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Effect of reservoir tillage on rainwater harvesting and soil erosion control under a developed rainfall simulator

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ABSTRACT

Soil erosion is a serious environmental threat in the Mediterranean region due to torrential rainfalls, and it contributes to the degradation of agricultural land. Techniques such as rainwater harvesting may improve soil water storage and increase agricultural productivity, which could result in more effective land usage. Reservoir tillage is an effective system of harvesting rainwater, but it has not been scientifically evaluated like other tillage systems. Its suitability for the conditions in Spain has not been determined. To investigate and quantify water storage from reservoir tillage and how it could be adapted to improve infiltration of harvested rainwater, a laboratory-scale rainfall simulator was developed. Rainfall characteristics, including rainfall intensity, spatial uniformity and raindrop size, confirm that natural rainfall conditions are simulated with sufficient accuracy. The simulator was auto-controlled by a solenoid valve and three pressure nozzles were used to spray water corresponding to five rainfall intensities ranging from 36 to 112 mm h^{-1} for 3 to 101-year return period with uniformity coefficients between 83 and 94%. In order to assess the reservoir tillage method under surface slopes of 0, 5, and 10%, three soil scooping devices with identical volume were used to make depressions in the following forms: a) truncated square pyramid, b) triangular prism, and c) truncated cone. These depressions were compared to a control soil surface with no depression. For the loam soil used in this study, results show that reservoir tillage was able to reduce soil erosion and surface runoff and significantly increase infiltration. There was significant difference between the depressions and the control. Compared to the control, depression (a) reduced surface runoff by about 61% and the sediment yield concentration by about 79%.

1. Introduction

Soil erosion is a major environmental threat in the Mediterranean region due to torrential rainfalls and the arid and semi-arid conditions, and it contributes to the degradation of agricultural land (Cerdà, 2002; Cerdà et al., 2009; Jordán et al., 2010; Lal, 1999). Rainwater harvesting has the potential to reduce soil erosion and improve the productivity of these areas. Rainwater harvesting is a general term used to describe the collection and concentration of runoff for many uses, including agricultural and domestic use (FAO, 1993; Oweis and Hachum, 2006). The rainwater harvesting strategy is based on discontinuities. And those discontinuities are found in nature (stones, plants, microtopography) (Kakembo et al., 2013).

"In situ" systems are the simplest and cheapest rainwater harvesting approaches and can be practiced in many farming systems. Also called soil and water conservation systems, they involve the use of methods to increase the amount of water stored in the soil profile by trapping or holding the rain where it falls (Brhane et al., 2006; Fleskens et al., 2005; Stott et al., 2001). Soil water conservation is main concern in semiarid land, and this is why harvesting rainwater is so important (Gao et al., 2013). Rainwater harvesting is being also, used by the plants and stones under natural conditions (Cerdà, 1997a,b, 2001). It may be close to the definition of micro-catchments techniques, but in any case, it becomes an alternative in arid and semi-arid regions, where precipitation is low or infrequent during the dry season, and there is a need to store the maximum amount of rainwater during the wet season for use at a later time.

Another concept related to "in situ" rainwater harvesting that involves different techniques is known as "Reservoir Tillage." This approach was developed under the consideration that tillage can provide increased levels of surface storage, and it may represent one of the most effective means of controlling both runoff and soil erosion. Reservoir tillage creates basins or pits to hold water in place, allowing it to

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infiltrate the soil and thus preventing runoff (Hackwell et al., 1991; Rochester et al., 1994). Soil bunds are a similar technique to reduce the connectivity of the runoff (Adimassu et al., 2013). Reservoir tillage has been defined by Patrick et al. (2007) as a system in which numerous small surface depressions are formed to hold and collect water during irrigation or rainfall to prevent surface runoff. Currently, reservoir tillage is used predominantly for soil erosion control in environments with high annual, but low intensity rainfall, such as semi-arid environments. This method has the potential to benefit semi-arid environments compared to other direct water harvesting methods, such as ridge and furrow (Kronen, 1994), because the large infiltration surface area created by the depressions and the small depth of ponded water in the shallow depressions are likely to result in higher infiltration rates and therefore less surface runoff and evaporative loss (Mrabet, 2002; Patrick et al., 2007). This is due to the fact that, when rainfall tillage is used, rainfall collects in the mini-reservoirs, allowing more time for infiltration, which in turn reduces runoff and its potential to detach and transport soil particles (Ventura et al., 2005).

For any given soil conditions, the volume of water harvested by a depression depends on the volume of the depression and its depth, which determines the maximum head of water in the depression. The volume of water further depends on the slope, which influences the reservoir capacity. Therefore, reservoir tillage under conditions of high evaporation rates and high-intensity rainfall should be adapted to maximize the volume of runoff collected without impeding water infiltration through compaction during the creation of the depressions, either by wheel traffic or by the implement itself. Patrick (2005) conducted a similar work on reservoir tillage. The project was carried out through modeling and experiments under soil bin, rainfall simulator and glasshouse environmental conditions, and the author reported that the reservoir tillage reduced surface runoff by 54% and 91% when the depressions were positioned along and across the slopes, respectively.

Rainfall simulation is an experimental method widely used to determine the relative erodibility of different soil materials and other hydrological model parameters, as well as to quantify the influence of different soil management systems, such as conservation tillage, on infiltration and runoff generation (Niebes et al., 2001). Rainfall simulators are research tools designed to apply water in a form similar to natural rainstorms. simulators permit a rapid collection of reproducible data in laboratory and field experiments (Aksoy et al., 2012; Esteves et al., 2000; Miller, 1987) and are widely used in semiarid environments where rainfall is low and soil erosion is a low frequency–high magnitude process that needs accurate measurements (Cerdà, 1999a,b).

Desirable characteristics for rainfall simulators used in erosion and hydrological studies include the rainfall intensity, spatial rainfall uniformity over the entire test plot, the drop size, its distribution and terminal velocity. Other important factors include the accurate control of rainfall intensity, the similarity to natural rainfall in terms of kinetic energy, the repeatability of the simulated rainstorms, and the improved mechanical and technical reliability for simple and easy transportation within research areas (Abudi et al., 2012; Cerdà, 1999a; Clarke and Walsh, 2007; Humphry et al., 2002; Lascano et al., 1997; Munster et al., 2006).

The main objectives of this work were: (i) to research, understand and quantify water storage from reservoir tillage and how it could be adapted to improve infiltration of harvested water for use in semi-arid environments; (ii) to determine the relationship between surface slope and water harvesting reservoir capacity; and (iii) to assess the rainwater harvesting effectiveness of different depression geometric forms under different soil slopes and different rainfall intensities.

With the aim and objectives stated for this study, specific hypotheses will be tested. Those hypotheses are: (1) to develop a laboratory-scale rainfall simulator to compare rainwater harvesting capacity, runoff and soil losses under variable rainfall intensities, (2) to achieve desirable characteristics for a rainfall simulator, include the rainfall intensity, spatial rainfall uniformity over the entire test plot, and the drop size in a form similar to natural rainstorms.

2. Materials and methods

2.1. Rainfall simulator design

A reliable, accurate rainfall simulator was needed for soil erosion studies on agricultural land. A laboratory-scale rainfall simulator was developed to compare rainwater harvesting capacity, runoff and soil losses under variable rainfall intensities. This is a tool that has been widely used for more than 50 years to evaluate hydrological parameters such as infiltration, runoff, and sediment yield because of its low cost and easy operation. It also permits data to be obtained under controlled conditions within relatively short time periods, and the results of rainfall simulation tests can be used for comparative purposes in erosion studies (Foster et al., 2000; Navas et al., 1990).

Precipitation data from the Madrid weather station (40° 24′ 43″ N lat.; 3° 40′ 41″ W long., 667 masl) were used to calibrate the rainfall simulation tests. A set of records from the 50-year time period between 1962 and 2011 was analyzed to calculate rainfall intensity. Maximum annual precipitations recorded during 30 min were converted into mm h^{-1}. According to Arnaéz et al. (2007), the data prediction was performed with a regression equation. The recurrence intervals and the exceedance probability for available data were derived according to (Blom, 1958).

The designed rainfall simulator has been settled on an A-frame steel structure of 35 mm of diameter. The legs are telescopic, which allow the height to be increased or decreased so as to keep the simulator leveled when placed on a slope for outdoor experiments. Three different axial flow full cone nozzles, Lechler (468.528.30 and 468.808.30) with spread angle of 120° and Lechler (468.726.30) with spread angle of 90° were selected for different rainfall intensities between 33 and 121 mm h^{-1}. These nozzles were fitted to a 20 mm steel pipe at the top of the structure at a height of 2.3 m with a triplet nozzle holder that eased the switching between different nozzles. This height is adequate for creating terminal velocities similar to natural rainfall for all drop sizes above the soil surface. The flow rate was auto-controlled by a solenoid valve (Bermad, 0.7–10 bar, ISO: PN 10, and 24 V AC), and the pressure was monitored by two glycerin manometers. RS pressure transmitter (348–8188) 4–20 mA analog output, and pressure regulator installed in the supplying pipe of the simulator.

A National Instruments LabVIEW® programming tool was used for building an application that consists of a customized user interface, a display interface for pressure monitoring and an on/off valve. The block diagram contains a graphical representation of the code consisting of functions to read from inputs, write to outputs and make calculations and decisions. The inputs and outputs (pressure transmitter and solenoid valve) were connected to a Data Acquisition Board (DAQB; National Instruments 6008 USB). The front panel is the user interface, which has controls for selecting the time flow and monitoring the pressure.

2.2. Rainfall simulator calibration

2.2.1. Spatial rainfall distribution

An experiment was carried out on the rainfall produced by the rainfall simulator in order to characterize its spatial rainfall distribution. The experiment aimed to get information about the homogeneity or heterogeneity of the rainfall and to determine the maximum area at which a homogeneous distribution of rainfall could be obtained. Twenty rain gauges (82 mm diameter) were placed on a 60 cm × 80 cm by 20 cm × 20 cm grid. Rain was collected in the gauges for 10 min of continuous flow from the simulator, and the volumes in each gauge were measured using a graduated cylinder in (ml) and then converted into intensity values (mm h^{-1}). The Coefficient of Variation (CV) and the