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A portable integrated rainfall and overland flow simulator

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Abstract

This paper describes a prototype of a portable rainfall simulator that can simulate a wide range of rainfall intensities with a kinetic energy similar to that of natural rainfall and, more innovatively, provide simultaneous or independent simulations of rainfall and overland flow at the microplot scale (0.70 m^2). The design of the rotating shutter disc makes possible a wide range of rainfall intensities, from 30 to 155 mm/h without changing nozzle type or working pressure. Overland flow intensity can be adjusted from 94 to 573 mm/h depending on nozzle type and working pressure. The flow is applied on the upper side of the experimental plot. The Christiansen coefficient of uniformity of the simulated rainfall varied between 81.4 and 85.1%, and the calculated kinetic energy was >90% the kinetic energy of corresponding natural rain. Special attention was paid to portability. Stainless steel was used whenever possible and the equipment was constructed in modules so that it could easily be dismantled and carried by two people. A telescopic-type frame allows operation on sloping ground.

Keywords: Rainfall simulator, overland flow, infiltration, erosion

Introduction

Rainfall simulators are used in studies ranging from determination of soil characteristics, such as water infiltration rate or surface storage, to specific erosion processes. They are especially valuable in studies aimed at characterizing the effect of different soil management types on soil properties (e.g. Gómez *et al.*, 1999) or at calibrating hydrological and erosion models (e.g. Connolly *et al.*, 1991). There are several reasons to use simulated rainfall. One is that it reduces the time and costs required for experimentation as experiments based on natural rainfall require a long period of monitoring. In addition, simulated rainfall allows better control of the experimental conditions and the possibility of repeating experiments under identical conditions, something which is not possible with natural rainfall.

There are several published reviews on rainfall simulators that cover in detail their evolution since the 1930s and their different designs (Peterson & Bubenzer, 1986; Cerdà, 1999). Several key parameters need to be considered in their design, e.g. impact velocity, drop size distribution and rainfall intensity, and these should be chosen depending on the aim of the study. Ideally, the rainfall simulator should be able to reproduce the average drop diameter, terminal drop velocity and the kinetic energy of natural rainfall. It is also important to simulate a wide range of intensities while maintaining the characteristics of the rainfall and its uniformity of application. The final design of a rainfall simulator is a compromise between these requirements, portability and ease of use in the field. The more important limitations are the restricted area over which rainfall can be simulated, the inability to completely match the characteristics of natural rainfall events, and the logistical difficulties of carrying out the simulations when and where necessary. These are some of the reasons that highlight the need for complementary studies using simulated and natural rainfall.

The use of rainfall simulators is necessarily limited to small working areas. Approximately 50% of the 229 simulators described by Cerdà (1999) simulate rainfall over areas <1.5 m^2. Rainfall simulations on areas of 0.75–1.5 m^2 have been used to study soil properties, surface sealing and interrill and splash erosion (Farres, 1987; Connolly *et al.*, 1991; Mohanty & Singh, 1996; Morin & Van Winkel, 1996; Gómez *et al.*, 1999). However, these simulators cannot be used for studying processes that are scale dependent, e.g. rill erosion as they require larger areas (e.g. Gómez & Nearing, 2005). Another shortcoming is the impossibility of achieving large overland flow depth and shear stress as required in studies of pesticide transport or detachment transport of soil mulch. For these types of studies, an overland flow simulator such as the one described by Wolfe *et al.* (2000) is required. We

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are not aware of any design that combines rainfall and overland flow simulation using a single unit on the same soil surface.

Regulation of rainfall intensity and kinetic energy in portable rainfall simulators can be achieved in different ways. In drop-forming-type simulators, rainfall intensity and drop size may be adjusted using an air stream without the need of changing the capillary tubes (Radke, 1995). In nozzle-type simulators, a common option is to maintain the nozzle type and working pressure, thus maintaining the kinetic energy of the rainfall while modifying rainfall intensity and reducing spray time. This can be achieved by using a rotating disk (Morin *et al*., 1967; Connolly *et al*., 1991), an oscillating nozzle (Hirschi *et al*., 1990) or a solenoid valve (Zegelin & White, 1982). Alves Sobrinho *et al*. (2002) developed a portable rainfall simulator, *InfiAsper*, based on the evolution of the rotating disk (Morin *et al*., 1967) to produce precipitation whose characteristics, drop diameter and impact velocity and kinetic energy were similar to those of natural rainfall. The main advantage of *InfiAsper* is the possibility of changing rainfall intensity without changing the pressure in the nozzles, and hence maintaining drop diameter and uniformity of application. Its main disadvantage is that the heavy mechanical control that regulates the rainfall intensity makes the equipment too heavy for easy transportation. This paper describes an evolution of the *InfiAsper* rainfall simulator, called *InfiAsper2*, whose main improvements are the replacement of the mechanical controls by an electronic one; a new adjustable rotating disk that is lighter and easier to adjust; and the integration of an overland flow module based on Wolfe *et al*. (2000). The objective of these modifications was to develop a fully portable simulator of rainfall, overland flow or both, that could be used in steep and rugged terrain with minimum staff.

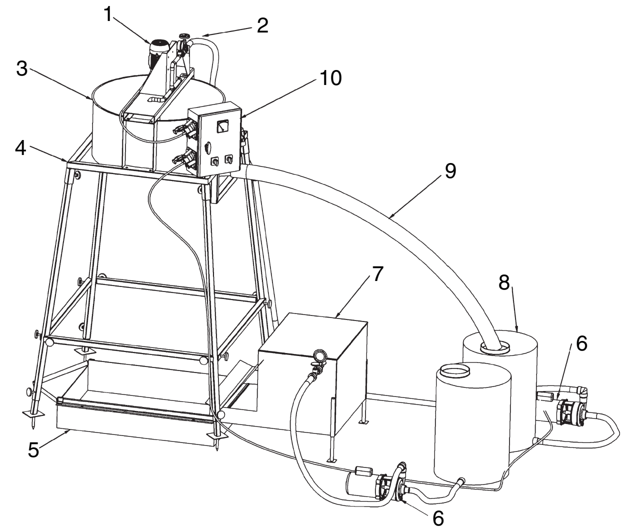

Figure 1 General view of *InfiAsper2*, integrated rainfall and overland flow simulator: (1) motor; (2) water application; (3) blocking device; (4) upper frame; (5) run-off collector; (6) water pump; (7) overland flow module; (8) tank; (9) excess water; (10) electric panel control.

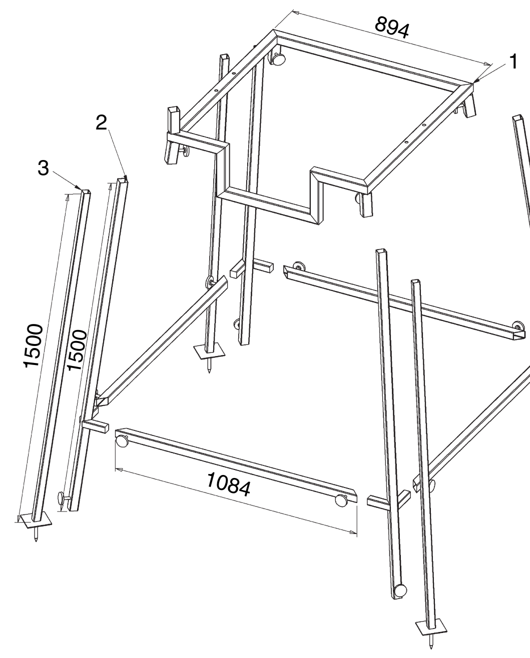

Figure 2 Framework unit: (1) upper frame; (2) lower frame; and (3) telescopic system. Units in mm.

Design and construction

Rainfall simulator

Figure 1 shows a general view of *InfiAsper2*. In the development of the prototype, special emphasis was given to increasing portability over distances of a few hundreds of metres assuming a field team of two. The rainfall simulator was constructed in five independent modules with a total mass of 132.5 kg. This facilitates transport and operation in the field as well as maintenance. The five modules are: (i) the framework, 33.9 kg; (ii) the water application unit, 71 kg; (iii) the electric system unit, 4.7 kg; (iv) the water pumping units, 4.2 kg; and (v) the run-off collector unit, 18.7 kg.

Framework. The framework unit is composed of welded iron frames made of steel square tubes (30 × 30 or 35 × 35 mm sections and 1.75 mm thickness) that can be easily assembled and disassembled (Figure 2). The height of each leg can be independently adjusted to level the water application unit placed in the upper part of the framework while allowing its use on steep or rugged terrain. The framework is designed for setting the nozzles 2.3 m above the ground. The framework may be covered with a canvas to protect the working area from the wind to ensure a uniform distribution of simulated rainfall.

Water application unit. The main components of the water application unit are a blocking device to intercept the water, two discs and their supporting structure, the water application device and a motor (Figure 3). The water application device consists of two nozzles, a copper pipe of 22-mm diameter, a manual valve and a water pressure gauge (Figure 4a). The excess water is captured by the blocking device (Figure 4b) and transferred back to the tank by gravity. After evaluating several nozzle types for drop size at different working pressures, the Veejet series models 80.100 and 80.150 (Spraying Systems Co.®) were used. The first model produces drops with an average diameter (D_{50}) of 1.8 mm at a working pressure of 32.7 kPa, whereas the second model produces drops of 2 mm D_{50} at a working pressure of 36.5 kPa. After evaluating the water profile distribution of individual nozzles of the selected models, several combinations of spacing between two nozzles and height of application were evaluated in terms of uniformity of application over the experimental plot area. Two nozzles separated by 0.4 m and set at 2.3 m relative to the soil achieved satisfactory rainfall uniformity in an area of 0.70 m^2 (0.7 m × 1 m). The achieved uniformity was similar to that obtained with similar designs of rainfall simulators (Morin *et al.*, 1967), measured by the Christiansen coefficient of uniformity (CUC) (Christiansen, 1942).

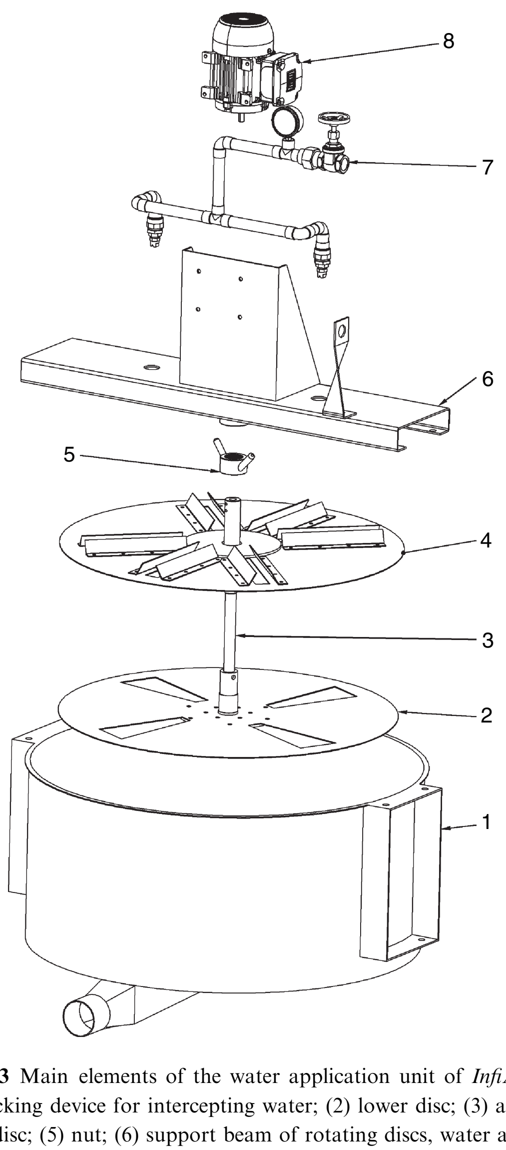

Figure 3 Main elements of the water application unit of *InfiAsper2*. (1) blocking device for intercepting water; (2) lower disc; (3) axle; (4) upper disc; (5) nut; (6) support beam of rotating discs, water application system and motor; (7) water application unit; and (8) motor.

One of the main changes in *InfiAsper2* compared with its original model (Alves Sobrinho *et al.*, 2002) is the rotating disk and its transmission mechanism. The new system significantly reduces the weight and makes construction easier. The new rotating disc is made up of two individual stainless steel discs 1.5 mm thick and 690 mm in diameter (Figure 5). The two discs have a different number of openings: the upper one has six openings, whereas the lower one has four. By varying the position of the discs, it is possible to have either two or four openings which can be fully or partially opened. Once a position is decided, the discs are fixed to the central axle with a single nut.

The water sprayed by the nozzles is interrupted by the rotating disk which reduces and regulates rainfall intensity while providing a constant rainfall with minimum variation of this intensity. The rotating disk largely determines rainfall intensity. In the previous *InfiAsper*, the regulation of the rotation of the disk (80 rpm) was made through a heavy gear train. In *InfiAsper2*, this mechanism is replaced by a frequency converter to regulate the rotation of the disk, and the power transmission is now carried out directly with a vertical axle.

Electrical system. It has a control panel which includes the frequency inverter, a rotating-control rheostat and two on–off switches for the motor and water pump. The frequency inverter must have a nominal power of 372 W, supplied by single-phase current of 200–240 V and frequency between 0 and 300 Hz. A portable generator with nominal power of 6 kW and 220 V produces enough energy for the electric motors that drive the shutter and the water pumps.

Water pump. This consists of a 372-W electrical water pump with 100-L tanks and aspiration and supply hoses. The number of required water tanks will depend on the required rainfall intensity and the duration of the simulations. The generator powers the rotating disk and the pump.

Run-off collector. This defines the experimental plot and collects the run-off. It is constructed using 2-mm-thick

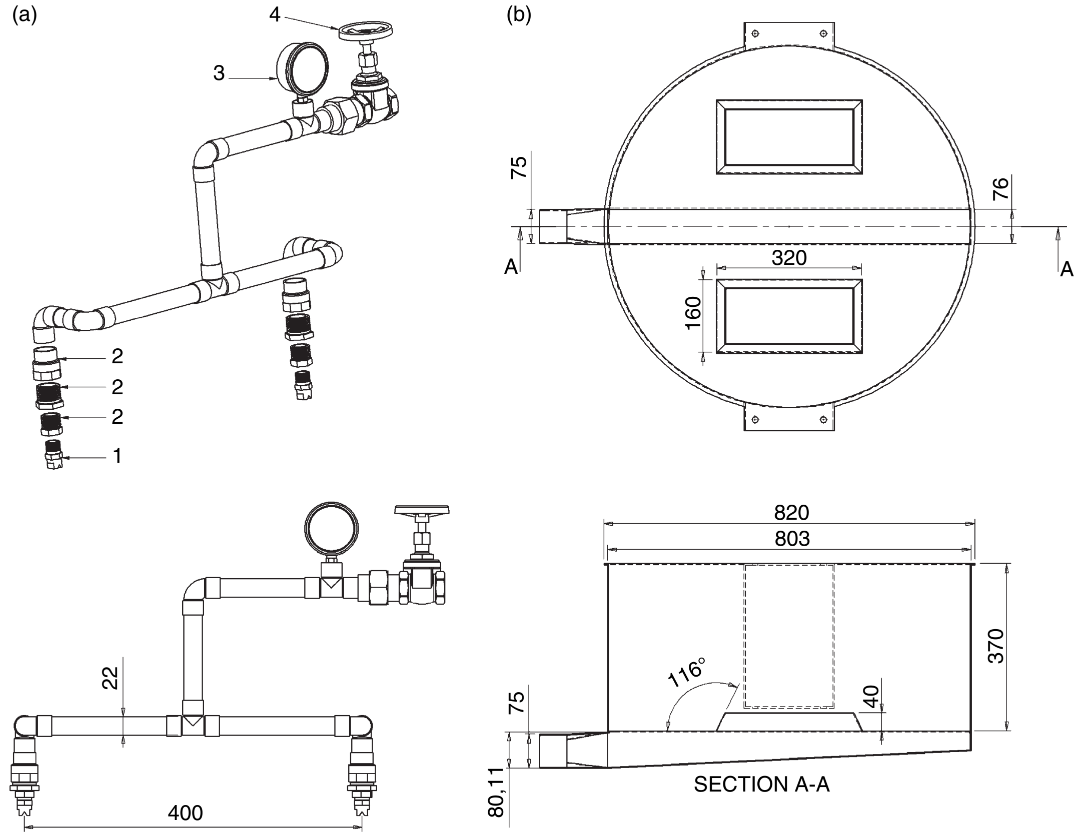

Figure 4 (a) Details of the water application unit: (1) nozzles Veejet; (2) connections; (3) water pressure gauge; (4) manual valve and (b) blocking device for intercepting water. Units in mm.

galvanized iron sheets forming a square frame of 0.7 m × 1 m and 0.16 m in height (Figures 1 and 6). The down-slope side has a triangular form that directs the water to a collecting point. A small hole on the ground must be dug under this point so that water and sediment can be collected and measured. In the usual mode of operation, the rainfall simulator is placed on top of the area of interest and the run-off collector is then pushed gently into the soil up to 0.12 m deep.

Overland flow applicator. It was constructed in galvanized iron. Figure 6a shows its main components: side frames and covers, support legs with levelling screws and a water supply system with a total mass of 34.1 kg. The water supply system includes an independent electric water pump of 740 W, aspiration and supply hoses, four TeeJet nozzles, a manual valve and a water pressure gauge. The hoses are connected to a 100-L tank. The overland flow projector has a bend radius of 0.34 m and ends in a hydraulic jump that ensures homogeneous depth of water flowing along the upper side of the plot.

The simulator can be operated in rainfall-only mode, overland flow or combined mode with each applicator working with its own independent pump (Figure 1). The applied overland flow may be set modifying the nozzle type and its working pressure (Wolfe *et al.*, 2000). In our design, we evaluated nozzle models TeeJet 100.015, 110.02, 100.04 and 110.05.

Validation

Rainfall intensity was determined using a tray of the size of the experimental plot. Each test lasted 12 min with three repetitions per test. The average rainfall intensity was determined by dividing the water depth in the tray by the duration of the test. The uniformity of the water distribution was determined using 42 rain gauges, 80 mm diameter and 120 mm high each, evenly distributed in the experimental tray, and then by calculating the Christiansen CUC. The average rainfall intensity was calculated from the average water depth in the gauges and the duration of the test. As above, there were three repetitions per test and each test lasted 12 min. All the calibration tests were performed with the nozzles placed 2.3 m above the surface and an angular velocity of the rotating disk of 80 rpm.

The impact energy of the water droplets originated in the nozzles was estimated using the equation proposed by Stillmunkes & James (1982):

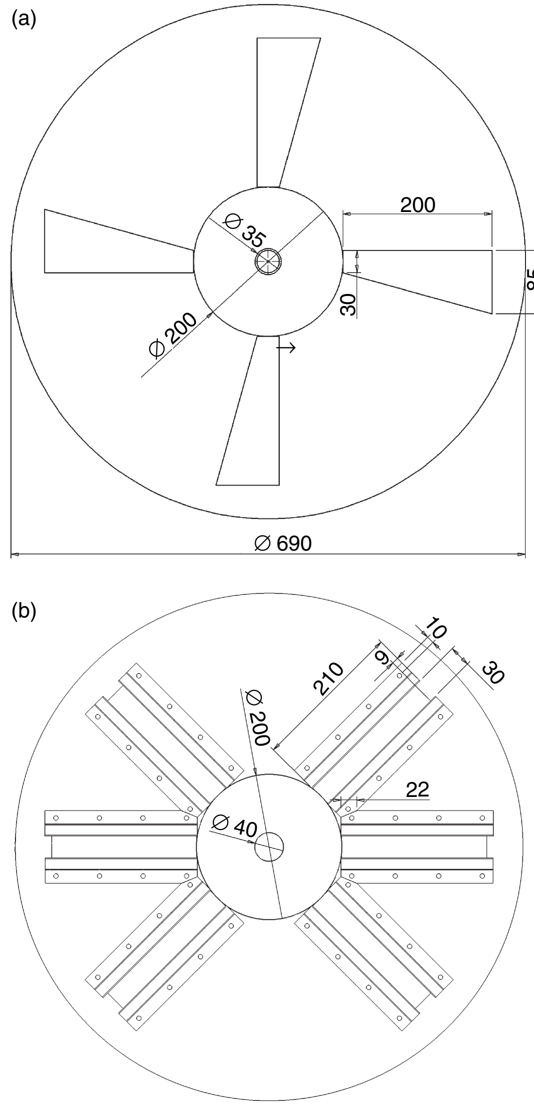

Figure 5 Rotating shutter: (a) lower disk, and (b) upper disk. Units in mm.

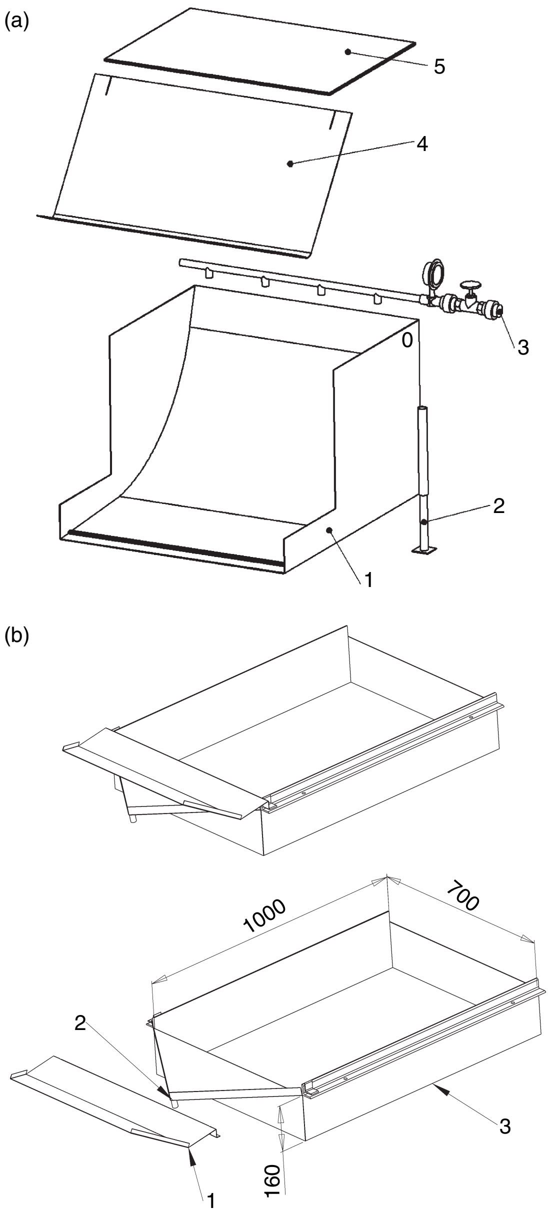

Figure 6 (a) Overland flow applicator device: (1) lateral overland flow; (2) support legs with a levelling gadget; (3) water application unit; (4) front cover; (5) upper cover; and (b) run-off collector: (1) front cover; (2) collector point; (3) lateral delimiter. Units in mm.

$$\mathrm{KE_s} = \frac{10^{-3}}{2}\rho_w L v^2 \tag{1}$$

where $\mathrm{KE_s}$ is the kinetic energy per unit area ($\mathrm{J/m^2}$), L the average water depth (mm), ρ_w the specific mass of water ($\mathrm{kg/m^3}$) and v the drop velocity (m/s).

The drop velocity was calculated using the equation of movement described by Stillmunkes & James (1982):

$$\frac{\mathrm{d}v}{\mathrm{d}t} = g - C_n v^2 \tag{2}$$

where g is gravity, C_n the drag coefficient and t time (s). Equation (2) was solved using the Runge–Kutta numeric method and assuming that the initial drop velocity was equal to the velocity when leaving the nozzle (Li & Kawano, 1995). The drag coefficient was estimated according to equation (3) proposed by Hills & Gu (1989):

$$C_n = 0.4671 d^{-0.9859} \tag{3}$$

where d, also abbreviated as D_{50}, is the average diameter of the drops (mm), which was determined using the flour method (Eigel & Moore, 1983) in a previous study (Alves Sobrinho *et al.*, 2002).

The kinetic energy of the natural rainfall was estimated using equation (4) from Wischmeier & Smith (1958):

Table 1 Average intensity of simulated rainfall in the calibration tests (*I*), Christiansen coefficient of uniformity (CUC) and ratio between the kinetic energy of the simulated and natural rain (KE_s/KE_n)

Rotating disk		Veejet 80.100 (32.7 kPa)			Veejet 80.150 (35.6 kPa)		
Number of openings	Aperture (%)	*I* (mm/h)	CUC (%)	KE_s/KE_n (%)	*I* (mm/h)	CUC (%)	KE_s/KE_n (%)
2	50	30.2 ± 2.4	82 ± 2.8	93 ± 1.4	41.8 ± 2.1	81 ± 3.1	97 ± 1.1
	75	44.2 ± 2.1	83 ± 1.8	90 ± 1.2	62.3 ± 2.0	82 ± 2.7	94 ± 1.4
	100	53.9 ± 1.4	83 ± 1.5	89 ± 1.5	74.5 ± 1.8	83 ± 2.5	92 ± 2.4
4	50	45.4 ± 2.2	84 ± 1.6	90 ± 1.3	76.5 ± 1.9	82 ± 2.6	92 ± 2.5
	75	68.9 ± 1.3	84 ± 1.3	87 ± 2.2	104.8 ± 1.4	83 ± 1.8	90 ± 2.7
	100	112.2 ± 1.2	85 ± 1.2	83 ± 2.6	156.7 ± 1.2	84 ± 1.4	87 ± 2.9

Values are given as average ± SD ($n = 3$).

$$KE_n = (17.124 + 5.229 \log I)It \quad (4)$$

where KE_n is the kinetic energy of natural rainfall per unit area (J/m^2), I the average rain intensity (mm/h) and t the precipitation period (h).

Table 1 presents the results of the calibration tests of the rainfall unit. *InfiAsper2* obtained high uniformity on the simulated area, with CUC between 81 and 85% similar to those obtained by similar designs (e.g. Morin *et al.*, 1967). The estimated kinetic energy of the rain produced by the simulator (KE_s) was 83–87% of the estimated kinetic energy of natural rain (KE_n) when using nozzles Veejet 80.100 and 80.150, respectively. *InfiaAsper2* allowed a broad range of rainfall intensities from a minimum of 30.2 mm/h – obtained with two half-shut openings – to a maximum of 156.7 mm/h – with four fully opened openings.

Table 2 presents the results of the calibration tests of the overland flow applicator unit. The flow rate is converted to the area of the run-off collector unit. By changing the nozzle size and its working pressure, we can simulate applications from 94 to 573 mm/h. The variability in flow application among the four nozzles was small, with a coefficient of variation <2% (data not shown).

Table 2 Results of the calibration tests of the overland flow unit: flow rate (mm/h), at 100, 150 and 290 kPa pressure, with four nozzles TeeJet model

Working pressure (kPa)	Nozzle type			
	Teejet 110.015	Teejet 110.02	Teejet 110.04	Teejet 110.05
100	94.1 ± 0.9	116.8 ± 2.5	228.3 ± 3.0	231.9 ± 8.3
150	122.2 ± 0.3	154.4 ± 1.9	329.5 ± 6.5	368.1 ± 22.8
290	179.9. ± 1.3	238.3 ± 2.5	479.2 ± 3.1	572.5 ± 17.4

Values are given as average ± SD ($n = 3$).

Field test

To investigate its capabilities, *InfiAsper2* was tested in the field in an area with a slope of 6% and a soil of loamy texture. The area was ploughed and covered with a stubble mulch that provided approximately 50% ground cover. Two consecutive simulations were made; the first was carried out in the rainfall-only mode at an intensity of 64.5 mm/h for 34 min. After a pause of 30 min, the second simulation was carried out for 31 min in the combined rainfall and overland flow mode, with the same rainfall intensity and an overland flow of 368.6 mm/h. The height of the water application unit over the ground was 2.3 m and the angular speed of the rotating disc was 80 rpm. The nozzles used were Veejet 80.150 working at 35.6 kPa in the rainfall applicator and TeeJet 110.05 at 150 kPa in the overland flow applicator. The equipment was transported and operated by two people and required 25 min for assembly. For field simulations 250 L of water was used.

Figure 7 presents the results from the two simulations. Run-off stabilized in a relatively short time, but took longer in the rainfall-only simulation as the soil was drier and the intensity of water application to the plot was less than in the combined simulation (9 vs. 2 min, respectively). The sediment concentration in the run-off also differed between simulations (Figure 7). In the rainfall-only simulation, the amount of soil transported by run-off was limited by the ability of the flow to detach the soil. In the combined rainfall and overland flow simulation, there was more energy to detach and transport the soil, something which is reflected in the larger sediment concentration. Soil movement occurred more rapidly in the combined simulation where most of the flow was quickly channelled into small rills that developed until reaching down to the edges of the collector plot. During that experiment, sediment concentration attained a maximum value, decreasing as did the growth in the rill network until final values were similar to those measured in the rainfall-only simulation (Figure 7). Sediment concentration in the rainfall-only simulation was dominated by sheet flow and

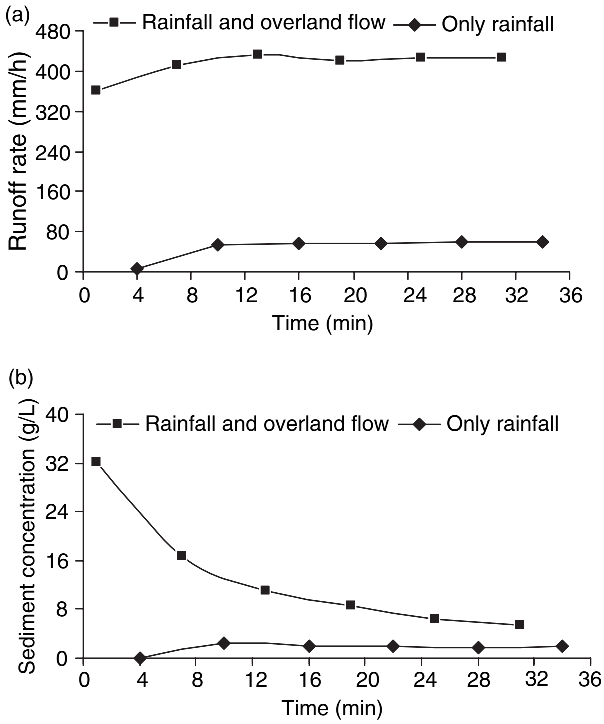

Figure 7 (a) Run-off rate for the evaluation tests, and (b) sediment concentration.

rain splash that evenly eroded the soil and transported the sediments at a constant rate.

Conclusions

In this paper, we present a prototype of a rainfall and overland flow simulator, *InfiAsper2*. The advantages over previous designs lie in flexibility of use, increased portability when compared with similar designs and versatility, as it simulates rainfall and overland flow independently or simultaneously using a broad range of intensities. This new and innovative design allows the use of a relatively sophisticated rainfall simulator which can also be used in the laboratory. Its use in the field requires a team of minimum two people, and it can be operated up to a few hundreds of metres from the nearest road and water source. This broadens the range of site conditions where the equipment can be used to investigate the effects of different management or soil conditions on soil erosion rates.

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