltered channels of the drainage network (recall the velocity map in Figure 6b for the present day). Note the positive aspects of increasing the resistance to flow in the channels (NbS B), which reduces the minor mode of the velocity to $[0.16, 0.24] \text{ m}\cdot\text{s}^{-1}$ (Figure 10b) and could favour sediment trap processes to restore deep incised channels.

3.4. Synergetic Benefits of the Wetland, In-Channel Macro-Roughness and Cultivation Systems in Olive Orchards

Considering the independent benefits of each nature-based solution, we combine three to maximise their effectiveness in terms of flood mitigation and soil conservation. Furthermore, we choose the optimal targeted placement of NbS because funding is always limited. We seek to delay the flood, attenuate the peak discharge in the urban area and favour infiltration processes across the watershed. At the same time, we want to prevent soil erosion in olive orchards, promote mechanisms for gully aggradation rather than gully erosion and reduce the catchment sediment budget.

Figure 11 shows a map of the optimal location of an NbS to provide the most benefits. The results of the distributed hydrological simulations described in the previous sections helped site and classify the actions (which were unknown a priori) as follows:

- First, the black rectangle in Figure 11 depicts the installation of a flood barrier with the crest of the earthen embankment at 406 m, the maximum height of 6 m and the dam crest length of 245 m. It should create an artificial wetland (purple area in Figure 11) as in previous simulations of type D.
- Second, from simulation type B, we delimited the extension of the main channel and the inundated floodplains along the Manillas stream (yellow area). Further, the tributary streams in green correspond to simulated flow depths larger than 0.5 m

outside of the Manillas stream. Then, ephemeral gullies in red were located using criterion $0.03 < h < 0.5$ m from Soil Science Society of America [51].

- Third, the river floodplains in blue, located in the headwater and near the town, are an extinct, ephemeral wetland and a stream confluence requiring restoration.
- Fourth, in the olive groves, we propose different cultivation systems for bed slopes lower (brown area) and larger (greenish blue area) than 10 degrees.

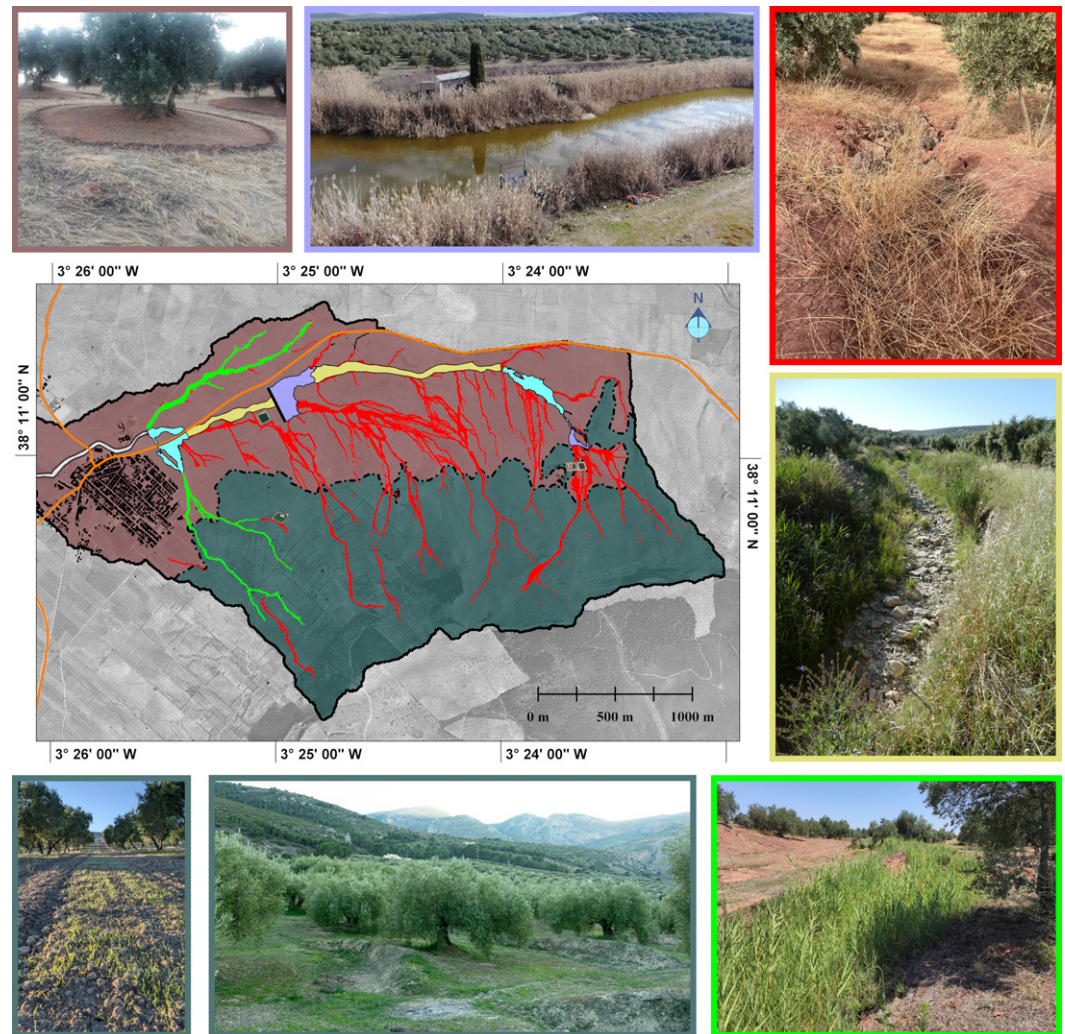


Figure 11. Optimal targeted placements of specific NbS to provide the most benefits and maximise their effectiveness for flood management and soil conservation, as described in Section 3.4. The photos illustrate the actions at each location, as indicated by the frame colour.

The following step in AFC [19] is choosing the model physical parameters at the targeted placements to achieve the optimal values of the objective functions. According to the minimum values of the peak water discharge and the erosion-prone area given, respectively, in Tables 1 and 2, we set the Manning roughness parameter $n = 0.2 \text{ s} \cdot \text{m}^{-1/3}$ in the green, yellow, and red areas, and $n = 0.025 \text{ s} \cdot \text{m}^{-1/3}$ in the olive groves for the CN64 setup (recall Section 2.2.4). The NbS that can reproduce the desired model parameters can only be selected and sized after the highly resolved CFD simulation of the flow depth h (1) and the velocity vector u (2).

The simulated hydrograph in Figure 12a (blue line) highlights the dynamic and transient nature of the surface waters across the draining basin. Its shape changes substantially regarding the current situation (black line).

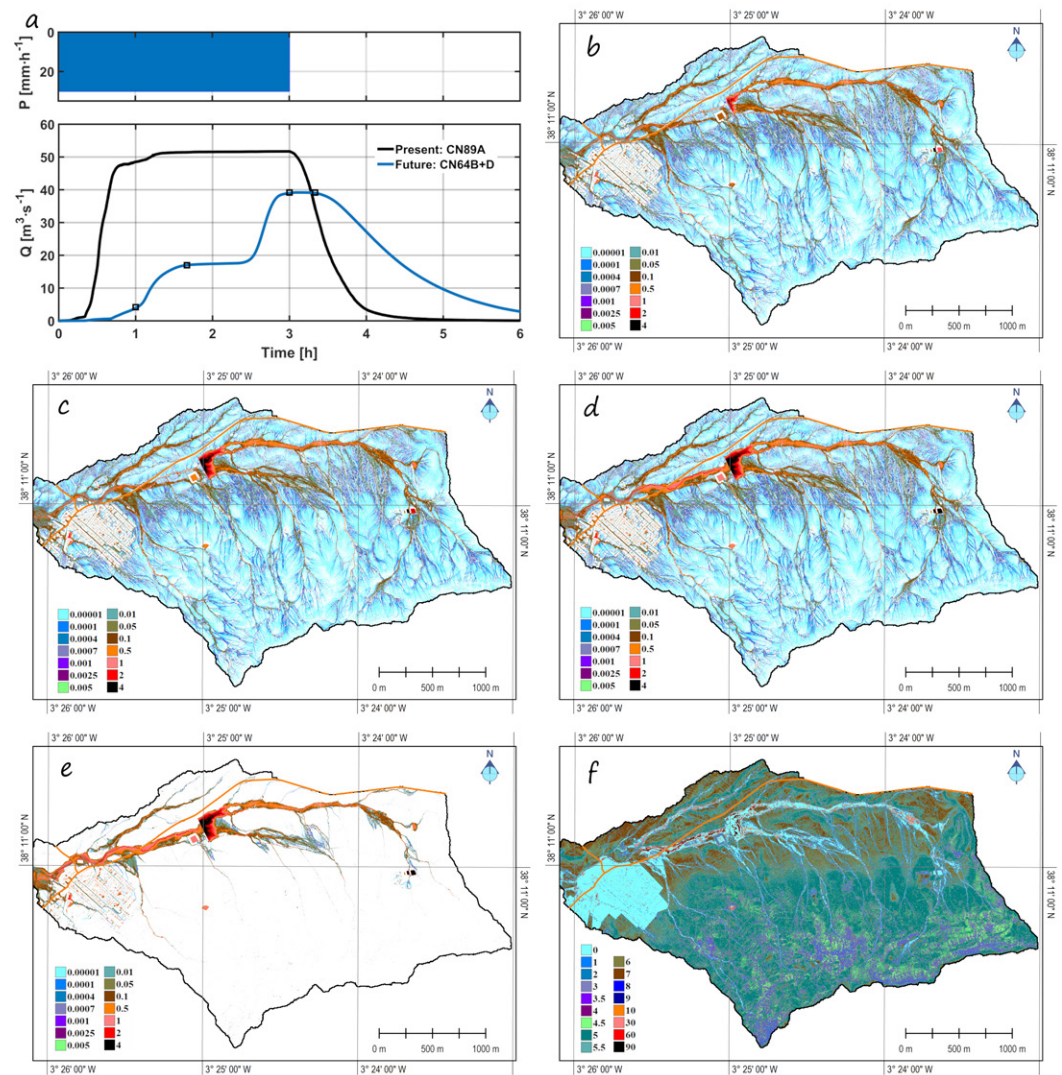


Figure 12. (a) Simulated hydrographs in the Manillas stream, near the town, for the current state (black) and the possible future (blue) after implementing the combined NbS B and D. (b–e) Snapshots of the simulated flow depth (in meters) with NbS B and D at $t = 60, 100, 180$, and 200 minutes corresponding, respectively, with the streamflows $Q = 4.2, 17.6, 39.2$, and $39.1 \text{ m}^3 \cdot \text{s}^{-1}$ (squares in panel a). (f) Maximum infiltration rate (in $\text{mm} \cdot \text{h}^{-1}$) achieved at the end of the rain (i.e., $t = 180 \text{ min}$) for the future scenario with NbS B and D.

Overall, we observe the mixed benefits of increasing the in-channel roughness in the drainage network and the installation of a flood barrier to create the artificial wetland. They protect against flooding by slowing down the flow and storing surface runoff. Hence, the rising limb exhibits two stages separated by a steady plateau associated with the wetland filling. After one hour of rainfall, the peak discharge in the urban area is only $Q = 4.2 \text{ m}^3 \cdot \text{s}^{-1}$, much lower than for the actual scenario CN89-A, which is $Q = 48.5 \text{ m}^3 \cdot \text{s}^{-1}$. The map of water depth at $t = 1 \text{ h}$ (Figure 12b) shows that the Manillas stream did not inundate the town. The early infilling of the wetland and the absence of flow downstream can also be appreciated in such a map. Forty minutes later, the water discharge reaches a steady state with $Q = 17.6 \text{ m}^3 \cdot \text{s}^{-1}$ until $t \approx 2.5 \text{ h}$. For this low value of the water discharge, the town remains again protected against flooding; see the map of flow depth in Figure 12c. At $t \approx 2.5 \text{ h}$, the wetland achieves its maximum capacity, and the water starts to flow downstream of the wetland barrier. Then, the second stage of the rising limb occurs up to reaching the peak water discharge $Q_{\text{max}} = 39.2 \text{ m}^3 \cdot \text{s}^{-1}$ at the end of the rainfall (i.e., $t = 3 \text{ h}$). The map of flow depth at that time is shown in Figure 12d.

Later, the water discharge remains constant near the urban area for about 30 minutes (i.e., up to $t = 200$ min). However, at that time, the rain had already ceased, runoff vanished in the watershed (see the flow depth map in Figure 12e), and the discharge monotonously decreased, vanishing approximately at $t = 6$ h.

The peak discharge for the combined NbSs B and D, $Q_{\max} = 39.2 \text{ m}^3 \cdot \text{s}^{-1}$, decreased with respect to the present value of $51.6 \text{ m}^3 \cdot \text{s}^{-1}$ as much as using uniquely NbS B, which yields $41.7 \text{ m}^3 \cdot \text{s}^{-1}$ (CN64-B in Table 1). The infiltration was responsible for the attenuation of the peak streamflow. The infiltration rate was at a maximum at that time, reaching the values depicted in the map of Figure 12f. In the agricultural area, the highest infiltration rates were around $7 \text{ mm} \cdot \text{h}^{-1}$ and occurred in the northern part. In the headwaters, the infiltration decreased to $2\text{--}5 \text{ mm} \cdot \text{h}^{-1}$ because of the effects of the slope in the curve number (recall Figure 5c). Though such values are low regarding the larger precipitation rate of $30 \text{ mm} \cdot \text{h}^{-1}$, the cumulative volume of water infiltrated during the whole hydrological event of 6 h is relevant.

To quantify the benefits of NbSs concerning infiltration, we computed the percentage of the groundwater volume relative to the total rainfall depth as

$$\eta = \frac{100}{V_r} \left[V_r - \int Q(t) dt - V_w \right]. \quad (11)$$

In (11), $V_r \equiv Q_{ss} D$ represents the volume of water of the design storm (4)–(5), $\int Q(t) dt$ is the volume of surface water that leaves the drainage basin, and V_w is the capacity of the wetland reservoir in the existing case. Evaluating (11), we concluded that the groundwater volume could be increased from $\eta = 4\%$ in the present day to $\eta = 20.5\%$ in the possible future.

To close the cycle, we need to choose the specific NbS that provoke the desired modification of the model's physical parameters. The flood barrier can be built with a vegetated crib wall using inert material and plants, see Figure 1 in Rey et al. [42]. The desired increase in hydraulic resistance can be achieved along the drainage network by adopting well-known actions for NFM. For instance, see Figure 11: (i) placing dry bush, small boulders, or another material across the ephemeral gullies (red frame photo), e.g., Quinn et al. [41]; (ii) flexible submerged vegetation in deeper streams with a confined flow (green frame photo), see Darby [43]; (iii) combined actions of gravel seeding in the streambed, see Hassan and Church [80], and riparian buffer installation in the Manillas stream (yellow frame photo) [44]. The proper sizing of plants and boulders requires physically-based equations, e.g., Wilson [81] and Nitsche et al. [82], respectively, using as input data the simulated values of flow depth and velocity for the optimal macro-roughness parameter $n = 0.2 \text{ s} \cdot \text{m}^{-1/3}$. This goal belongs to soil and water bioengineering, see Zaimes et al. [23], and lies out of the scope of this work. We propose adopting sustainable production techniques in the olive grove; see Tombesi et al. [20] and recent innovations explicitly designed for erosion management. For small bed slopes, we suggest the application of plant residue mulches, leaving the soil untilled and covering it with prunings or other plant residues outside of the tree canopies (brown frame photo). For medium-gradient slopes, water collection pits collect large amounts of water during intense rainfall. The live plant covers, e.g., *Brachypodium Hybridum* BHJHIN [46], along the middle of the orchard lanes also prevent soil erosion and improve infiltration (greenish blue frame photo).

4. Conclusions

The set of fluvial geomorphological features presented in the sections above proves the development of extreme soil erosion and sedimentary processes in a complex, non-linear way over an agricultural watershed dedicated to traditional olive growing. The formation of ripple/dune over a plane bed in the floodplains of the main stream is uncommon in overland flows, as these bedforms are characteristic of deep rivers rather than shallow flows. It reflects the high sediment load and transport capacity of sub-daily pluvial floods. Overland flows have sculpted extreme gullies in the olive groves because of cultivation

systems incompatible with the growth in the magnitude of extraordinary rainfall events under the current climate change scenario.

Active flow control through nature-based solutions can drive olive groves to a more desired state. Highly resolved CFD simulations of hydrological and hydraulic processes using the 2D Saint-Venant equations yield the optimal location of an NbS to provide the most benefits for minimising the water discharges and the erosion-prone area, maximising the soil infiltration capacity. Sub-metric spatial resolutions are required to resolve many microtopographic features of the terrain and the NbS, controlling overland flow and sediment transport connectivity. Affordable computational times can be achieved only by using GPU-accelerated numerical codes. The software IBER+ adopted in this study is suitable for catchment areas up to 20 km² with spatial resolutions of 1 m² now common in LiDAR-DEM.

Future works can overcome several limitations that impede scaling up the proposed method over larger draining basins (<1000 km²) by means of exascale multi-GPU HPC technology as the recent SERGHEI-SWE [27]. However, as commented throughout this paper, the available software packages adopt the assumption of small bottom slopes intrinsic to the Saint-Venant equations. Further research is required for overland flows on steep slopes, which need a unified theory and an efficient numerical scheme and its implementation in an open-source code. We could thus improve the effectiveness and acceptance of NbS at larger scales for the natural management of floods and soil erosion.

We have proven, theoretically, the effectiveness of adaptive practices for sustainable olive growing and NbS actions in gullies and streams for mitigating the risk of flood and erosion in steep-slope basins (mean value of 20%) with high rainfall rates (around 30 mm·h^{−1}). As funding is always limited, the optimal targeted placements of NbS have to be delimited from the simulated flow depth, velocity and shear stress maps. To ensure NFM in the long term, private landowners and communities must adopt sustainable cultivation systems in olive orchards, mitigating soil erosion and preventing the silted-up state of NbSs. These actions help protect from flood, favour soil conservation and are aligned with sustainably managing and restoring modified ecosystems. Furthermore, they address societal challenges effectively and adapt current practices to climate change, simultaneously providing human well-being and biodiversity benefits. Future works on the real verification of the proposed NbS would require regional policies to break some barriers that limit effective implementation at local scales.

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Abbreviations

The following abbreviations are used in this manuscript:

AFC	Active Flow-Control
CN	Curve Number
CFD	Computational Fluid Dynamics
DEM	Digital Elevation Model
EEA	European Environmental Agency
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
GPU	Graphics Processing Unit
HPC	High-Performance Computing
IPCC	Intergovernmental Panel on Climate Change
LiDAR	Light Detection and Ranging
MDPI	Multidisciplinary Digital Publishing Institute
MedECC	Mediterranean Experts on Climate and Environmental Change
MSL	Mean Sea Level
NbSs	Nature-based Solutions
SCS	Soil Conservation Service
2D-SVE	Two-Dimensional Saint-Venant Equations

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