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Communication

Rainwater: Harvesting and Storage through a Flexible Storage System to Enhance Agricultural Resilience

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Abstract: Many climatic variables are projected to occur with more intense and frequent extreme events, possibly unpredictable patterns and negative feedback loops with other environmental processes. Agriculture has faced uncertainty regarding ground temperature and rainfall distribution during the last few years, making water availability one of the major concerns for farm management. In this scenario, rainwater harvesting could represent a powerful tool to mitigate this problem, and consequently, the research community has been fostering new technical solutions. On the other hand, a few studies on agronomic assessment of rainwater harvesting systems are present in scientific literature. The present study reports preliminary data of a long-term study on a Flexible Water Storage System (FWSS) evaluating the possibility of enhancing agriculture systems resilience, shifting from rainfed production to irrigated agriculture relying on excessive rainfall, collectible from extreme events. The idea of intercepting excess rainfall, which is generally lost, thanks to an innovative water harvesting system, and using it to mitigate drought stress for crops is in line with sustainable approaches aiming to improve the resilience of agricultural systems. The results highlighted that the system studied could potentially collect an annual average of 831.7 m^3 of water, mitigating the excess of water in the ditch that can potentially cause flooding and storing fresh water to provide irrigation during dry periods.

Keywords: rainwater harvesting; flexible water storage; rainfall distribution; rainfed agriculture; irrigated agriculture

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1. Introduction

The resilience of agriculture systems is a crucial topic to be addressed by both researchers and policy makers. Among the various shocks which can involve agro-food production, climate change is one of the main stress factors. The scarcity of water and its availability during the growing season for irrigation is one of the main problems that agriculture has faced during the last few decades. The agricultural sector is one of the principal actors in water capitation and consumption, accounting for 24% of the abstracted water, which can go up to 80% in southern regions [1].

Climate change and uncertainty make agriculture depend on natural freshwater basins or underground water to a greater extent when rainfall distribution along the year presents a changing pattern [2–4]. The Mediterranean area is considered a hotspot of global warming [5,6], with studies highlighting how this part of the world will probably experience the most predominant drying trend worldwide [7,8]. Generally, climate trend studies predicted a further drying scenario, with decreasing rainfall and increasing average temperatures. On the other hand, studies focused on meteorological data gave a more complex view of the phenomenon [9–11]. Indeed, some works highlighted increasing rainfall trends in the Mediterranean areas with a climate which seems to switch to wetter conditions [9,12]. Such controversial statements could be explained by a change in the rainfall distribution linked to a seasonal shift and variation in sea surface temperature [13,14]. The key aspect of climate change in this zone is, in fact, not the decreasing amount of precipitation but the fact that rainfall is becoming more and more concentrated in shorter periods, alternating with longer dry periods [15,16]. This means that even in a very wet year, there could be long intervals of droughts, which will deplete water and food stocks, threatening the stability of food systems [17]. These droughts could alternate with concentrated rainy events that can cause floods, which may accentuate human vulnerability and intensify land degradation processes [17].

It is estimated that 12% of the world's arable land could be waterlogged frequently, leading to approximately a 20% crop yield reduction [18,19]. Soil waterlogging is predicted to become an increasingly widespread phenomenon in frequency and magnitude [1].

Considering the situation described, the future projections foresee the need to apply new water management systems along the entire chain of capitation and distribution in agriculture. In fact, to make agriculture resilient, the sustainable use and supply of water could be achieved [15,20], but also new sources of fresh water and storage systems could be identified.

Water from rainy events, when opportunely conveyed and treated, can represent a precious source of freshwater [21], which would otherwise be lost if properly stored. A storage possibility is offered by rainwater harvesting (RWH), which is a technique used to accumulate rain on different structures, such as cisterns and tanks, and to use it for further purposes [22].

As reported by current literature, RWH represents a valid system to improve the agricultural water management system at the farm level [23,24] since it can reduce stormwater runoff by collecting water and increase crop yield through irrigation [23–26]. On the other hand, several studies in water harvesting have documented the critical role of ponds and pans, check dams, terracing, and percolation tanks [27–30]. In fact, traditional RWH systems still show some concerns, such as land consumption, high evaporation in hot climates, and the possibility of accidents for both people and animals looking for water in dry periods.

However, different water harvesting structures have their particularities and purposes but require specific stational conditions [31]. For example, check dams have been well recognized in China and India for alleviating the problem of water scarcity and preventing floods [32–34]. Nevertheless, check dams are only suitable in catchment areas of around 25 ha, and agricultural ponds are available only for small flat areas with slopes close to 5% [27,33]. Identifying the optimal system, design, and position for water storage facilities is the key step to maximizing the water collected and crop production, especially under climatic uncertainty and in areas with complex topographic conditions.

For this reason, a mobile and modular system could facilitate the design phases, allowing it to be adapted to different agricultural management [23,24]. Considering what is written above, an interesting alternative solution for RWH consists of the Flexible Water Storage System (FWSS). FWSS is a solution designed to face the major drawbacks of typical RWH systems. This system indeed does not require land consumption, and it can be easily folded and moved elsewhere according to the farmer's need. Contrary to the pond, water is not directly exposed to sunlight; thus, evaporation and microbial activities are not promoted, and higher water quality is expected.

Notwithstanding these very interesting features, FWSS is still not widely applied, and there is a lack of scientific evidence which is able to evaluate the overall sustainability of this storing and irrigation systems. Relying on such an innovative system could indeed be an interesting approach to tackle the issue of climate change and seasonal shifts, reducing the water runoff derived from rainfall events and storing it in a flexible system to be used during drought periods.

Despite this, only a few studies dealt with such a topic, mainly from the environmental and economic perspectives without offering new insights into its utilization in farm management and the opportunities derived from its application [23,24].

Considering what is written above, there is a need to investigate such a topic with specific field tests in order to fill the knowledge gap that still exists. The aim of the present work is to provide the literature with significant information on the application of an FWSS system for water management at the farm level. The objectives of this study were (i) to quantify the freshwater collectible from a ditch by using an FWSS system for a three-year experiment and (ii) to evaluate the possibility of using this water as supplementary irrigation to cultivate an irrigated crop.

2. Materials and Methods

2.1. Study Area

This research was conducted at the experimental farm of CREA-IT (Council for Agricultural Research and Economics—Research Centre for Engineering and Agro-Food Processing) in Monterotondo (Rome, Italy—WGS84-UTM33T 42°06′09″ N 12°37′43″ E 23 m a.s.l.). The farm has a total extension of about 4.3 ha, consisting mainly of arable land and woody crops for biomass production. The agricultural area is 3.8 ha, and the remaining parts are streets and a railway line. The ditch objective of this study is 1.5 m width and 1 m depth, and it starts from the railway and goes along the street connecting the cultivated fields with a local water stream for a total length of 945 m (Figure 1). The agricultural area is not irrigated, so the ditch has the only function to collect the surface and sub-surface water runoff to avoid waterlogging and drain the surrounding fields. In case of overflow, the agricultural management (e.g., mechanical operations) and crop development and yield of the adjacent fields are affected.

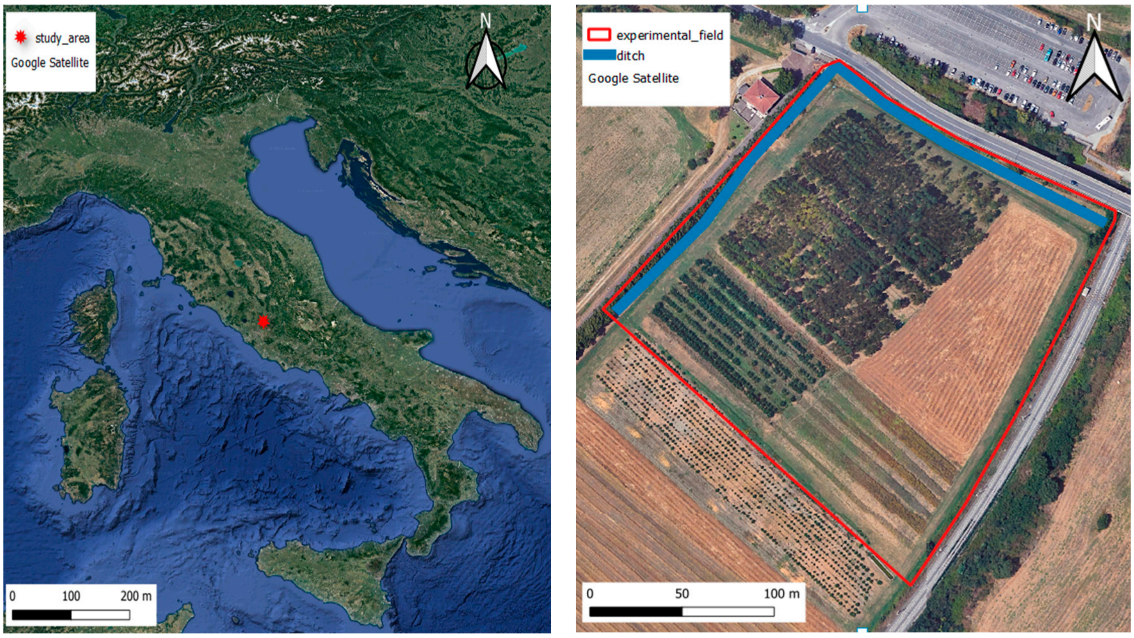


Figure 1. Satellite image of the area at different scales.

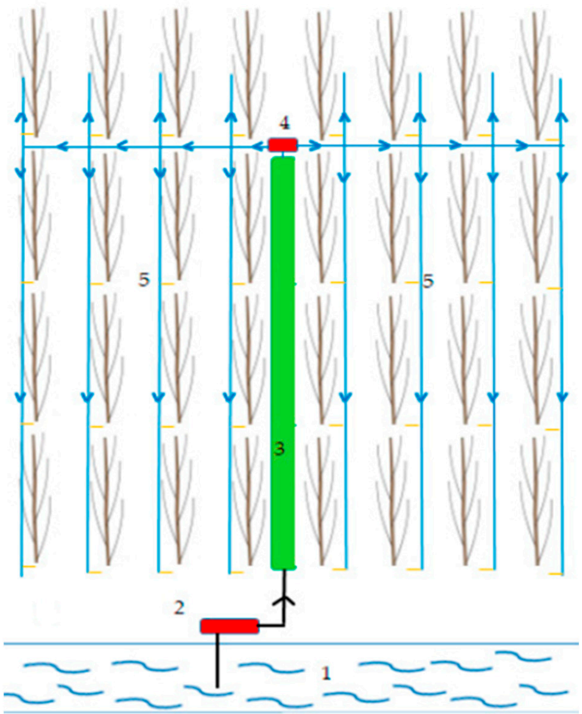
The agricultural context is typical of Mediterranean climate; it is mostly flat, and mainly cereals and oilseed crops are cultivated under rainfed conditions. The most spread perennial crop is olive tree (*Olea europaea* L.), and in some cases, poplar (*Populus* L.) plantation is dedicated to bioenergy production.

2.2. Meteorological Data

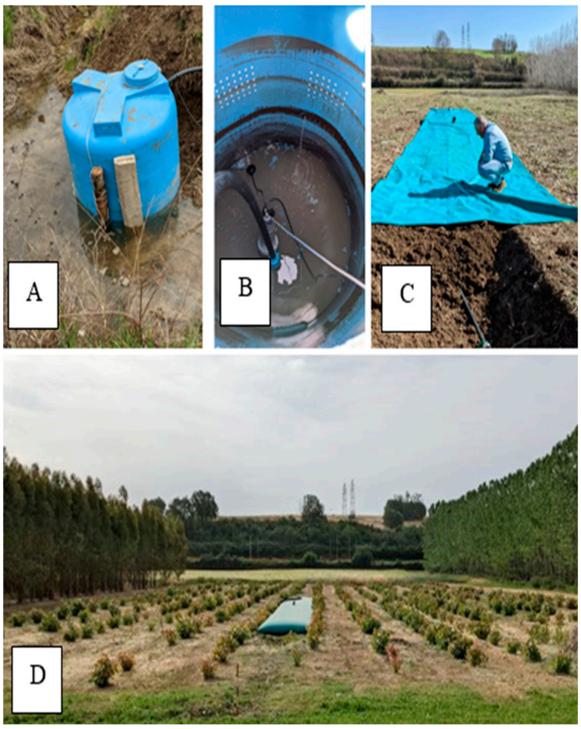
Weather data were acquired with a station Davis Vantage Pro2™ 6152 that includes the Integrated Sensor Suite (ISS), which houses and manages the external sensor array, and the console, which provides the user interface, data display, and calculations. There is a weather link that lets the weather station interface log weather data and upload weather information to the internet with a computer (Rate F.A. Wireless Vantage Pro2TM & Vantage Pro2TM Plus Stations). The device is located in the study area, and although it allows the acquisition of much more data (wind direction, relative humidity, solar radiation), this study focused only on the data acquired regarding rainfall and temperatures of the last 3 years.

2.3. Flexible Water Storage System (FWSS)

The Flexible Water Storage System (FWSS) is a rainwater harvesting system (RWHS) that is made of polyvinyl chloride (PVC). The FWSS measures 3 m wide and 23 m long and is capable of storing 50 m^3 of water. System loading is carried out via an electric water pump that automatically pumps the water through a filter from a ditch when the water level in the seasonal stream increases, as it happens after an extreme rainfall, directly into the FWSS. The water extraction system was installed in the lowest elevation point of the ditch, in a natural soil depression. The system can pump 42 liters per minute, and a special valve regulates the flux in just one direction to prevent accidental emptying. Moreover, an automatic liter counter was installed on the extraction pump to monitor the quantity of water extracted. When the FWSS reaches its maximum capacity, the blow-off valve opens, preventing overpressure. The water can be stored and used during the dry season without leaking water or smells. The FWSS is equipped with inlet and outlet pipe connections, which allows, if necessary, for the expansion of the capacity by adding other devices. CREA-IT has an agroforestry plantation consisting of Medium Rotation Forestry (MRF) of poplar for bioenergy production, which was used as a storage site for the FWSS. Despite being mobile, the system was positioned in December 2019 in the inter-row of the MRF poplar plantation, thus reducing the movements of the system and not taking up cultivable surfaces. Figure 2 shows the diagram and the photo scheme of the FWSS prototype.



(**a**)



(**b**)

Figure 2. (**a**) Schematic view of the FWSS. Numbers refer to the main components of both systems: (1) ditch and seasonal water stream, (2) loading system (including electric pump, pipes, and connections), (3) water storage system, (4) electric pump for water delivery, (5) water usage (e.g., irrigation system). (**b**) (A) Detail of the water extraction point; (B) automated extraction pump; (C) newly installed FWSS front view; (D) FWSS partially full.

Starting from January 2020, every first day of the month, the quantity of water extracted from the ditch was quantified by recording the value registered by liter counter installed on the extraction pump. At the end of each year, the liter counter was reset, and the annual amount of water collected was calculated. The annual average of water extracted after three years of experiment was used to estimate the available additional water for irrigation of an irrigated agricultural area of 1 ha adjacent to the FWSS system.

3. Results and Discussion

Data acquired regarding rainfall and temperatures over the last 3 years are depicted in Figure 3, while Table 1 describes the rain distribution over the study period.

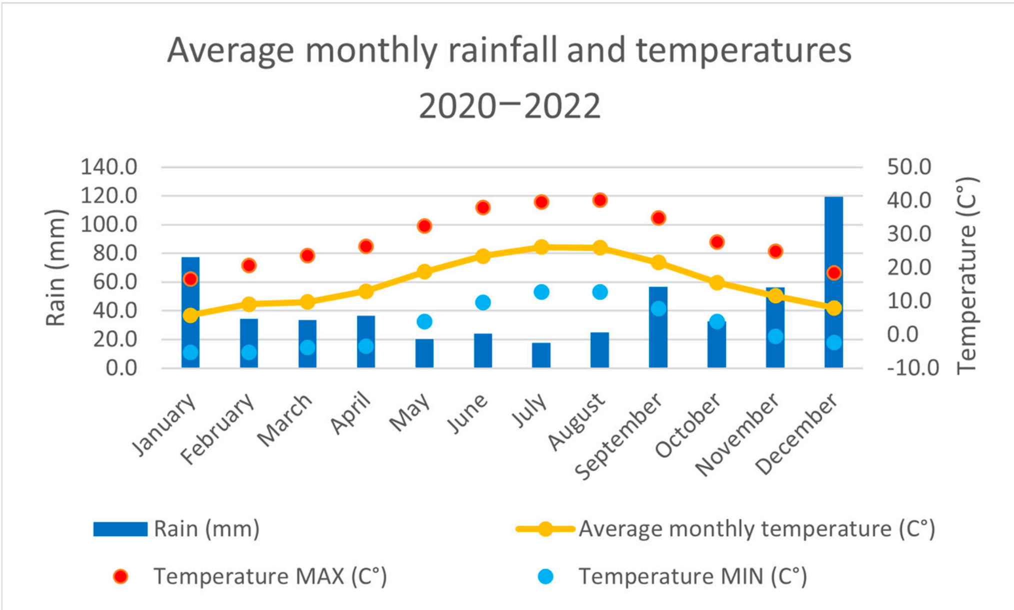


Figure 3. Average monthly rainfall and temperatures of the area during the study period.

Table 1. Rain distribution in the area during the study period.

Year	January	February	March	April	May	June	July	August	September	October	November	December	Tot
Rain (mm) 2020	14.8	20	26	25.4	21.4	22.6	1.6	55	69.6	79.4	59.2	186.6	581.6
Rain (mm) 2021	195.6	54.6	47.2	58.6	14.4	25.4	5.4	1.2	0.6	1.4	10.8	47.5	462.7
Rain (mm) 2022	21.8	28.6	27.8	27.4	22.4	24.4	46.2	19.2	98	17.2	99.4	123.7	556.1

In this area, the rainfall is distributed on average over 90 rainy days, with a very pronounced peak in autumn and a minimum in summer. The average temperature in the coldest month (January) is 7.7 °C, while in the warmest month (July, August) is 25.6 °C.

In the last three years (Table 1), the average annual rainfall was 533.5 mm. The rainiest year was 2020 (581.6 mm), while the dryest year was 2021 (462.7 mm). The monthly average rainfall in the last three years was 44.5 mm, but in the period of September–April, it is recorded as 85% of the annual rainfall. So, from May to August, the monthly rainfall was 21.6 mm, while from September to April, it was 55.6 mm. With such rain distribution, the only possibility for farmers is cultivating non-irrigated crops according to rainfed agricultural management. Furthermore, this situation creates a double problem: a water shortage in late spring and summer and water excess in autumn and winter.

During this three-year experiment, it was possible to collect (Table 2) an annual average of 831.7 m^3 of water with the FWSS installed. The capacity of the system is only 50 m^3, so the water collected is represented by the water extracted by the ditch, quantified by the automatic liter counter, stored in the FWSS, and reintroduced in the ditch from the blow-off valve. The water potentially collected from the system could have a double function: (1) mitigate the excess of water in the ditch that can potentially cause flooding and (2) provide irrigation water for the crops during dry periods. In fact, the challenge of growing intense rainfall is paralleled by the increasing prolonged drought [35]. It is important to emphasize that the use of water storage alone cannot be sufficient to solve the problem of the impacts of opposing climate extremes (such as intense rainfall and drought) in 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.

Table 2. Amount of water collected by using the FWSS systems installed.

Year	Amount of Water Collected (m^3)
2020	907
2021	721
2022	867

The water collected by the FWSS system studied, besides mitigating the excess of water in the ditch, could be utilized to irrigate a cash crop in late spring and summer when rainfall is reduced in the study area. The annual average of 831.7 m^3 of water that is potentially collectible in the study area corresponds to 83.17 mm of rainwater in the area of 1 ha, which is 15% of the total rain amount.

If this additional water resource was distributed only in the period of April–September, it would amount to 13.9 mm, which is equivalent to 31% of the recorded monthly rainfall in the study period (i.e., 44.5 mm). From the FWSS, the water could be distributed through low-pressure irrigation systems like drip irrigation.

Based on the study of Akangle Panme F. et al. (2022) and Akkamis M. et al. (2023), the water requirements of potatoes (Solanum tuberosum) are about 260 mm and 261 mm, respectively [36,37]. Potatoes are a very spread crop, with an annual surface crop of about 46,000 ha in Italy and 4,500,000 ha in Europe in the last three years [38]. In the study area, potatoes are the most spread crop cultivated in the spring–summer period (April–September). According to the meteorological data acquired, the precipitation in the growing period of potatoes was 179.9 mm on average over the three years. By using only rainwater, it would not be possible to cultivate potatoes, but if the water collected by the FWHS were used as supplementary irrigation, it would reach a quantity of 263 mm of water during the growing period, allowing cultivation as reported by previous studies.

The results highlighted that by collecting supplementary water from rain that is stored in an FWHS system, allowing its distribution only when required by the crop, it is possible to find new opportunities for enhancing agricultural resilience. New crops to be cultivated or incorporated into the existing rotation and new opportunities to increase farmer income could be identified.

4. Conclusions

In recent years, the rainfall pattern has changed in quantity and frequency. Considering this scenario, farmers face problems related to prolonged dry periods alternating with excess precipitation with consequent floodings and water logging. Among water harvesting systems, the FWSS has not been properly studied to date. The findings of other studies showed that the system performed better in both environmental and economic aspects with respect to other traditional water harvesting techniques (i.e., ponds). Nevertheless, a real case study was still missing [23].

Preliminary data obtained in the framework of a long-term study highlighted the suitability of the system installed to mitigate the excess water in the ditch that can potentially cause flooding and collect supplementary water to provide irrigation for the crops during dry periods.

Furthermore, the system studied allowed for the collection of water that is not subjected to leak, smell, or evaporate as in the case of traditional water harvesting techniques. Collected water, beyond being properly stored, could be used according to crop requirements with specific irrigation systems.

The FWSS studied is equipped with inlet and outlet pipe connections, which allows, if necessary, for the expansion of the capacity by adding other devices. In fact, during the study period, the amount of water collected was 16 times higher than the storage capacity of the FWSS and was reintroduced in the ditch. This specific design and its mobility make the FWSS adapt to every condition.

After this preliminary study, the results will be capitalized to add other devices to collect all the water potentially storable in the area, even rainwater from the lowly loaded traffic streets of farms, set up a comparative study between rainfed crops and irrigated crops (by using FWSS system), and investigate the environmental impact of the Flexible Water Storage System through life cycle analysis (LCA) and life cycle costing (LCC) methodology. The long-term effectiveness of the systems will be evaluated based on the modeling of data acquired and identify new crops to be cultivated in the area as alternatives to potatoes.

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