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Steep-slope viticulture: The effectiveness of micro-water storage in improving the resilience to weather extremes

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ABSTRACT

Steep-slope vineyards are widely distributed in the Mediterranean region and have a pivotal role in wine production, economic development, and cultural heritage. Nevertheless, they are threatened by climate change in terms of opposite weather extremes, such as heavy rainfalls and long-lasting droughts. In response, rainwater harvesting systems have emerged as valuable solutions for managing water resources and controlling related problems. Of primary importance is the identification of suitable sites for installation. However, a systematic selection procedure still needs to be explored; it is necessary for morphologically complex vineyards that include historical features of significant cultural value (such as terraced systems). To fill this gap, this study employed a high-resolution overflow simulation model that combines a set of criteria to identify the optimal network of water harvesting structures (also drawing on traditional knowledge) and quantify the potential for water storage during rainfall of varying intensities. The study area considered is located within the "Soave Traditional Vineyards" (north of Italy) site, a Globally Important Agricultural Heritage System (GIAHS) recognized by FAO. The surface overflow was simulated considering two key rainstorms that occurred in the last few years at different time intervals. 53 potential sites for water harvesting were selected according to field survey, runoff simulation, and topographic analysis. The results indicate that the water potentially collected from designed sites could have a double function: (1) mitigate the surface overflow that can potentially cause downslope terrace collapse or even flooding villages; (2) provide irrigation water for vineyards during water scarcity scenarios. The spatial distribution of the water collected could undoubtedly guide sustainable decisions in steep-slope viticultural systems under climate change forcing.

1. Introduction

The steep slopes accommodate some of the most important vineyards in Italy. Examples are the rural landscapes of the Veneto region (such as the hills where Amarone, Prosecco, and Soave wines are produced), the Valtellina valley (Lombardy region), the Langhe (Piedmont region; UNESCO Cultural Landscape), the Gran Sasso National Park (Abruzzo region) as well as Trentino Alto Adige, etc. (Eynard and Dalmasso, 1990). The "Soave traditional vineyards" (Veneto region, Italy) is a traditional terrace agricultural landscape that economically supports more than 3000 families in the past 200 years (Globally Important Agricultural Heritage Systems (GIAHS), 2018). The GIAHS programme safeguards the social, cultural, economic, and environmental goods and services these rural areas provide. A further relevant reality in Veneto region (Italy) is the steep-slope viticulture of the Colline del Prosecco di Conegliano e Valdobbiadene, a UNESCO World Heritage site. Here the terracing practice of *ciglioni* has been adopted since 17th century. Another example is coming from the south of Italy: the ingenious techniques of cultivating head-trained bush vines called "alberello", which can successfully protect vineyards from the wind and it is transmitted for centuries by vine growers and farmers of the Mediterranean island of Pantelleria (Chironi et al., 2020). However, these high-value landscapes are often experiencing extreme weather events, and these are predicted to continue in the future (Bai et al., 2013; Yin et al., 2018).

The challenge of growing intense rainfall is paralleled by the increasing prolonged drought (Straffelini and Tarolli, 2023). On the one hand, climate change tends to have a more dramatic impact on steep-slope agriculture than in other agriculture landscapes since the fraction distributed in the arid climate class will double in the future (Wang et al., 2022a). One of the worst examples is the drought that occurred in the north of Italy in 2022, where 40% of the crop for the whole country and water levels have reached the lowest in the last 70

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years (Levantesi, 2022). On the other hand, the increasing intensive rainfall led to landslides and even flooding in steep-slope areas (Chen et al., 2018; Tarolli and Straffelini, 2020; Wang et al., 2022b). The area of Soave traditional vineyards has been exposed to extreme rainfall events that have caused extensive damage. Among the most severe is the October 31, 2010, event (more than 100 mm of rain in 72 h recorded at a nearby weather station), which caused a creek to overflow and extensive flooding that caused millions in damage and fatalities. More recent intense storms recorded in the area occurred on 1st September 2018 and on 29th August 2020. Both events caused devastating consequences for the vines and economic losses for the local farmers (Pijl et al., 2022). The 2020 event played an important role on farms and the public on the issue of climate change and associated impacts (also due to an unprecedented downburst occurrence). On that occasion, surface runoff caused extensive land degradation in several farms and along rural roads. In addition, steep slopes in agricultural areas tend to be more susceptible to water deficits if control measures lack (Kimaro, 2019). Considering that water source management will be more complex due to future climatic conditions, mitigating climate-induced effects like extreme localized rainfall and prolonged droughts is urgent for the suitable development of steep-slope viticulture.

Compared to other kinds of farmlands, the physical transport of water is more difficult and expensive in steep-slope agriculture due to its complex topography. In this case, rainwater harvests are indispensable water supplies for irrigation and groundwater recharge (Wu et al., 2018). Water storage and harvest facilities are the best solutions for making each drop of water useful and decreasing surface overflow at the same time (Adham et al., 2018). Rainfall water can be collected in different approaches like runoff interception, infiltration improvement in soil, and integrated watershed management (Rockström and Falkenmark, 2015). Water harvesting technique such as dams, ditches, tank, and ponds etc., combined with crop management has been proven as a plausible approach to address the water shortage issues and have been widely applied in many countries for years (Deora and Nanore, 2019; Morgado et al., 2022; Munyasya et al., 2022; Odhiambo et al., 2021; Zhang et al., 2021). For instance, Kumar et al. (2008) derived suitable sites for water conservation structures like check dams, contour bunding, recharge pits, wells, and contour trenching on the regional scale (Kumar et al., 2008). Furthermore, successful water conservation measures have multiple interacting implications in biophysical, economic, and ecological systems (Wordofa et al., 2020).

Although the grapevines are experiencing previously unseen conditions due to extreme weather (Helder and João, 2018; Naulleau et al., 2022), few studies have been working on the more resilient sustainable water management in steep-slope vineyards. Identifying the optimal position for water storage facilities is the key step to maximizing the water collected and crop production, especially under extreme weather in areas with complex topographic conditions. The main objective of this paper is to present a prototype of a water harvesting system consisting of low-impact micro storages. In detail, the goals are: (1) to simulate hydrological processes in steep-slope viticulture for different rainfall events; (2) to design a water reservoir system in optimal sites for both alleviating the runoff and harvesting rainwater with minimal disturbance to the local site, giving the value of landscapes protected by FAO; (3) to quantify the water collected (therefore also the runoff reduction) of the designed water management system, to be potentially re-used then for irrigation. This study provides new insights for farmers and decision-makers in exploring rational and economic-feasible water resource management, which is meant for developing sustainable steep-slope vinicultural systems, particularly in the context of climate change and intense water pressure.

2. Materials and methods

2.1. Study area

The study area is situated in the north-eastern part of the Soave vineyard (North of Italy), a valley called Brognoligo (Fig. 1, 45°27′12.07″ N; 11°16′41.98″ E), covering about 20 ha. Brognoligo is one of the most historic areas for wine production in the area of Soave. It is famous for manually producing full-bodied and structured wine in a dry system. The study area is on a steep slope with an average gradient of 17 degrees. The elevation ranged from 98 to 217 m. Annual precipitation is around 1200 mm. The dominant soil type in this area is clay. The main land use is vineyard (Fig. 1). Fig. 1 (middle) is a 3D map of overflow simulation to illustrate the potentially critical points in terms of flow accumulation in the study area. Fig. 1 shows that all the runoff during the rainfall flows towards the downslope village (white arrow in the figure). The only drainage system in the village is a 1-meter-deep and 0.5-meter-wide ditch (Fig. 1, picture c).

2.2. The surface runoff simulation

To quantify the efficiency of the water reservoirs, we applied the SIMulated Water Erosion (SIMWE) model to simulate overland flow in different rainfall scenarios with and without designed water reservoirs. SIMulated Water Erosion (SIMWE) was developed by Mitas and Mitasova (1998), a physically distributed model well recognized for real-time overflow simulation, which is widely used in flood risks estimation, surface runoff analysis, and accumulation as well as drainage systems design in recent years (Li et al., 2020). The SIMWE model can quantitatively describe the spatial-temporal water distribution in the complex agro-hydrological process with only a few input data. The input of SIMWE includes an elevation raster map, Manning's roughness values (-), and rainfall excess (mm h^{-1}); the output includes a water depth raster map (m) and a water discharge raster map (m^3/s). Considering the SIMWE has a higher estimation for hydraulic risk with a high-resolution elevation input map (Li et al., 2020), this study applied a 1-meter high-resolution digital elevation model. The topographic dataset was produced by LiDAR data. The runoff simulation is based on two extreme rainfall events that occurred in the Veneto region on September 1st 2018 (82.4 mm h^{-1} 5-minutes step) (Pijl et al., 2020) and August 29th 2020 (182.0 mm h^{-1} 5-minutes step; as indicated in Pijl et al., 2022, this intensity was an estimation, but consistent with values recorded by local authorities). The Manning's roughness coefficient (-) and rainfall excess (mm h^{-1}) values implemented in the hydrological model have already been validated and based on previous research in Soave (Pijl et al., 2022; Straffelini et al., 2022), are reported in Table 1.

2.3. Water storage locations and design

53 potential sites were identified for water harvesting systems based on field survey and runoff simulation (Fig. 2). Different size of water reservoirs was developed according to the traditional knowledge of local farmers (farmers were interviewed; they also showed us some abandoned examples of micro-storages) that two generations ago were used to deal with these kinds of water storage solutions, now no longer proposed. The water storage volume was designed according to the amount of simulated runoff (water depth), and the surrounding environment ranges from 4 m^3 to 30 m^3. All the designed sites are generated by "digging the hole" on the ground with locally available materials, similar to the picture e in Fig. 1. The operation of the water collection facilities in the study area is achieved by modifying the elevation of DTM. The site of water storages facilities meets four conditions as follows: (1) in the position where have potential runoff; (2) in a direction perpendicular to the simulated overflow to intercept runoff more effectively; (3) parallel to the contour lines to reduce the practical difficulties; (4) between rows of vines where without interfere vineyard

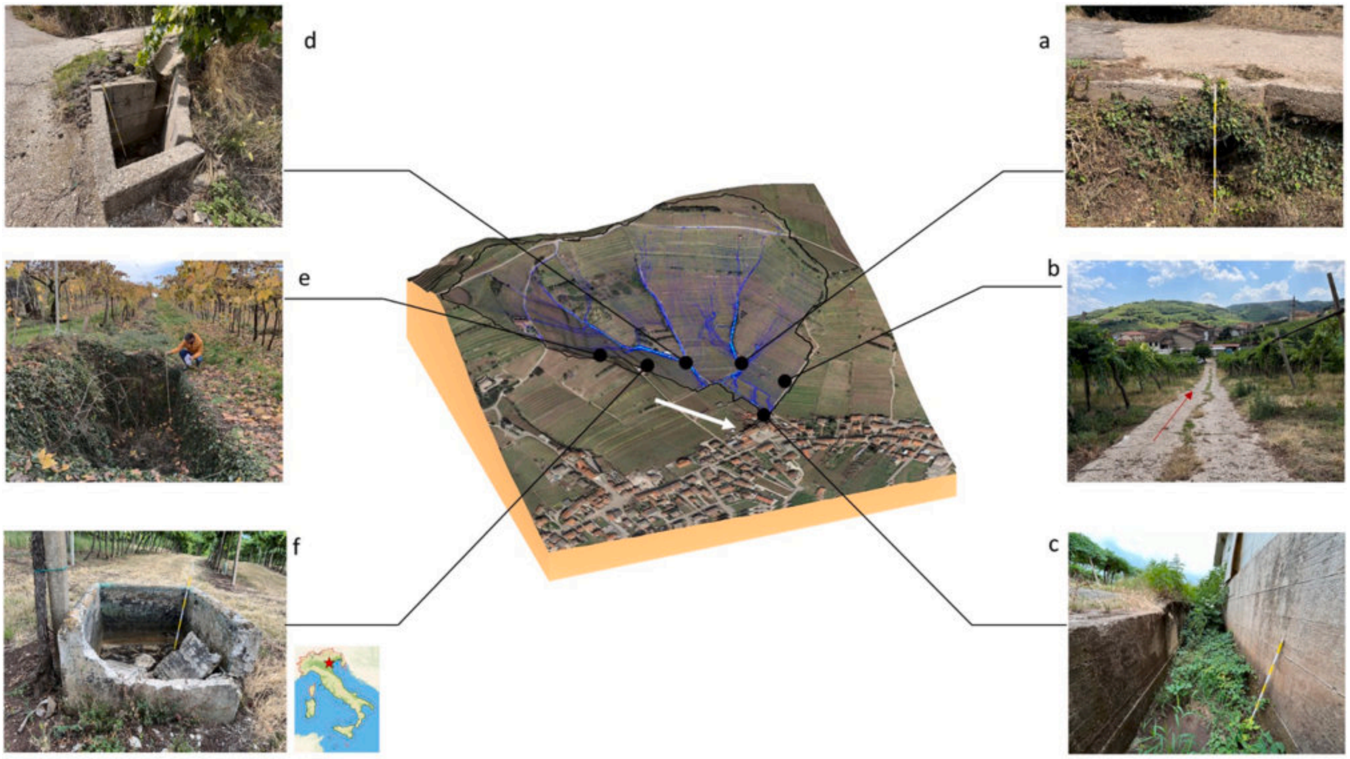

Fig. 1. The location of the study area (middle); The 3D overflow simulation in the study is made by SIMWE model to illustrate the potential hydrological risk; the Outline of the study area is labeled in black color; Runoff simulation is labeled by blue color; a: The drainage system under the road; b: Runoff enters the village along the steep-slope road; c: The main drainage system in the study area; d: Water storages in the road; e: Water storages in the vineyard; f: Abandoned water storage (photos by Wendi Wang). The location of the village downstream is indicated by the white arrow.

Table 1
Main information and parameters used for simulations using the SIMWE model.

	Scenario 1	Scenario 2
Data	September 1st 2018	August 29th 2020
Rainfall	82.4 mm h^{-1}	182.0 mm h^{-1}
Manning's roughness values	0.1 for vineyard and 0.013 for designed water storage	0.1 for vineyard and 0.013 for designed water storage
Rainfall excess (mm h^{-1})	45.1 for vineyard and 82.4 for designed water storage	145.1 for vineyard and 182.0 for designed water storages

cultivation. Considering the increasing climate change influence on steep-slope agriculture landscapes, we separately based runoff simulation on two rainfall scenarios in 5 min and 10 min to identify the runoff intercepting and water-saving function of the designed water reservoir under extreme rainfall events. We chose the maximum 10-minute interval for two reasons: (1) the peak rainfall recorded in this area, 182.0 mm h^{-1}, lasted for 5 min (Pijl et al., 2022). (2) The model reaches a "steady state" after 10 min as the input and output values are in equilibrium. The investigation area highlighted by the red circle (Fig. 2) is where to detect runoff reduction. This area is chosen below the designed water storage and perpendicular to the direction of the simulated runoff simultaneously.

2.4. *Statistical analysis*

The significance of mitigation of surface runoff by designed water management systems was statistically analyzed in different hydrological simulations. Specifically, water depth values for each simulated rainfall intensity and at the two event times were compared. The gridded values of model outputs were imported and analyzed in R software. The comparison was made using the one-way ANOVA test to determine the differences between the simulations and the post-hoc Tukey-Kramer test to perform the pairwise comparison between the scenario without (before) and with (after) the implementation of the storages.

3. Result

3.1. *The simulation of runoff*

Fig. 3 shows the simulated water depth (blue label) value before and after putting designed water reservoirs based on the rainfall events interval considered. In the same time interval, the water depth and surface overflow at 182.0 mm h^{-1} are much higher than at 82.4 mm h^{-1}. Similarly, in the same rainfall scenario, the water depth in 10 min is higher than in 5 min. Simulated water fluxes showed that water from the upslope mainly followed the ditches located in the center of the study area, accumulated in the downslope, and finally converged at the outlet of the terraces, which is the only drainages system mentioned before (Fig. 1, picture c). In the 82.4 mm h^{-1} (5-minutes) rainfall scenario, the average water depth and discharges are 0.07 m and 0.04 m^3/s. In the 82.4 mm h^{-1} (10-minutes) the average water depth and water discharges are 0.09 m and 0.07 m^3/s. In the 182.0 mm h^{-1} (5-minutes) rainfall scenario, the average water depth and discharge are 0.016 m and 0.013 m^3/s. In the 182.0 mm h^{-1} (10-minutes) simulation, the average water depth and discharge are 0.019 m and 0.02 m^3/s.

Fig. 4 shows the magnification of the runoff path before and after putting water storage in several critical areas. Water accumulation in designed water storage facilities was highlighted by red rectangular. The average water depth harvested by designed water storages facilities is 0.07 m, 0.09 m, 0.26 m, and 0.30 m in the 82.4 mm h^{-1} (5-minutes), 82.4 mm h^{-1} (10-minutes), 182.0 mm h^{-1} (5-minutes), 182.0 mm h^{-1} (10-minutes) rainfall scenarios, respectively. Our result showed that low-tech and simple water resource management facilities could collect water effectively in steep-slope agricultural landscapes, which is

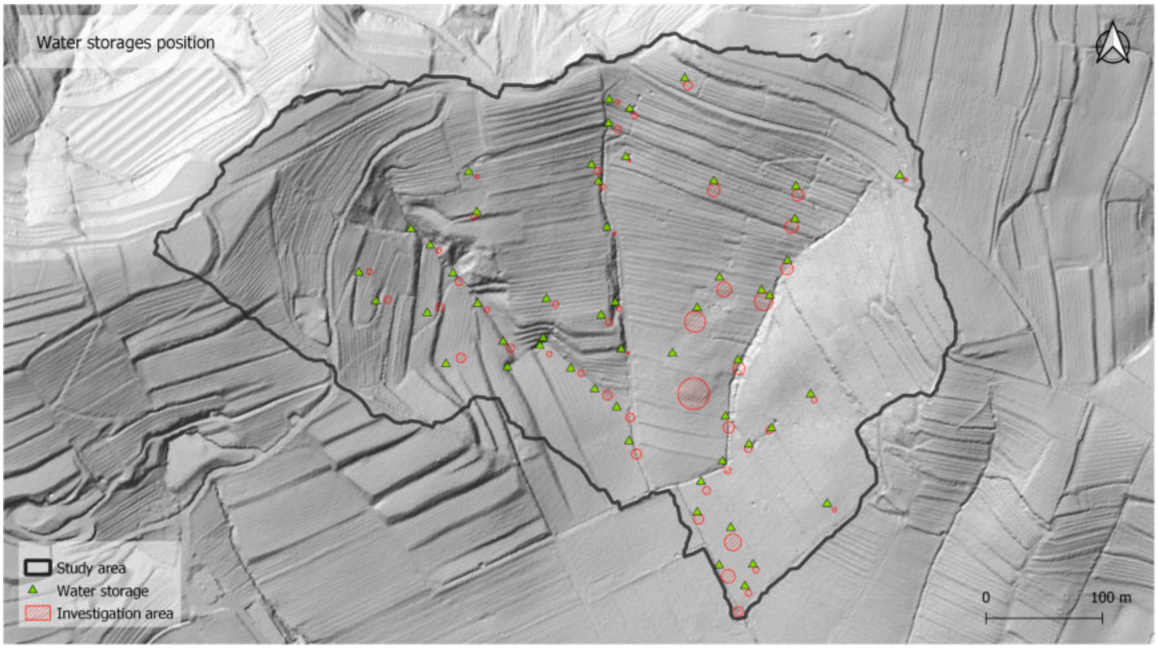

Fig. 2. The position of designed water storages (green triangle) and investigation area (red circle) for runoff decrease analysis.

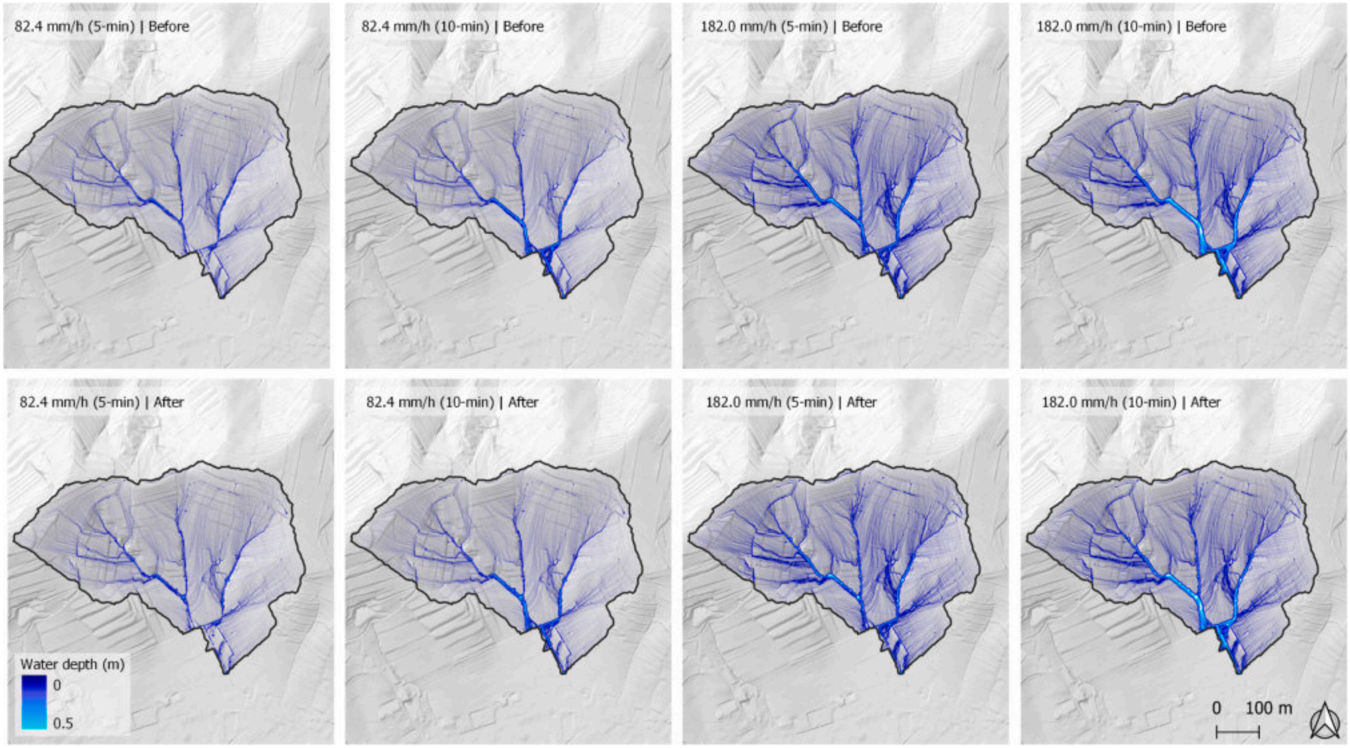

Fig. 3. simulated runoff distribution before and after putting water reservoirs under 82.4 mm h^{-1} (5-minutes), 82.4 mm h^{-1} (10-minutes), 182.0 mm h^{-1} (5-minutes), 182.0 mm h^{-1} (10-minutes) rainfall scenarios.

especially important for areas that are difficult to access by machinery due to poor traffic conditions.

3.2. *The effect of water resource management on runoff mitigation*

Our result indicated that a water reservoir can decrease runoff significantly in the 82.4 mm h^{-1} (5 min) scenario, 82.4 mm h^{-1} (10 min) scenario, 182.0 mm h^{-1} (5 min) scenario, 182.0 mm h^{-1} (10 min) scenario with the p-value less than 0.000001, 0.000001, 0.001, 0.001 separately. It is interesting to note that in both 5 min simulations in 82.4 mm h^{-1} and 182.0 mm h^{-1} rainfall events, the effect of water decreased is much more significant in 10 min simulation, which can be reflected by P-value tests returned < 0.000001. The water depth data in the investigation area (closed to the outlet) before put water storages in 82.4 mm h^{-1} (5 min) scenario, 82.4 mm h^{-1} (10 min) scenario, 182.0 mm h^{-1} (5 min), 182.0 mm h^{-1} (10 min) scenario is 0.026 m,

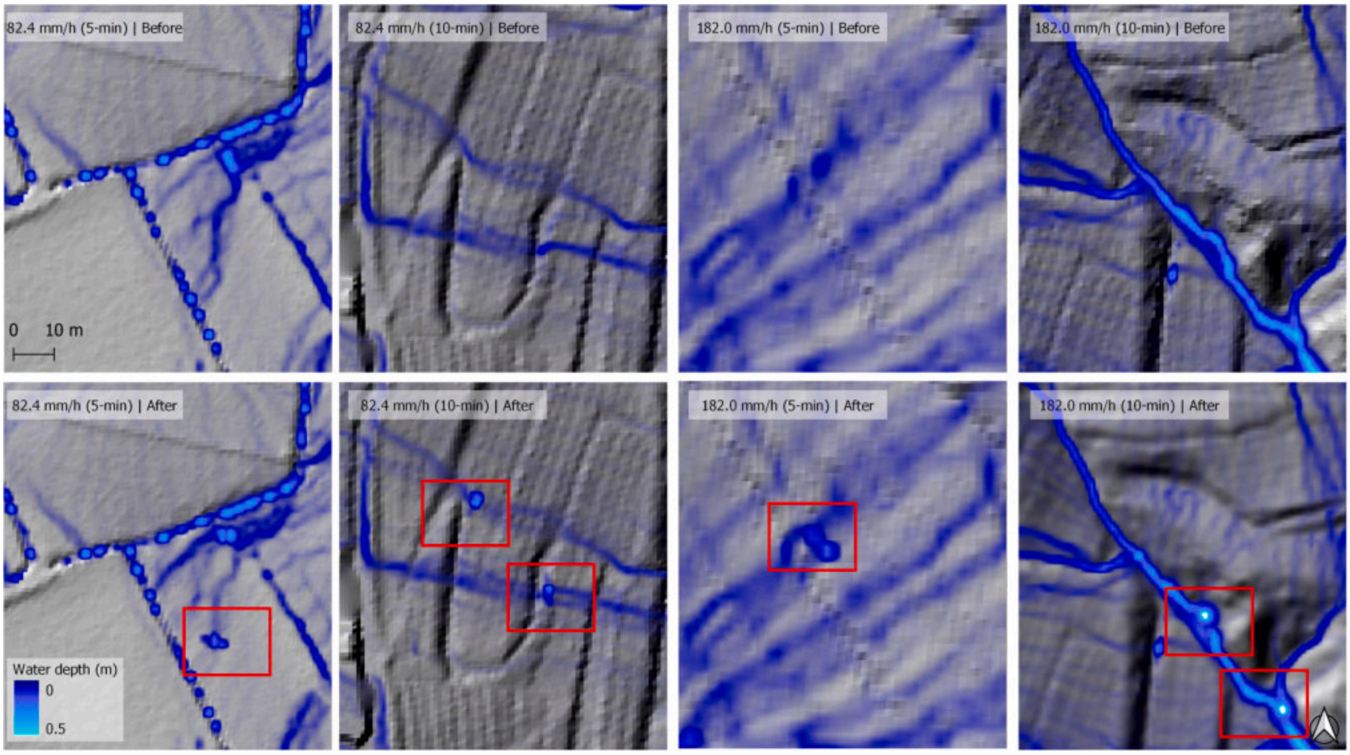

Fig. 4. Detailed map of comparison of simulated runoff in several positions before and after placed water reservoirs. Red rectangular highlighted the water accumulation in the position of putting designed water storage by SIMWE.

0.040 m, 0.058 m, 0.078 m. The water depth data after put water storages in 82.4 mm h^{-1} (5 min) scenario, 82.4 mm h^{-1} (10 min) scenario, 182.0 mm h^{-1} (5 min), 182.0 mm h^{-1} (10 min) scenario is 0.024 m, 0.033 m, 0.053 m, 0.069 m Fig. 5.

3.3. *Assessment of water amount saved by designed water storage*

Fig. 6 shows the water saved in the designed water reservoir in different scenarios. The most efficient water storages are highlighted in Fig. 6. It is worth mentioning that the more effective water storage facilities are mainly located in the middle and lower reaches of the study area. The overall location remains the same, although it changes slightly under different climatic conditions. According to the calculation, 33.67 m^3 of water was saved in the 82.4 mm h^{-1} (5 min) scenario, 41.92 m^3 in the 82.4 mm h^{-1} (10 min), 116.74 m^3 in the 182.0 mm h^{-1} (5 min), and 134.7 m^3 in the 182.0 mm h^{-1} (10 min) scenario. If we

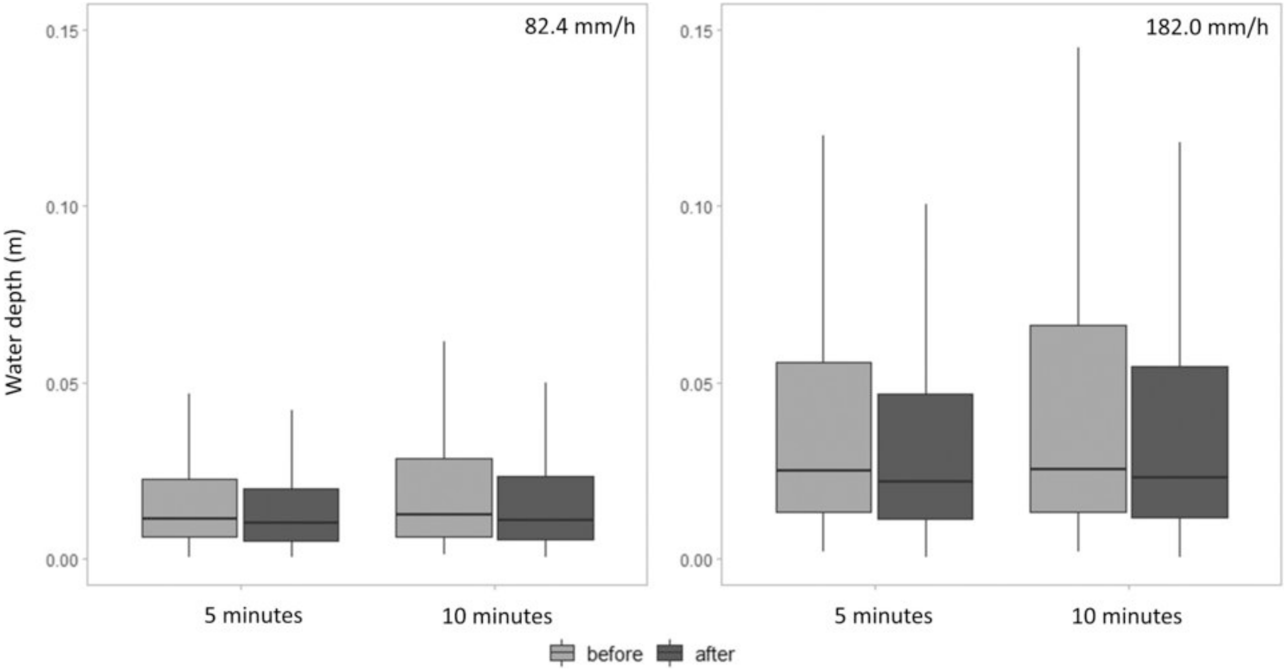

Fig. 5. The runoff comparison before and after implementing water storage in the investigation area (Investigation area highlighted by the red circle in Fig. 2).

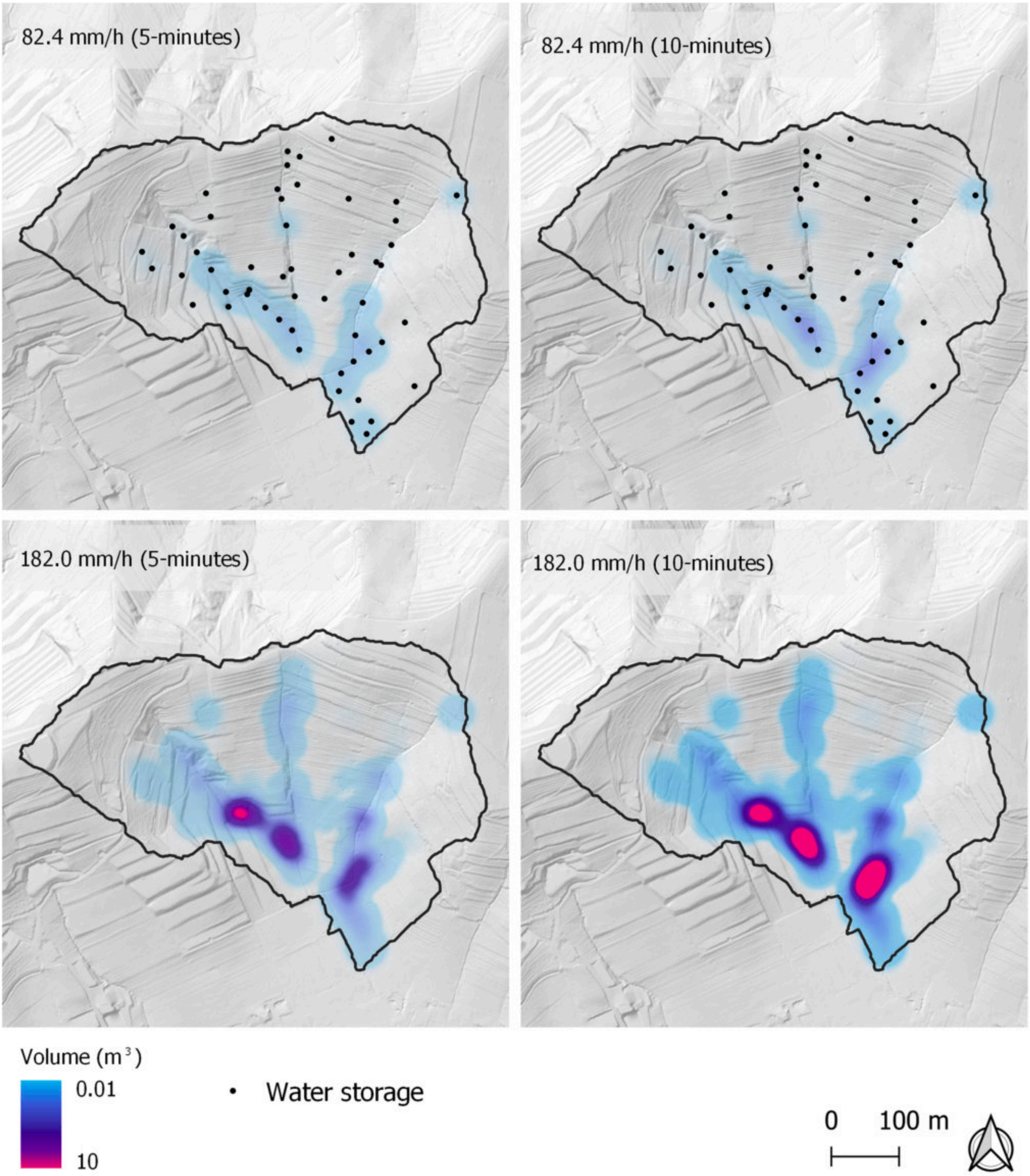

Fig. 6. The map of the spatial distribution of water amount saved by designed water storage in four different scenarios.

assume that all the water storage facilities are filled with water, 500 m^3 of water can be potentially collected.

4. Discussion

4.1. The importance of designing site-specific water storages facilities for the steep-slope viticulture landscapes

Our study concludes that the micro water storage systems have an enormous potential for water saving in steep-slope agriculture. In this study, the micro water storages network was designed for four reasons: (1) As one of few agricultural heritage sites worldwide recognized by FAO in the GIAHS list, Soave traditional agricultural systems were not allowed to make massive land use shifts such as the construction of big dams or large farm ponds, since it had already maintained by locally adapted management (GIAHS, 2018); (2) To avoid larger and complex infrastructure that can be unstable on a steep-slope, all the designed water storages in this study are at a maximum depth of 1 m for safety reason; (3) for a site-specific reason. Several studies have documented the critical role of ponds and pans, check dams, terracing, percolation tanks, etc., in water harvesting (Ammar et al., 2016). However, different water harvesting structures have their particularities and purpose and require specific construction conditions (Vema et al., 2019). For example, check dams have been well-recognized in China and India for alleviating the problem of water scarcity and preventing floods (Balooni et al., 2008; Yuan et al., 2022). However, check dams are only suitable in the catchment area ≥ 25 (ha), and agriculture ponds are available for small flat areas with slopes $\leq 5\%$ (Ammar et al., 2016). The Percolation Ponds are suitable on moderate slopes of 5–10% also more tend to recharge groundwater instead of irrigation water use (Christy and Lakshmanan, 2017); research has consistently shown that above-water harvesting facilities are not plausible in the steep slopes viticulture with low runoff potential and high permeability (Vema et al., 2019); (4) The difficulty in transporting water in steep-slope vineyards; (5) Economic acceptable by local farmers. The introduction of complex new water storage systems can largely decrease water stress and the risk of crop failures in different scales of farming systems (household, community, and catchment). However, in this case, the investment cost is also expensive. An economically feasible system with locally available material approaches is advisable in steep-slope agriculture for multipurpose use (Rockström, 2000). Tiwari et al. (2018) also emphasized the importance of time-saving and cost-effectiveness in water resource management. Our research highlighted the significance of the revival of traditional agricultural water harvesting facilities, which is also well recognized by some other countries like India (Balooni et al., 2008).

4.2. *Improve water management efficiency by combining the smart irrigation systems for dry spell mitigation*

In our study, 500 m^3 of water can be potentially collected. Based on the previous research, the minimum water consumption in the vineyard is 300 mm yr^{-1} (Medrano et al., 2015) and approximately an entire month's water requirements for a hectare of vineyard. In the Mediterranean areas, rain usually comes in sporadic, unpredictable storms and is mainly lost in evaporation and runoff, leaving frequent dry periods during the crop-growing season (Oweis and Hachum, 2006). Many researches about smart irrigation systems, such as pressurized irrigation systems and Automation of Farm Irrigation, are applied for optimal irrigation scheduling (Bwambale et al., 2022; Kamienski et al., 2019; Ommani, 2011; Oweis and Hachum, 2006; Vij et al., 2020). However, only a few studies focus on the water source for irrigation in mountainous areas. One of the ideas from Precision Agriculture is to combine intelligent agricultural irrigation systems with designed water harvesting systems, where funding allows, to solve the problem of over-irrigation in steep-slope viticulture and thereby improve water productivity. Optimal distribution of limited water resources can also be coupled with improved irrigation management options and technologies such as Supplemental, Deficit, Sprinkler, and Drip irrigation. In this way, tangible water productivity can be achieved on a sustainable basis (Baig et al., 2013; Geerts and Raes, 2009; Man et al., 2017). The collection of rural water can also be used to develop livestock farming and ecosystem diversity (Rockström, 2000). Water management guidelines should highlight maximum water productivity rather than land productivity (Geerts and Raes, 2009; Oweis and Hachum, 2006). Interesting is the optimization of the storage design to minimize water infiltration within the system and evaporation after water collection. In the first case, an impermeable layer (such as a sheath) should be installed to prevent percolation; in the latter, a shade net (useful to reduce the surface water temperature and retain it during evaporation) or a system of floating elements can be considered.

4.3. *Runoff reduction via utilization of micro water harvesting systems*

Our study concluded that micro water reservoir systems could significantly intercept runoff and harvest water in extreme rainfall events to be potentially used for irrigation during drought periods. These dual benefits are not necessarily coincident in all types of water harvesting techniques (Sample and Liu, 2014). Most studies of water harvest techniques have focused on water supply exclusively or large water harvesting facilities (Garg et al., 2022; Landicho et al., 2022). In this study, we aim to identify the influence of a micro-water harvesting system with minimum land modifications. However, more water harvesting facilities are recommended to mitigate the hydrologic risk of extreme rainfall events, especially considering that all runoff eventually drains downstream in the village.

5. Limitations and future challenges

The accuracy of the rainfall-runoff relationship simulated is highly dependent on the input data, model complexity, users (Adham et al., 2018), and data availability for model calibration and validation in complex morphology areas are usually lacking. Therefore, a limitation of this study could be determined by the use of a hydrological model and remote sensing data for process evaluation, which inevitably incorporates errors. Nevertheless, the SIMWE model based on high-resolution remotely sensed data used in this research has already been successfully tested in the wine-growing region and combined with field trials for verification (Pijl et al., 2020; Straffelini et al., 2022). Future challenges include the application of diverse high-resolution datasets (for example, based on UAV-SfM) in the delineation of potential sites for water harvesting structures and water leakages detection, which is also confirmed by previous studies (Abdulla Umar Naseef and Thomas, 2016; Chartzoulakis and Bertaki, 2015; Engman, 1991; Hammer et al., 2011; Waseem Ghani et al., 2013). In addition, real-time monitoring systems provide a shoulder to the farming industries in monitoring and tracking agricultural water use and improving the effectiveness of water retention measures at multiple scales (Foster et al., 2020). There is a need for further research on the hydrological model development involving both surface and sub-surface parameters such as groundwater discharge and evapotranspiration. A novel way of estimating the trends of global irrigation dynamics based on multiple satellite products was reported recently (Zhang et al., 2022). The development of finer spatiotemporal resolution satellite-based products will significantly increase the effectiveness of water resource management in the future (Zhang et al., 2022). The spatial design and organization of the vineyard can considerably affect surface runoff pathway and accumulation patterns (Pijl et al., 2020); thus, the same initiative should be repeated in other steep-slope viticulture to avoid site-specific biases. This study clearly illustrates the water amount harvested by the designed method for irrigation use, but this stands in contrast with the actual amount of irrigation in the study area. However, this research aimed to demonstrate the technical and methodological feasibility of incorporating water harvesting facilities based on remote sensing and modeling. In the scenario analyzed, 500 m^3 of water can be harvested per 20 ha of vineyard, thus about 25 m^3/ha. At the operational level, further exploration of micro-water harvesting systems is encouraged to obtain the maximum amount of water possible and to minimize leakage due to infiltration or evaporation. Combining micro water storage on steep slopes with larger ponds in morphologically suitable areas with storable volume could be interesting. For instance, in Italy, a farmer could construct up to 50 m^3/ha storage facility without special permissions; this value is indicated in the new national legislative proposal to address drought in agriculture (D.L. 39/2023). The feasibility of larger infrastructures depends on the type of study area. In the case of steep-slope cultural landscapes (such as the vineyard analyzed in this research), further permitting constraints may arise in addition to construction difficulties due to complex morphology. It is also recommended to line the interior of the storage with waterproof materials to limit infiltration, combined with appropriate and sustainable covers to limit evaporation. It is important to emphasize that the use of micro water storage alone cannot be sufficient to solve the problem of the impacts of opposing climate extremes (such as intense rainfall and drought) in steep-slope agriculture. Indeed, they need to be incorporated into a multidimensional planning strategy that combines water harvesting and precision irrigation with a series of targeted interventions. Promoting conservation agriculture techniques to maintain and improve soil organic carbon content could be useful for soil water retention. Particular attention should be paid to the vineyard grass cover to protect the soil, limit runoff, and increase biodiversity. Finally, in cases where manual cultivation of the fields is not suitable, light mechanization is recommended to limit soil compaction. Implementation of a water storage network combined with sustainable vineyard management and proper monitoring can therefore become a winning strategy in steep-slope vineyards (especially in the case of traditional and cultural landscapes) for mitigating the adverse effects of climate change.

6. Conclusion

Improving water resource management in traditional landscapes is important for designing sustainable and climate-change-resilient agricultural systems. This study designed a potential water harvesting network including 53 sites for collecting rainwater based on indigenous knowledge, field survey, runoff simulation, and topographic analysis. The study area is the FAO-GIAHS site of Soave (Italy), which has provided social, cultural, economic, and environmental goods and services for over 200 years for local people (Vigotti, 2021). The results show that these simple, micro-harvesting systems can considerably reduce the surface overflow (with P values tests returned <0.001) and effectively collect rainwater in different rainfall conditions. According to the calculation, 33.67 m^3 of water was saved in the 82.4 mm h^{-1} (5 min) scenario, 41.92 m^3 was saved in the 82.4 mm h^{-1} (10 min), 116.74 m^3 saved in the 182.0 mm h^{-1} (5 min), and 134.7 m^3 saved in the 182.0 mm h^{-1} (10 min) scenario. A total of 500 m^3 of water can be collected and used for emergency irrigation during drought. The maximum drop in water depth at the outlet of the study area was 2 cm at 82.4 mm h^{-1} (5 min) scenario and 182.0 mm h^{-1} (5 min) scenario. Our work illustrated the urgent need to revival traditional and cost-effective water resource management in steep-slope viticulture. Furthermore, we discussed that combining new irrigation technologies with designed water harvesting facilities will have a multiplier effect on improving water use. Given the specificities of steep-slope agriculture, there is a need to promote various indigenous water harvesting facilities and improve water productivity rather than designing more complex and expensive water management methods that are difficult for farmers to accept, except when funding is available. Sustainable development can only be achieved when the water resource management systems are adapted to the local natural, economic, and social environment in steep-slope viticulture.

CRediT authorship contribution statement

W.W. and **P.T.** conceived and designed the research; **W.W.** and **E.S.** wrote the first draft and edited the manuscript and figures; **E.S.** validated the dataset and the method; **P.T.** reviewed and edited the final version of the manuscript and supervised the entire research project.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

Data will be made available on request.

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