Rainwater harvesting techniques as an adaptation strategy for flood mitigation

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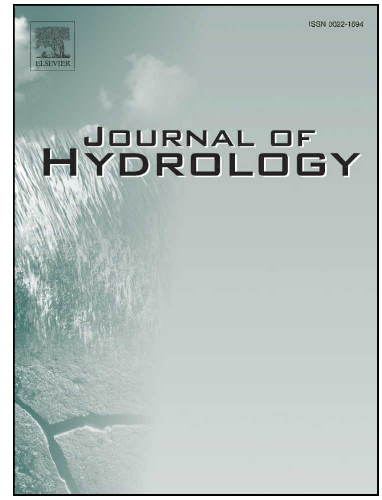

Research papers

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Title

Rainwater harvesting techniques as an adaptation strategy for flood mitigation

Highlights

- Modelling the impacts of rainwater harvesting techniques (RWHT) on surface runoff at the field and basin scale.
- Assessment of hydraulic performance of indigenous micro-catchment RWHT in terms of flow peak, volume and runoff coefficient reduction.
- Extreme rainfall events simulated through the implementation of a hydraulic model in HEC-RAS.
- RWHT as a sustainable strategy for flood mitigation.

Abstract

The development of adaptation and mitigation strategies to tackle anthropic and climate changes impacts is becoming a priority in drought-prone areas. This study examines the capabilities of indigenous rainwater harvesting techniques (RWHT) to be used as a viable solution for flood mitigation. The study analyses the hydraulic performance of the most used micro-catchment RWHT in sub-Saharan regions, in terms of flow peak reduction (FPR) and volume reduction (VR) at the field and basin scale. Parametrized hyetographs were built to replicate the extreme precipitations that strike Sahelian countries during rainy seasons. 2D hydrodynamic simulations showed that half-moons placed with a staggered configuration (S-HM) have the best performances in reducing runoff. At the field scale, S-HM showed a remarkable FPR of 77% and a VR of 70% in case of extreme rainfall. Instead at the basin scale, in which only 5% of the surface was treated, 13% and 8% respectively for FPR and VR were obtained. In addition, the reduction of the runoff coefficient (R_c) between the different configuration was analyzed. The study critically evaluates hydraulic performances of the different techniques and shows how pitting practices cannot guarantee high performance in case of extreme precipitations. These results will enrich the knowledge of the hydraulic behavior of RWHT; aspect marginally investigated in the scientific literature. Moreover, this study presents the first scientific application of HEC-RAS as a rainfall-runoff model. Despite some limitations, this model has the effective feature of using very high-resolution topography as input for hydraulic simulations. The results presented in this study should encourage stakeholders to upscale the use of RWHT in order to lessen the flood hazard and land degradation that oppresses arid and semi-arid areas.

Keywords

Rainwater harvesting techniques; Extreme rainfall; Runoff; Hydraulic modelling; Flood mitigation; Arid and Semi-Arid climate

1. Introduction

Arid and semi-arid (ASA) regions worldwide are characterized by a climate with a low amount of rainfall concentrated during short rainy seasons. In these areas, the most used farming system is rainfed agriculture which is totally based on rainfall to grow crops. To deal with the low amount of annual rainfall and extreme climatic uncertainty, farmers have developed several agricultural techniques to harvest rainwater (Ammar et al., 2016). During the past thirty years, many authors have named these agricultural practices with different terms such as: Runoff Water Harvesting is the term used by Salazar et al. (Salazar and Casanova, 2011), Rainwater Harvesting Practice (Vohland and Barry, 2009), or the novel term of Climate-Smart Agriculture (CSA) technologies (Partey et al., 2018). In this work, the term Rainwater Harvesting Techniques (RWHT), adopted by Biazin et al. (2012), will be used. RWHT have been used in worldwide ASA countries (Middle East, China, India, Americas and Africa) over the history but their use was put aside during the green revolution in which new technologies resulted more successful (Gould et al., 2014; Mekdaschi Studer and Liniger, 2013). Nowadays, in the era characterized by climate changes (CC), the utilization of rainwater harvesting techniques is rediscovered as an adaptive behavior to cope with the increasing water scarcity and climate exacerbation (Mukheibir, 2010; Ray and Simpson, 2014; Turton and Ohlsson, 1999). CC are considerably modifying the hydrology and the response of watersheds to extreme events. Focusing on sub-Saharan Africa, the hydrology of the Sahelian strip has changed several times over the last 70 years. Different studies have found three distinct periods characterized by a specific hydrological behavior. The first period can be extended from the installation of the first rain-gauging stations (middle of the last century) to the end of the 1960s in which rain fell abundantly with a constant pattern. The second comprises the twenty-year period (1970-1990) called "the great drought" characterized by a long deficit period. The third period starts from the end of the 20^{th} century and shows a slight increase in precipitation. Even if the annual total amount of precipitation almost reached the average of the entire recorded period, rainfall events show a greater interannual variability that is leading to an exacerbation of rainstorms. Particularly, the rainfall regime of the last twenty years is characterized by a smaller number of rainy days and a significant growth of the occurrence of extreme daily rainfall (Panthou et al., 2014). This corresponds to an increase of hydrodynamic intensity, in which the hydrological cycle is characterized by longer dry spells and higher precipitation intensity (Giorgi et al., 2011). With the ongoing global warming, this is one of the climate anomalies that is affecting African countries nowadays ("National Centers for Environmental Information", 2019). The higher frequency of extreme events tied with the incessant land cover changes are leading to severe floods (Aich et al., 2015, 2016; Amogu et al., 2015; Luc Descroix et al., 2012; Mahé and Paturel, 2009). Recent studied highlighted how the frequency of flooding events is greatly increased in the last twenty years and their occurrence will increase in following years (Tamagnone et al., 2019; Wilcox et al., 2018). Thus, impelling is the necessity to develop policies and strategies concerning flood risk mitigation. This study investigates hydraulic performances of RWHT, meaning the effectiveness in runoff reduction, exploring their capability as non-structural flood mitigation techniques. The features of simplicity, replicability, efficiency, adaptability, and the low cost of implementation and maintenance make the use of RWHT suitable in a wide range of contexts (Al-Seekh and Mohammad, 2009). Moreover, about 70% of the entire sub-Saharan population is employed in the agricultural sector and could potentially put their effort in spreading these techniques on a wider range of drylands (Rockström et al., 2010). Nowadays, RWHT are primarily used to increase soil water storage, soil fertility and consequently crop yield (Walker et al., 2005). Many studies have analyzed the benefit in crop production provided by the adoption of these techniques (Hensley et al., 2011; Malley et al., 2004; Tabor, 1995; Zougmoré et al., 2003). RWHT have been used also to restore degraded land. The functions of decreasing surface runoff, reducing erosion of fertile topsoil and increasing infiltration are effective in contrasting the ongoing desertification in drought-prone areas (Reij, 2009). Other studies have developed different techniques to identify suitable sites where the use of RWHT could be successful (Adham et al., 2016; Ammar et al., 2016; Kahinda et al., 2008). Until now, the concept of flood reduction coupled with RWHT has been analyzed primarily in flood-prone urban areas (Freni and Liuzzo, 2019; Haider et al., 2019; Palla et al., 2017; Teston et al., 2018). On the contrary, few studies have investigated and evaluated the effect of RWHT on runoff reduction in rural environments. Al-Seekh and Mohammad (2009) and Ali et al. (2010) conducted tests on artificial runoff plots to directly measure the amount of runoff after rainstorms. Welderufael et al. (2008) implemented a Morin and Cluff (MC) runoff model to investigate the rainfall-runoff relationships on treated and non-treated fields of Dera, Ethiopia. Verbist et al. (2009) combined on-site measurements with the use of the software HYDRUS-2D to evaluate the effect of an infiltration trench on a hillside in Chile. The work presented here provides a quantitative assessment of the hydraulic performance of RWHT through advanced hydraulic modelling, expanding also the scale of the analysis from the farming field to a watershed scale. Different hydraulic simulations have been carried out to study: firstly, the performance of the most used micro-catchment rainwater harvesting techniques (MC-RWHT) in terms of runoff reduction implementing a conceptual hydraulic model (field scale); secondly, the flood mitigation assessment of a real watershed due to the addition of RWHT (basin scale). The outcomes demonstrate how RWHT are an efficient strategy to reduce runoff overflowing out of farm fields, decreasing the amount of water that quickly is supplied to the receptor river during severe rainstorms. Several stakeholders could benefit from the original contribution of this study such as farmers, countryside/regional planners and governance to develop mitigation and adaptation strategies. Furthermore, this is the first study in which a rainfall-runoff model is implemented using the hydraulic software HEC-RAS (v 5.0.6), adopting precipitation as a boundary condition. This software has been created as a hydraulic software and still presents some limitations in the transformation of precipitation in runoff. Despite these constraints, the possibility to use measured hyetographs (or forecast) in an hydraulic freeware and considering future upgrades in which hydrological tools will be added open interesting opportunities for innovative hydrological-hydraulic studies. The structure of the paper has been organized into four parts. The first part reports the materials such as data and topography, and describes the methodologies used in this research. The second part sets out results. Section three deals with discussions related to the outcomes. In the last section conclusions and future perspectives are drawn.

2. Materials and Methods

In this paper a series of acronyms have been used and repeated, therefore for clarity are summarized in Table 1.

Table 1

The glossary of acronyms used in the text.

Acronyms	Full Names
ASA	Arid and Semi-Arid
RWHT	Rainwater Harvesting Techniques
MIC-RWHT	Micro-Catchment Rainwater Harvesting Techniques
CC	Climate Changes
DSM	Digital Surface Model
R_c	Runoff Coefficient
FPR	Flow Peak Reduction
EV	Excavation Volume

The workflow followed in this work is schematized in Fig. 1.

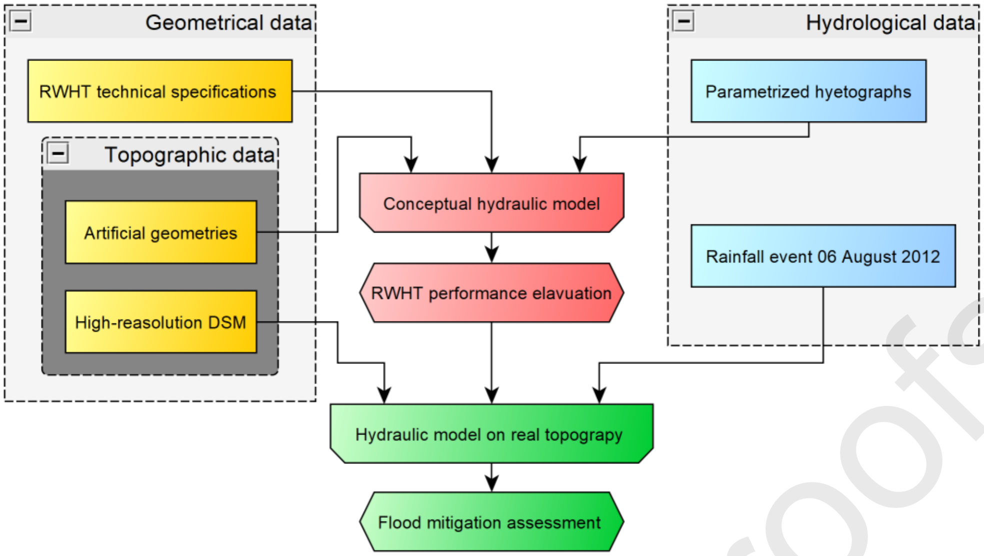


Fig. 1. Scheme of the methodology implemented in this work.

2.1 Study area

Different RWHT have been developed by indigenous farmers from ASA regions all over the world. In this study, RWHT mainly used in the African Sahel have been analyzed. The Sahelian strip is located between the parallel 10° N and 17° N and includes, from west to east, big countries such as Senegal, Mauritania, Mali, Burkina Faso, Niger, Chad, Sudan (Fig. 2). Its climate is characterized by an annual pluviometry that range from about 100 mm at the north to 800 mm at the south (Ali and Lebel, 2009). It has an ecological dry season of 8-9 months and a rainfall pattern mainly concentrated in August. The ongoing climate changes seem to provide more water availability in Sahelian countries (Seidou, 2018) but with a greater spatial and temporal variability that do not help populations to overcome water scarcity. Some studies showed that almost 50% of the annual rainfall amount falls in the occurrence of extremely short (a few hours or less) rainstorms with high intensity (Balme et al., 2006). This type of climate provides vast opportunities for water harvesting.

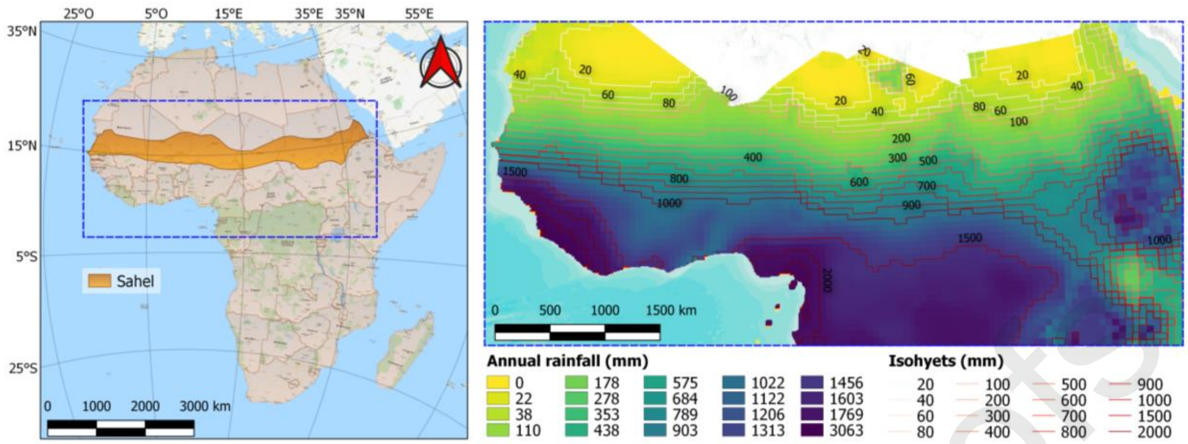


Fig. 2. The geographical location of the Sahelian belt. Enlargement: long-term annual rainfall (1960-2014) and isohyets of the sub-Saharan area (HarvestChoice, 2015).

2.2 Geometrical data

RWHT technical specifications

During the last thirty years, different researchers have classified the RWHT on the base of specific factors such as size, location, design, etc. Water harvesting systems were classified by Oweis et al. (Oweis, 1999; Oweis et al., 2001) and a detailed list of the most used was reported in the work of Yazar and Ali (2016). This study is focused on micro-catchment RWHT (MIC-RWHT) commonly used in sub-Saharan countries (Biazin et al., 2012; Boers et al., 1986; Boers and Ben-Asher, 1982; Mekdaschi Studer and Liniger, 2013). They can be collected in four main categories related to the type of processing technique (Fig. 3).

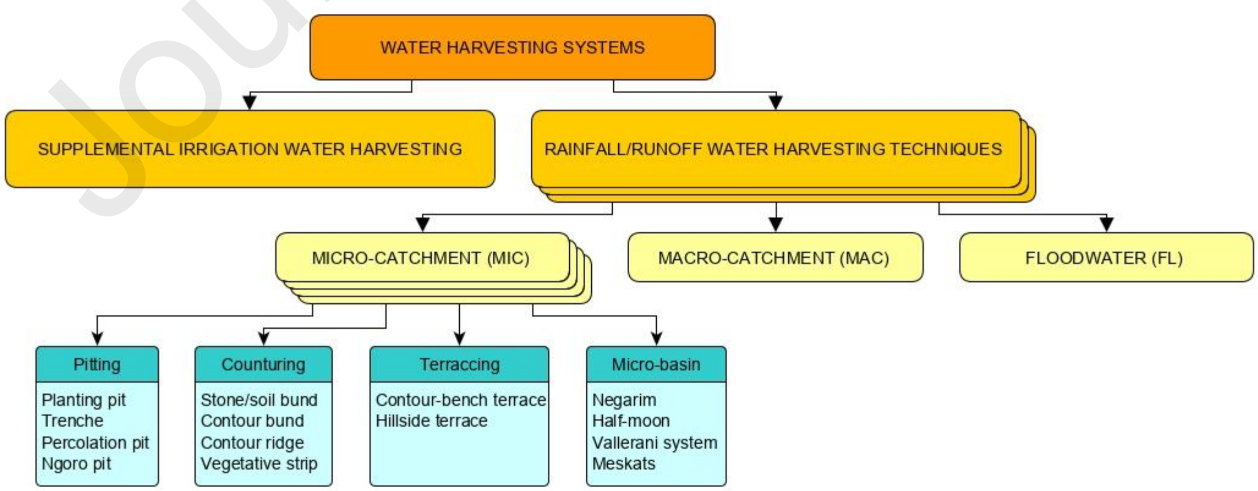


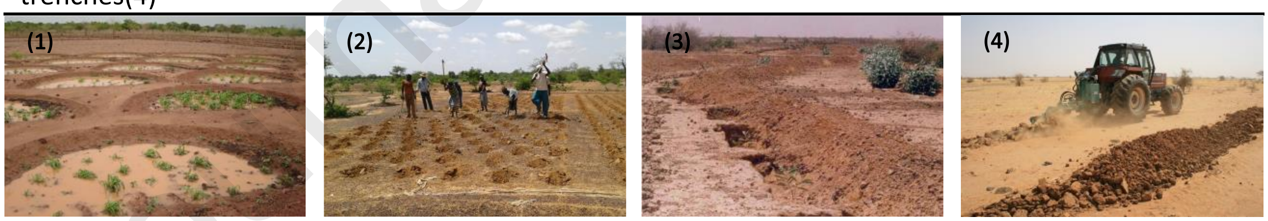
Fig. 3. Classification of RWHT and the most common on-farm MIC-RWHT in sub-Saharan countries.

The design of these systems varies depending on the place where the technique has been developed and consequently, it is possible to find different technical features (Mekdaschi Studer and Liniger, 2013). In this work, the authors have analyzed 4 different techniques (half-moons, planting pits, hand-dug trenches, Vallerani trenches) following technical specifications reported in the Global Database on Sustainable Land Management ("WOCAT", 2019), which are displayed in Table 2.

Table 2

Technical specification and pictures of the analyzed MC-RWHT (source: "WOCAT", 2019).

	Width/ diameter (m)	Length (m)	Area (m^2)	Depth (m)	Excavation Volume (m^3)	Spacing between structures (m)	Vertical interval between structures (m)	N° of structures per hectare (n/ha)
Half-moons(1)	4	-	6.32	0.3	1.9	3.5	2	350
Planting pits(2)	0.3	-	0.13	0.2	0.03	1	1	5180
Hand-dug trenches(3)	0.6	3.5	2.1	0.6	1.11	4	3.4	365
Vallerani trenches(4)	0.5	4	1.57	0.4	0.63	1.6	5.6	325



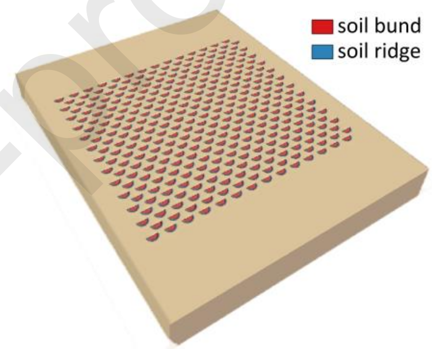
Topographic data

The hydraulic analyses carried out in this work have used two different topographic data as input geometry. Firstly, in order to schematize an agricultural field with and without RWHT, a conceptual hydraulic model was implemented using a series of artificial geometries. These were built shaping the selected RWHT on a plain square of 1 ha, with a constant slope of 1%. The four analyzed RWHT have been modelled following two geometrical schemes: (a) aligned framework and (b) staggered framework. An unmodified plain square was kept as reference geometry to carry out comparisons between the different configurations. All geometries have been manipulated using the processing tools of QGIS (QGIS Development Team, 2009). In this article, the abbreviation listed in Table 3 will be used to identify outcomes related to each simulated configuration. Geometrical scheme of the configurations is displayed in Fig. S1 (see supplementary material).

Table 3

Identification code of the different configurations used as the geometry of the conceptual hydraulic model. On the right: a tridimensional view of the geometry with the S-HM configuration.

Identification code	Configuration
U-PS	Unmodified plain square
A-HM	Aligned half-moons
S-HM	Staggered half-moons
A-PP	Aligned planting pits
S-PP	Staggered planting pits
A-HT	Aligned hand-dug trenches
S-HT	Staggered hand-dug trenches
A-VT	Aligned Vallerani trenches
S-VT	Staggered Vallerani trenches



Secondly, hydraulic simulations were carried out on a real watershed next to the village of Touré, Niger. The settlement is located along the left bank of the Sirba River, the main tributary of the Middle Niger River Basin. Its inhabitants have been affected by floods several times during the last decades, with important losses of houses, cattle and goods (Fiorillo et al., 2018; Massazza et al., 2019). The topography is represented by the digital surface model (DSM) of the riverine territory. The DSM was elaborated during aerial surveys with a drone by Belcore et al. (2019) at the end of the wet season 2018. The DSM has a high-level of resolution of 8 cm. Since the riverine territory is characterized by the presence of a series of gullies flowing into the river, a hydrological analysis was carried out to delineate the watersheds that collect rainwater into each gully. The elevation model of the widest basin (26 ha) has been used to implement the hydraulic model on a real geometry. Successively, the DSM of the basin was modified in order to simulate the presence of RWHT on a farming area (target agricultural fields highlighted in Fig. 4, about 5% of the whole watershed). Outcomes from the hydraulic model will be identified with the name “original” and “modified” respectively having as geometry input the unmodified DSM and the modified DSM.

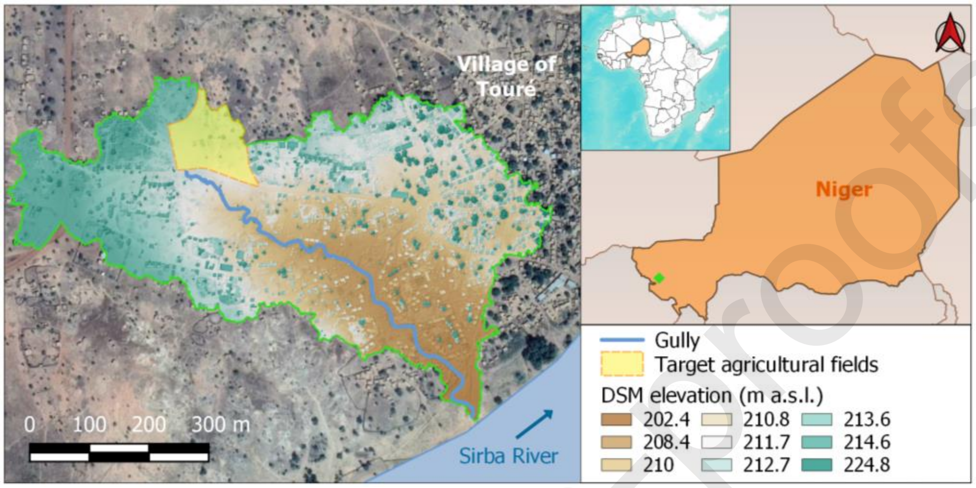


Fig. 4. Topography and hydrography of the analyzed watershed.

2.3 Hydrological data

Hydraulic analyses carried out in this study focused on hydrometeorological extremes that are the causes of floods. Thus, extreme and heavy rainfall have been chosen as inputs for hydraulic simulations. Following the results showed by Panthou et al. (2014), extreme rainfall for the analyzed study region corresponds to precipitation of 40 mm that occurs on average less than 2.5 times per year. Instead, 20 mm was chosen as magnitude for heavy rainfalls with a yearly occurrence lesser of 10 times. Typically, the evolution of these events can be associated to an Organized Convective System (OCS), in which the front of the convective cell brings the mayor part of the rain and it is followed by a stratiform trail (Mathon et al., 2002). Hyetographs produced by this convective system are organized in two well-defined intervals: a high-intensity peak (often with a duration lesser of an hour) followed by a low-intensity constant tail (Fig. 5). The shape of OCS hyetograph lends itself well to being disaggregated and parameterized in order to obtain a reconstructed realistic hyetograph. In order to obtain a realistic hyetograph for both extreme and heavy rainfall, the 5 parameters model proposed by Balme et al. (2006) was chosen to create the inputs for the rainfall-runoff model. All parameters are related to the total event rainfall P and are calculated as follows:

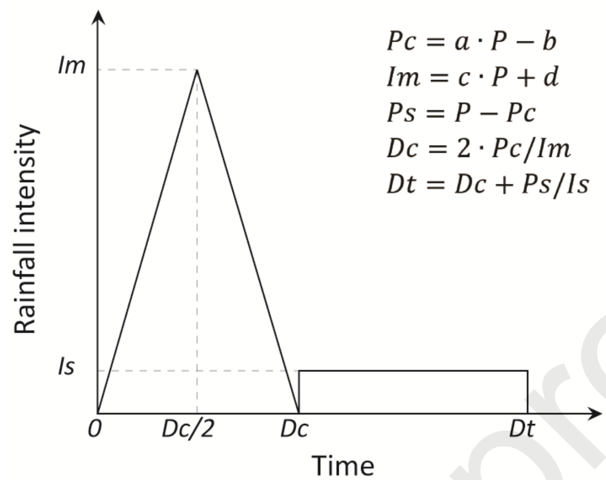


Fig. 5. Disaggregated hyetograph.

where Pc is the total precipitation of the convective part, Im is the maximum rainfall intensity, Ps is the total precipitation of the stratiform part, Dc is the duration convective of the convective part, Dt is the total duration of the rainfall event and Is is the stratiform intensity. The coefficients, that were calibrated optimizing the efficiency of the parametrized hyetograph to simulate real precipitation events, are a=0.89, b=0.08, c=2.1, d=0.53 and Is=1.5 mm/h. The parametrized hyetographs for the two analyzed events are displayed in Fig. 6.

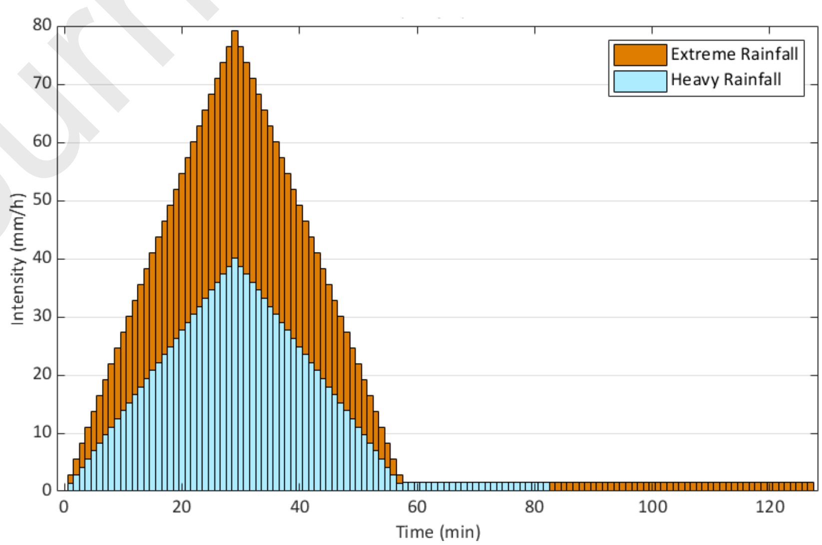


Fig. 6. Hyetographs for the two parametrized events, heavy and extreme rainfall.

In addition, to simulate a real event on a real topography, the hyetograph with the highest intensity of the wet season 2012 was selected from the nearest rain-gauge station (Koyria station) to the village of Touré (see Fig. 7).

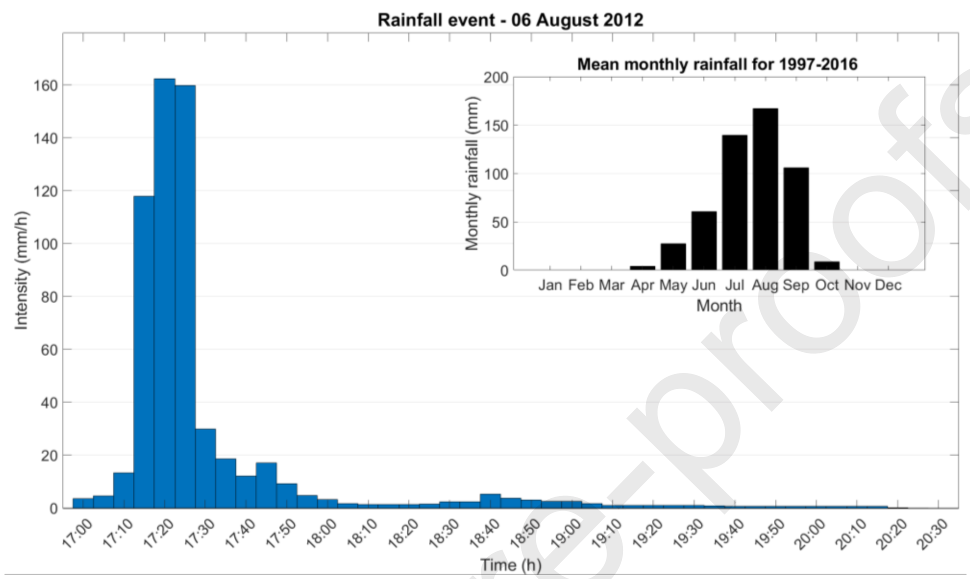


Fig. 7. Rainfall intensity of the rainstorm of 06 August 2012 and mean monthly rainfall for the twenty-year period 1997-2016 at the Koyria station. The high intensity highlights the power of rainstorms that frequently strike these regions.

Agricultural practices such as tillage, digging or crust removal cause changes in the features of the terrain such as infiltration rate or water holding capacity (Ndiaye et al., 2005). The most widely used method to take into account all these features is the Soil Conservation Service Curve Number (SCS-CN) method (Soil Conservation Service, 1985; Mishra and Singh, 2003). The runoff produced by a rainfall event is calculated through the following equations:

$$\begin{cases} R = {(P - I_a)^2}/{(P - I_a + S)} & if\ P > I_a \\ R = 0 & if\ P < I_a \end{cases}$$

Considering:

$$S = \left({100}/{CN} - 1\right) \cdot S_0$$

$$I_a = 0.2 \cdot S$$

Where R is the runoff depth, P is the total rainfall depth, I_a is the initial abstraction, S is the potential maximum retention; the unit of all variables is mm. S_0 = 254 mm is a conversion parameter and CN is the Curve Number that defines the permeability rate of the analyzed soil. In this study the SCS-CN method was conventionally used not to convert the amount of rainfall in runoff; instead, it was inversely used to evaluate the value of CN correspondent to the runoff attenuation of each analyzed configuration. Then, from the calculation of the R, it is possible to define the Runoff Coefficient (R_c) as the ratio between the runoff depth (R) and the rainfall amount (P). The value of R_c will give the evaluation of the efficiency in terms of runoff mitigation among the different configurations.

2.4 Hydraulic model

The rainfall-runoff model was set up to calculate the hydrographs at the outlet of each configuration. To achieve this purpose the HEC-RAS v5.0.6 software (Hydrologic Engineering Center–River Analysis System, (Brunner, 2002) was used with the configuration "rain-on-grid". This set up allows using hyetographs as boundary conditions. A direct uniform precipitation is applied on the 2D computational domain and when runoff is generated, the hydraulic model computes the flow propagation solving the Shallow Water Equations (SWE). The solver allows choosing between two sets of equations based on the type of flow: Momentum equations (full SWE) and Diffusion-wave equations (DWE). The former represents the complete form of the SWE, instead, the DWE represents an approximation used in case of shallow frictional and gravity flow. For all hydrodynamic analyses, DWE have been used. HEC-RAS has been chosen for the capability to use very high-resolution topographic data without leading to illogical long run time. The code makes use of the sub-grid bathymetry approach (Casulli, 2009; Casulli and Stelling, 2011) in which hydraulic radius, volume and cross-sectional area of each computational cell are pre-computed and this allows to use a relatively coarse computational grid without compromise the fluid simulation. This approach permitted to take advantage from the high-resolution DSM and accurately simulate the smaller RWHT. Since all results of these study are comparisons between different simulations, a constant Manning's coefficient was applied to all configurations.

2.5 Statistics

In order to investigate the relation between geometrical features and hydraulic performance of the RWHT analyzed, a statistical dependence between these variables has been searched. The Pearson's correlation coefficient was applied to evaluate the linear correlation between variables. Correlation coefficient values range from -1 to 1, where ±1 is the perfect positive (or negative) correlation and 0 is the absence of correlation. The level of statistical significance α was also calculated to test the robustness of the correlation. Correlation is statistically significant if $\alpha<0.05$.

3. Results

3.1 Conceptual model: RWHT performance evaluation

The hydraulic performance of the analyzed RWHT were evaluated through comparisons between outcomes coming from the different configuration simulated. The first hydraulic performance evaluated is the flow peak reduction (FPR) related to each configuration. FPR was evaluated as the reduction of the maximum flow rate compared with the outcome of the plain configuration (U-PS). Hydrographs at the outlet are displayed in Fig. 8, showing the different response of each RWHT to rainfall events.

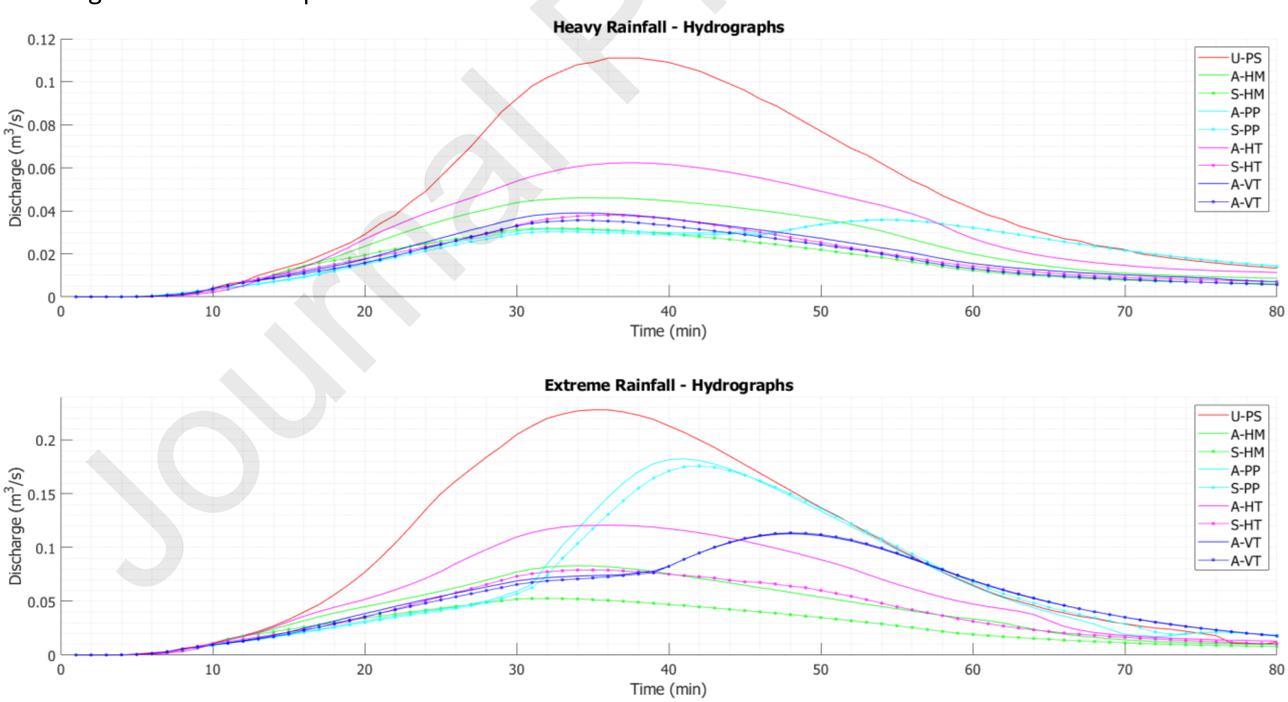


Fig. 8. Hydrographs for the two parametrized rainfall events.

Moreover, the maximum discharge with the related FPR per each output is reported in Table 4.

Table 4

Outcomes of each configuration simulated: the peak of the hydrograph (Q_{max}) and related flow peak reduction (FPR).

Coloring: from the worst performance (red) to the best performance (green).

		U-PS	A-HM	S-HM	A-PP	S-PP	A-HT	S-HT	A-VT	S-VT
Heavy	Q_{max} (m^3/s)	0.111	0.046	0.032	0.036	0.036	0.062	0.038	0.039	0.036
Rainfall	FPR (%)	-	58%	71%	68%	68%	44%	66%	65%	68%
Extreme	Q_{max} (m^3/s)	0.228	0.083	0.053	0.183	0.176	0.121	0.079	0.113	0.114
Rainfall	FPR (%)	-	64%	77%	20%	23%	47%	65%	51%	50%

Both hydrographs and FPR show how the configuration S-HM (staggered half-moon) has the best performance with a value of flow peak reduction higher than 70%. Relevant is the difference in the performance of the two smallest RWHT, A-PP and S-PP. Observing the trend of the hydrograph can be highlighted two marked phases: before the filling and after the filling of the storage volume. Before the filling, planting pits strongly slow the flow being homogeneously distributed on the ground. Despite this optimal behavior, the small size of the dug basins cannot retain a large amount of water and when pits are filled the global friction decreases and the outgoing discharge quickly increases. This phenomenon is equivalent to the "*principles of non-uniform floodplain storage*" explained in the Principles of River Engineering (Jansen et al., 1994) where the volume of the flow wave exceeds the storage volume. For the heavy rainfall, the A-PP and S-PP hydrographs show a "chopped head" wave up to the minute 46, then the flow reduction fails and the discharge increases. Instead, for the extreme rainfall, this behavior is much more marked leading to a slight FPR (20%-23%). Indeed, the storage capacity already run out at minute 28. This behavior can be observed also for the A-VT and S-VT. Both configurations fail in case of the extreme event showing an evident increase from the minute 39 to 49. On the contrary, heavy rainfall does not use up all the retention capacity of the Vallerani technique, avoiding the abrupt change of slope in the outflow hydrographs. The second performance evaluated is the volume reduction (VR) at the end of each simulation. Fig. 9 displays the cumulated volume over the time of each simulation. VR was evaluated as the reduction of the cumulated volume flowed out of the domain compared with the outcome of the plain configuration (U-PS).

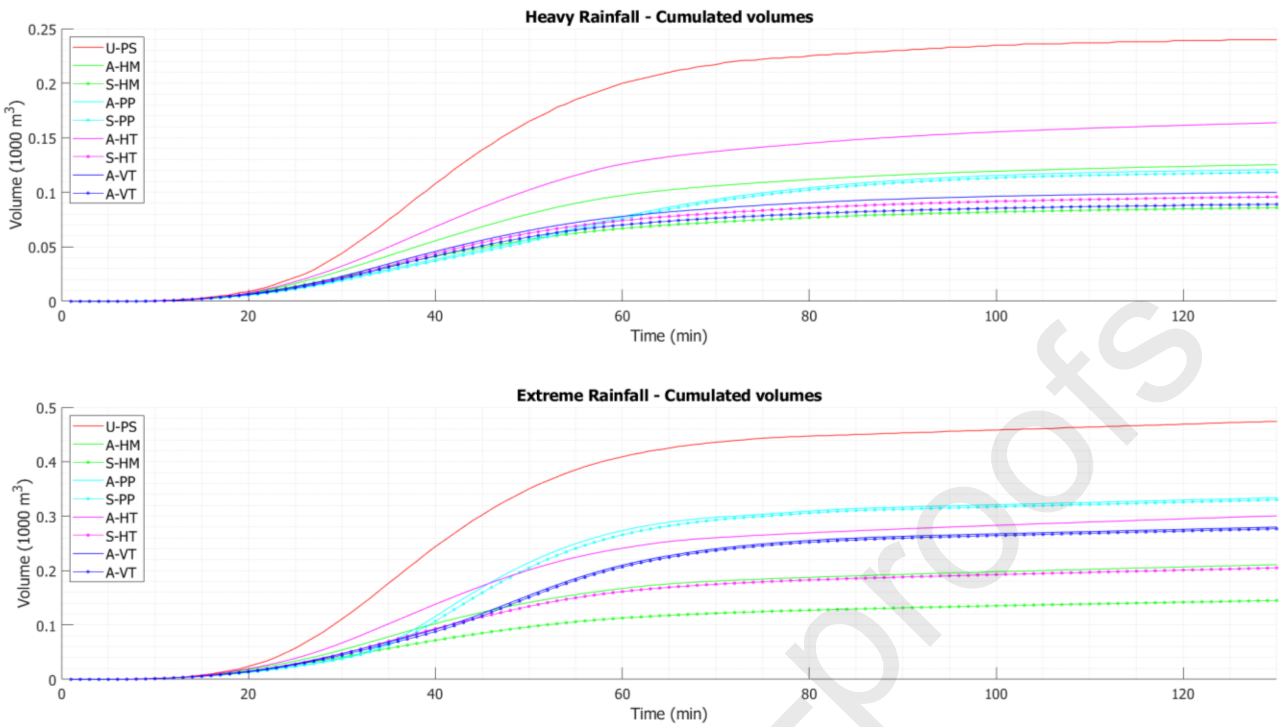


Fig. 9. Cumulated volume for the two parametrized rainfall events.

The total volume flowed out of the domain during the simulation (V) and the VR per each configuration is summarized in Table 5.

Table 5

Outcomes of each configuration simulated: cumulated volume (V) and related volume reduction (VR). Coloring: from the worst performance (red) to the best performance (green).

		U-PS	A-HM	S-HM	A-PP	S-PP	A-HT	S-HT	A-VT	S-VT
Heavy Rainfall	V (1000 m^3)	0.236	0.121	0.083	0.118	0.115	0.158	0.093	0.098	0.087
	VR (%)	-	49%	65%	50%	51%	33%	61%	59%	63%
Extreme Rainfall	V (1000 m^3)	0.472	0.209	0.144	0.332	0.328	0.298	0.203	0.278	0.275
	VR (%)	-	56%	70%	30%	30%	37%	57%	41%	42%

Subtracting V of the different configurations from U-PS volume it is possible to evaluate the amount of retained volume in each RWHT. The retained volume is water that does not reach immediately the receptor water body, slowing down the growth of the flood wave. These results also confirm that S-HM has the best performance and they are able to intercept the greater amount of runoff. Utilizing the concept behind the SCS-CN method, knowing the cumulated volume from simulations it is possible goes back to the CN that characterizes the modified surface and discovers the relative runoff depth (the net amount of precipitation that generated the cumulated volume).

Table 6

Curve Number of each configuration and the related runoff depth (R).

		U-PS	A-HM	S-HM	A-PP	S-PP	A-HT	S-HT	A-VT	S-VT
Heavy	CN	100	95.4	92.6	95.1	95.0	97.2	93.4	93.8	92.9
Rainfall	R (mm)	20	10.3	7	10	9.8	13.4	7.9	8.3	7.3
Extreme	CN	100	89.2	84.5	95.3	95.2	93.9	88.8	93	92.8
Rainfall	R (mm)	40	17.7	12.2	28.2	27.8	25.3	17.2	23.6	23.3

Since that SCS-CN method is based on a relation between P and R that follows power-law, for a small amount of precipitation a small variation of the CN produces a great change of R. This means that, for example, an extreme event of 40 mm on a field with staggered half-moons produce the same runoff of an event with an amount of rainfall of 12 mm on a non-treated surface. On the other hand, the same amount of runoff can be observed on a surface with RWHT for rainfall events with an intensity much higher than on a plain surface. These results can be translated into the variation of runoff coefficient (R_c) related to each adopted technique. The R_c values are summarized in Table 7. Focusing on the most efficient practice, the application of staggered half-moons on a completely crusted soil (almost waterproof with a R_c close to one) could lead to a significative reduction of the runoff coefficient meaning that only one-third of the total amount of rain will flow downstream the cultivated field.

Table 7

Runoff coefficient (R_c) for each configuration analyzed.

		A-HM	S-HM	A-PP	S-PP	A-HT	S-HT	A-VT	S-VT
Heavy Rainfall	R_c (-)	0.51	0.35	0.50	0.49	0.67	0.39	0.41	0.37
Extreme Rainfall	R_c (-)	0.44	0.30	0.70	0.70	0.63	0.43	0.59	0.58

To evaluate whether the efficiency of the analyzed configuration is uniquely related to the design of the technique itself, a series of correlations have been searched. The most characterizing feature of each RWHT is the volume of the single micro-catchment, excavation volume (EV). For this reason, the correlation between FPR and VR and this characteristic has been explored.

Table 8

Correlation of EV with VR (EV-VR) and with FPR (EV-FPR). The correlation coefficient (ρ) and level of significance into parenthesis (α).

		ρ (Pearson)
Heavy Rainfall	EV-VR	0.100 (0.813)
	EV-FPR	-0.247 (0.556)
Extreme Rainfall	EV-VR	0.886 (0.003)
	EV-FPR	0.909 (0.002)

All coefficients show a significant correlation with both VR and FPR for extreme rainfall. Conversely, correlations for heavy rainfall seem do not exist. To deeply understand whether geometrical arrangement affects the analysis, correlation coefficients have been calculated considering separately each configuration.

Table 9

Correlation of EV with VR (EV-VR) and with FPR (EV-FPR) for the two geometrical configurations, aligned and staggered RWHT.

			ρ (Pearson)
Heavy Rainfall	Aligned configuration	EV-VR	-0.267 (0.733)
		EV-FPR	-0.536 (0.464)
	Staggered configuration	EV-VR	0.83 (0.170)
		EV-FPR	0.524 (0.476)
Extreme Rainfall	Aligned configuration	EV-VR	0.911 (0.089)
		EV-FPR	0.902 (0.098)
	Staggered configuration	EV-VR	0.993 (0.007)
		EV-FPR	0.967 (0.033)

As reported in Table 9, there is a strong positive correlation for both configurations in case of an extreme event. Observing the heavy rainfall, staggered configuration shows a marked correlation with EV, even if with a low level of significance due to the small size of the sample. Instead, no correlation can be found for the aligned configuration. The demonstration can be found in the different behavior of RWHT for the two geometrical configurations. Indeed, A-HM and A-HT show a much lower efficiency than the staggered equivalent.

3.2 Real watershed: flood mitigation assessment

Staggered half-moon (S-HM) showed the best performance in terms of flow peak and volume reduction and so R_c decrease. Thus, S-HM was chosen as RWHT to be tested on the real topography. Hydraulic simulations were carried out on the original and modified topography. Fig. 10 displays how the original surface has been modified with the addition of staggered half-moons.

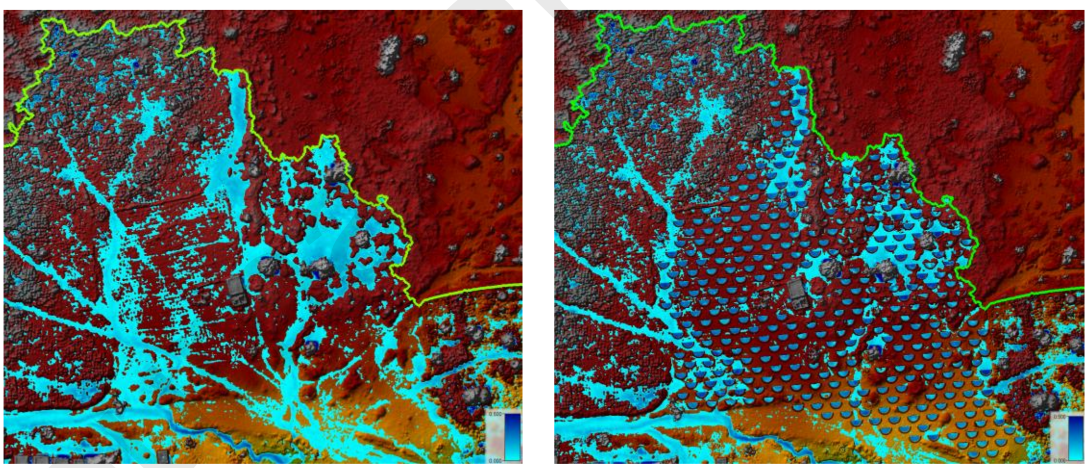


Fig. 10. Overland flow pattern for the (a) original and (b) modified topography. All images display the water depth at the peak of the rainfall event (coloring: from light blue = 0.05 m to dark blue = 0.3 m).

Three scenarios have been analyzed: the two parametrized rainfall events and the rainstorm occurred on 06 August 2012. The outflow has been calculated at the closure section of the basin and hydrographs have been compared. Hydrographs are reported in Fig. 11.

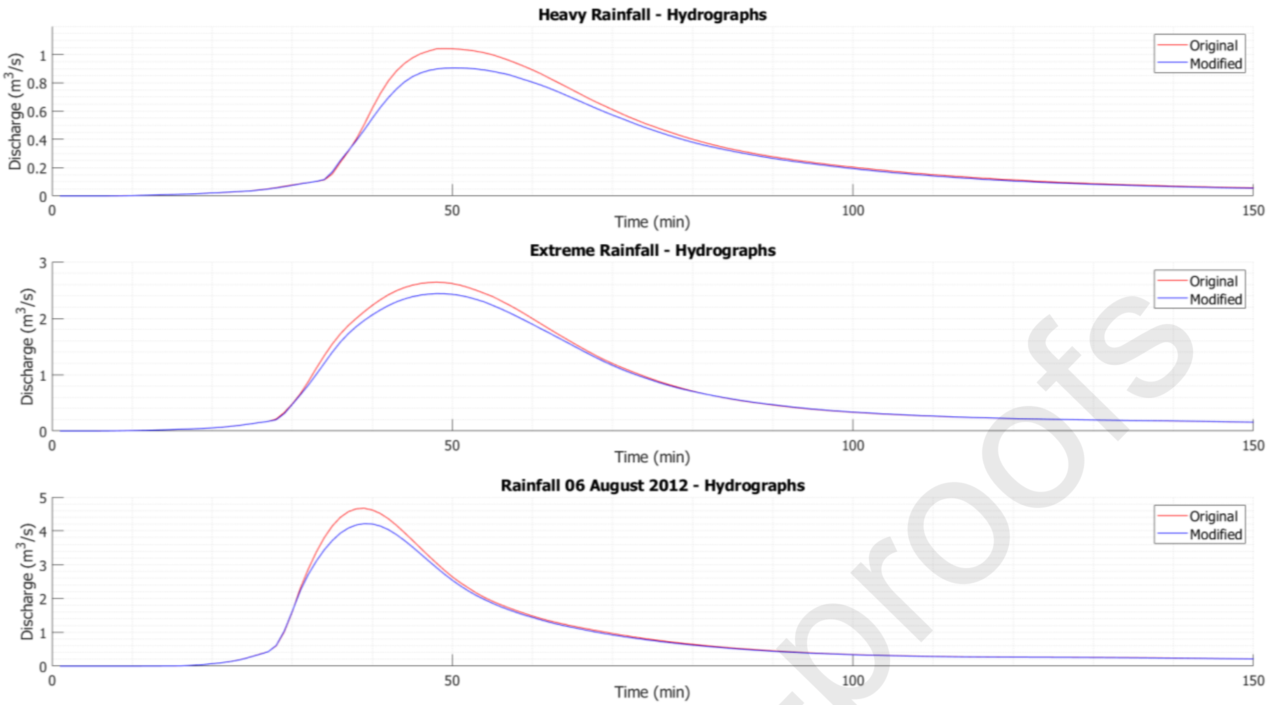


Fig. 11. Hydrographs calculated for the three analyzed scenarios. Simulation on the original topography (red line) and on the modified topography (blue line).

The parametrized events produce a similar hydrograph with a marked flow peak reduction for the heavy rainfall. Despite only the 5% of the basin surface was treated with S-HM, all hydrographs show a significant FPR around 10% highlighting the benefit of the presence of RWHT (see Table 10). The mitigation effect of the RWHT leads to the generation of smaller flood wave along the basin.

Table 10

Outcomes from the three scenarios simulated: the peak of the hydrograph (Q_{max}) and related flow peak reduction (FPR).

		Heavy Rainfall	Extreme Rainfall	Rainfall 06 August 2012
Original	Q_{max} (m^3/s)	1.041	2.641	4.668
Modified	Q_{max} (m^3/s)	0.905	2.447	4.214
	FPR (%)	13%	7%	10%

In terms of VR, the modified layout shows a decrease in performance as the intensity of the rainfall increases (Table 11). This negative trend is due to that most of the HM storage volume has been overfilled by the increasing overland flow during the event.

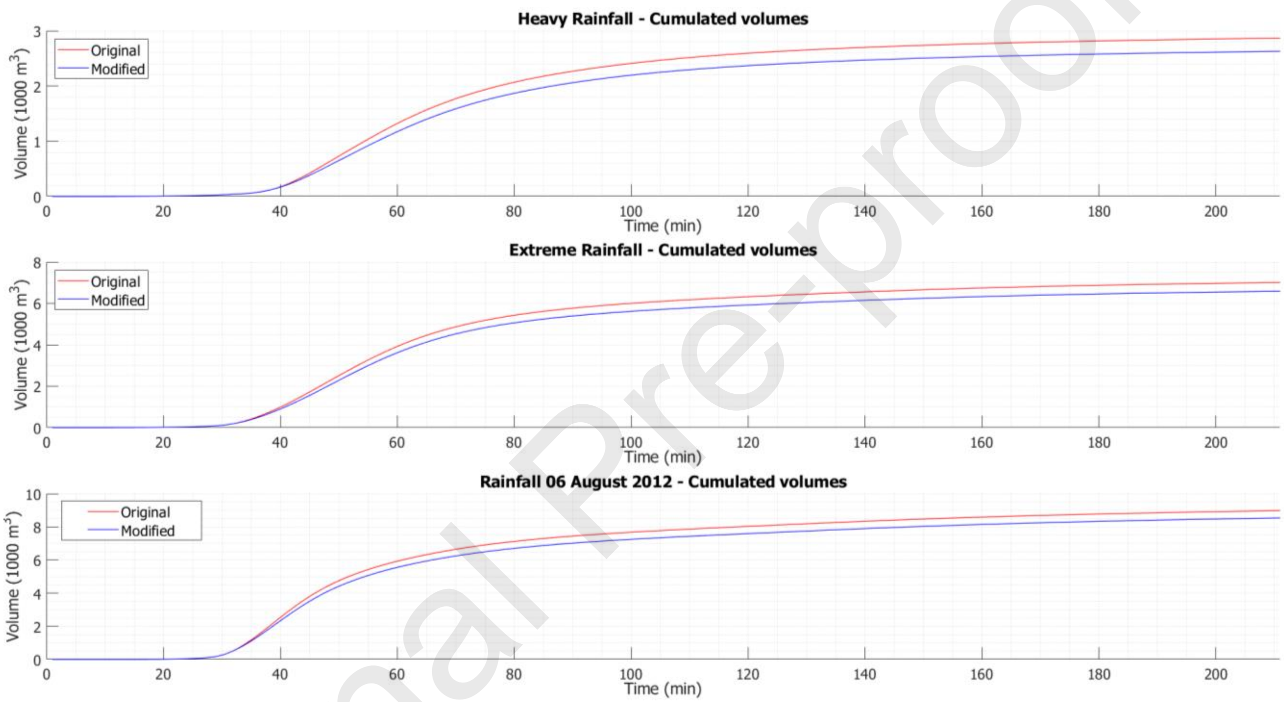


Fig. 12. Cumulated volume for the three scenarios.

Table 11

Outcomes from the three scenarios simulated: the cumulated volume (V) and related volume reduction (VR).

		Heavy Rainfall	Extreme Rainfall	Rainfall 06 August 2012
Original	V (1000 m^3)	2.868	7.005	8.98
Modified	V (1000 m^3)	2.628	6.584	8.537
	VR (%)	8%	6%	5%

Comparing the values of FPR and VR can be noticed that they have not the same trend (see Table 10 and Table 11). Observing the FPR, S-HM seems to be more efficient for the real rainfall even though the magnitude (P≈50 mm) is higher than the extreme rainfall (P=40mm). This is due to the shorter duration of the event which allows collecting the initial runoff more efficiently. The Rc values evaluated for the two configurations are reported in Table 12.

Table 12

Runoff coefficient (Rc) for the three scenarios analyzed.

		Heavy Rainfall	Extreme Rainfall	Rainfall 06 August 2012
Original	R_c (-)	0.54	0.66	0.68
Modified	R_c (-)	0.5	0.62	0.65

4. Discussions

Application of RWHT induces a series of positive impacts that lead to an improvement of dryland ecosystems functioning such as aquifer recharge and increase in soil moisture (Vohland and Barry, 2009). The main scope of RWHT is to collect as much water as possible during the rainy season minimizing variability in water availability to prevent deficits during dry spells (Rockström et al., 2002). This should prevent crop failures enhancing food security (Komariah and Senge, 2013). They are used not only for crop production but also as micro-basin to plant trees coping with the issue of deforestation that affects Sahelian regions. This study analyzes another important aspect related to RWHT, how RWHT can be used as a smart and sustainable solution to mitigate flood hazard. Results reported in the previous section show how the retention capacity of RWHT may lead to a consistent reduction of the runoff, both at the scale of the agricultural field (conceptual model) and at the basin scale. From the different RWHT and geometrical configurations examined, it was found that in all cases the staggered configuration has superior performance than the aligned configuration. For this reason, independently of the adopted technique, farmers should use a staggered arrangement as agricultural practice. Moreover, S-HM has the best performance among the different precipitations. The good performance of planting pit and Vallerani trenches, for heavy rainfall, indicate that these techniques should be preferably used in arid areas (northern border of the Sahelian strip) where the amount of rainfall per event does not exceed their storage capacity. In semi-arid region characterized by more intense precipitation, half-moon or hand-dug trenches are preferable rather than micro-basins with very small size. Building a large number of MC-RWHT will increase the water holding capacity of the whole basin reducing the runoff and the potentially dangerous flood wave downstream. Moreover, the decrease of runoff causes a reduction of sediment transport capacity of the overland flow preventing topsoil erosion with losses of precious nutrient. Surface runoff running on bare crusted soil has a high erosive potential also in flatland and often digs rills and gullies develop a vast drainage network. The impoverishment of vegetative coverage during the great drought enhanced the propagation of gullies losing tones of fertile soil (L. Descroix et al., 2012; Leblanc et al., 2008; Mamadou et al., 2015). Thus, RWHT accomplish also the task of anti-erosion action against flash floods. Avoiding the accumulation of the overland flow in narrow channels, RWHT protect the agricultural surface by rill and gully erosion. Moreover, storing rainwater, they noticeably raise the survival capacity of the emerging vegetation. Reducing overland flow, RWHT provide a remarkable reduction of the runoff coefficient of treated areas. Results from hydraulic simulations report that changes of R_c are related to the efficiency of the adopted rainwater harvesting technique. This parameter will identify the hydrological response to rainstorms of the improved agricultural field. The wider use of these techniques could stop the uninterrupted increase of runoff coefficient that is affecting Sahelian watersheds since the 1960s (Descroix et al., 2018). This hydrological phenomenon was designated as “Sahelian Paradox” and many studies have tried to explain which the natural or anthropological drivers are. First of all, the long dry spell called “the great drought” (1968-1991) led to a heavy land use/land cover modification characterized by vegetation dying with consequent formation of bare soil exposed to crusting and erosion (Amogu et al., 2010; Leblanc et al., 2008). This drastically changed the surface hydrological features reducing the water holding capacity of the soil with a direct increase of the R_c. Therefore, the development of policies aimed to spread the use of RWHT could be the solution to reverse the hazardous positive trend of R_c. Since a positive correlation has been found between storage volume and hydraulic performance, mainly for extreme events, it is fundamental keeping constant the maintenance of each micro-basin every year. Displacement of topsoil caused by sheet erosion (induced by raindrops or sheet flow) and consequent sedimentation might reduce the storage capacity during the monsoon season. For this reason, the RWHT design should avoid excessive spacing between structures. Furthermore, it is fundamental planning the type of maintenance based on the purpose for which RWHT are used. For example, RWHT for food production are often filled with organic manure or compost to enhance the nutrient supply rising the soil fertility (Aune et al., 2017; Critchley et al., 1991; Roose et al., 1999; Zougmoré et al., 2003) but in doing so the storage capacity of the single structure drastically drops down, reducing the efficiency in terms of runoff mitigation

5. Conclusion

Considering the long series of catastrophic floods that have been affecting sub-Saharan countries, more effort is requested to develop effective strategies aimed to improve flood hazard and risk management. Climate changes and environmental degradation have been identified as the drivers that are causing the exacerbating of flooding events. Therefore, sustainable land management aimed at the use of climate-smart agriculture practices would be a valid solution to face these problems. The present study gives an assessment of the hydraulic performance of MC-RWHT evaluating the applicability of these techniques as a strategy for flood prevention and mitigation. Hydraulic simulations were set out to investigate the capability of these techniques to reduce the outgoing flow from a conceptual and from a real basin. This study shows that the choice of the staggered arrangement gives always better performance than the aligned configuration. Staggered half-moon resulted in the most efficient RWHT in terms of flow peak and volume reduction. A weakness of the hydraulic model used is that some components of the hydrological balance are neglected (infiltration and evapotranspiration) focusing only on the movement of the overland flux. However, this assumption is compatible with the temporal scale of simulations. Further works should use integrated hydrological models involving all parameter of the hydrological cycle in order to expand the temporal scale of the analyses. Despite these limitations, the study shows how treating the land surface with RWHT lead to a remarkable reduction of the runoff coefficient of the whole basin. Thus, upscaling the use of these techniques will improve the landscape and hydrological functions of drylands. Authority could opt for a large reservoir to prevent floods and retain water but in this type of climate dominated by extremely high evaporation ratio would lead to the wastefulness of resource. In these countries where most of the inhabitants are agro-pastoralists, farmers should invest in RWHT facing simultaneously with food security and flood risk. Furthermore, social factors play an important role in these communities where the concept of improving lands that are communally used is unfamiliar. The success/failure of the RWHT strongly depends on the acceptance of the system by the local population, which should be actively involved in the implementation and maintenance of such rainwater harvesting systems. Thus, a participative collaboration between land users (farmers) and planners (watershed authority) would lead to an improvement of indigenous practices and dissemination on a wider scale. The challenge for the future of these regions will be the development of watershed management strategies that involve RWHT as a driver for environmental restoration and flood mitigation.

Supplementary materials

Fig. S1.

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