A Portable Rainfall Simulator for Plot–Scale Runoff Studies

J. B. Humphry, T. C. Daniel, D. R. Edwards, A. N. Sharpley

Abstract. *Rainfall simulators have a long history of successful use in both laboratory and field investigations. Many plot–scale simulators, however, have been difficult to operate and transport in the field, especially in remote locations where water or electricity is unavailable. This article describes a new rainfall simulator that is relatively easy to operate and transport to and from the field while maintaining critical intensity, distribution, and energy characteristics of natural rainfall. The simulator frame is constructed from lightweight aluminum pipe with a single 50 WSQ nozzle centered at a height of 3 m (9.8 ft). An operating nozzle pressure of 28 kPa (4.1 psi) yields continuous flow at an intensity of 70 mm h^{-1} (2.8 in. h^{-1}) over a 1.5– × 2–m (4.9– × 6.6–ft) plot area with a coefficient of uniformity of 93%. Kinetic energy of the rainfall is about 25 J m^{-2} mm^{-1} (142.8 ft–lb ft^{-2} in.$^{-1}$), approximately 87% of natural rainfall. The simulator can be easily transported by two field personnel and completely assembled or disassembled in approximately 10 min. Water usage is at a minimum as the simulator utilizes only one nozzle.*

Keywords. *Rain simulator, Runoff, Water quality, Erosion.*

Rainfall simulators have been used with much success throughout the last 75 years to conduct research on infiltration, surface water runoff, and soil erosion. Meyer (1965) and Young and Burwell (1972) pointed out the advantages of using simulated rain as opposed to natural rainfall. While natural rainfall is desirable, as it represents natural conditions at a given place, data acquisition is very slow and the spatial and temporal distribution of rainfall intensity, duration, and kinetic energy cannot be controlled (Moore et al., 1983). Rainfall simulators have the ability to create controlled and reproducible artificial rainfall, which in turn expedites data collection (Thomas and Swaify, 1989) and allows comparison of soils and management variables among locations (Sharpley et al., 1999).

While rainfall simulators can be very useful tools, there are performance limitations (Mech, 1965) due to their inability to simulate all aspects of natural storms. Limitations in the design tend to be study–specific and usually involve plot size, simulated rainfall intensity, and the definitions of the terms portable and inexpensive. Several different simulators have evolved, differing primarily in method of drop formation and intensity control (Shelton, 1985). Mutchler and Hermsmeier (1965) and Bubenzer (1979) describe simulators as being one of two types: 1) simulators that produce rainfall from nozzles, and 2) simulators using drop formers such as hanging yarn or tubing tips. Simulators using nozzles are generally preferred over drop–former simulators because they have the capability of yielding greater intensities, are more portable, and can effectively cover larger plot areas. Also, spray–nozzle simulators produce a more randomly distributed rainfall drop pattern compared to drop forming simulators, which tend to produce raindrops of equal size in the same location.

Nozzles used on early rainfall simulators were very simple and limited in their applications. Duley and Hays (1932) used an ordinary sprinkler can, and Lowdermilk (1930) used two horizontal pipes each fitted with orifices and placed on either side of a plot. Advancements in nozzle design began in 1936 when the USDA–Soil Conservation Service took interest in rain simulation for erosion investigation (Mutchler and Hermsmeier, 1965). These early nozzles were limited in their ability to simulate the physical characteristics of natural rainfall such as kinetic energy and drop–size distribution. Another major advancement came with the development of the rainulator by Meyer and McCune (1958), which used Veejet 80100 nozzles to produce median drop diameters yielding a kinetic energy approximately 80% of natural rainfall. The rainulator had many desirable characteristics of natural rainfall not previously found in a single rainfall simulator, however, it was complex to operate requiring much labor and time. Swanson (1965) improved upon Meyer and McCune's design by developing a simulator that utilized rotating booms that carried continuously spraying Veejet 80100 nozzles. The rotating boom simulator was mounted on a trailer to help improve mobility, but still required 2 hours for three or four people to disassemble and load the simulator for transport. Using the same nozzle, Foster et al. (1982) developed a more portable simulator (plot to plot within 30 min) that produced a wide range of intensities up to 130 mm h^{-1} (5.1 in. h^{-1}).

Moore et al. (1983) designed a simulator similar to that described by Foster et al. (1982) using Veejet 80150 nozzles,

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The authors are **J. Byron Humphry**, Graduate Student, **Tommy C. Daniel**, Professor, University of Arkansas, Fayetteville, Arkansas; **Dwayne R. Edwards, ASAE Member Engineer,** Professor, University of Kentucky, Lexington, Kentucky; and **Andrew N. Sharpley**, Soil Scientist, USDA–ARS, University Park, Pennsylvania. **Corresponding author**: Tommy C. Daniel, University of Arkansas, PTSC 009, Fayetteville AR 72701; phone: 501–575–5720; fax: 501–575–7465; e–mail: tdaniel@uark.edu.

achieving a wide range of intensities, acceptable uniformity, and portability. Shelton et al. (1985) improved on the complex operating mechanisms of the Veejet nozzles by using continuous–application, wide–angle, square–spray nozzles (Spraying Systems Fulljet 30WSQ and 50WSQ). These investigators were able to utilize continuous–application without excessive intensities by injecting air into the water stream, obtaining acceptable median drop diameters, and finding that drop velocities after 3.0 m (9.8 ft) of fall were within 2% of terminal velocities.

Miller (1987) made the simulator described by Shelton et al. (1985) more versatile by regulating the water flow through the 30WSQ nozzles with the use of a solenoid–operated valve. Variable intensities were produced by adjusting the output of the nozzles using a variable–speed cam–switch assembly to control the opening and closing of the valves. Miller (1987) also found that the kinetic energy distribution over a 1–m^2 (10.8–ft^2) plot, produced by the 30WSQ nozzle, was within the limits reported for natural rainfall. Miller's simulator sacrificed the continuous flow of Shelton et al. (1985) for increased portability offered by the use of solenoids.

Despite any differences in the design or performance of the simulators described above, there are common characteristics desired in all simulators. Meyer (1965), Shelton et al. (1985), and Moore et al. (1983) compiled lists of these characteristics that can be divided into two categories: rainfall and design characteristics. Desirable rainfall characteristics address drop–size distribution, fall velocity, kinetic energy, intensity, uniformity, and continuous application. Design characteristics deal with water usage, operation requirements, acceptable plot sizes, portability, and cost. Few simulators, if any, satisfactorily possess all of these desired traits. Because the characteristics are closely related, often one must be sacrificed to excel in another. The intended use or the nature of the study often dictates the characteristics required of a rainfall simulator.

While erosion research may have been the initial focus of rainfall simulation techniques, within the last decade scientists have also recognized their advantages as a central component of water quality investigations, especially field research involving runoff. For example, in areas of intense livestock production, manures are normally applied at rates designed to meet crop nitrogen requirements (Sims, 1993). Done over the long–term, however, this practice results in over–application of phosphorus (P) and a gradual but consistent increase in the level of P in the surface soil (Sharpley et al., 1996). Continued P enrichment of the surface soil can result in eutrophic runoff because of the known relationship between the amount of P in the soil and that contained in the runoff (Sharpley, 1995; Pote et al., 1998). In response, several states have used agronomic soil tests to identify threshold soil P levels perceived to limit eutrophic runoff (Sharpley et al., 1996). However, from a regulatory standpoint, insufficient data exists to implement P–based control strategies that are scientifically defensible. Because of the lack of data, the National P Project was created to coordinate research across the United States to provide a sound scientific basis for establishing threshold soil P levels in areas where P enrichment of water may impair water quality (Sharpley et al., 1999; http://www.soil.ncsu.edu/sera17). The project is a consortium of federal/state agencies and universities funded jointly by USDA–NRCS, USDA–ARS, and USEPA. Currently, there are over 20 scientific collaborators across the United States conducting research under the auspices of the Project and rainfall simulation techniques serve as the centerpiece for developing threshold P levels across diverse soil and geographic locations, i.e., the relationship between the level of P in the soil and that contained in the runoff. For the results to be comparable from a national standpoint, our goal is to have all investigators use the same simulator and conduct investigations using a common protocol (http://www.soil.ncsu.edu/sera17). For example, a common rainfall intensity, runoff sampling, and parameter analysis will be used. Obviously, new demands and expectations are being focused on the rainfall simulator.

Our purpose for designing a new rainfall simulator was to improve upon the designs of Shelton et al. (1985) and Miller (1987) that would allow us to conduct runoff studies in remote areas with minimum difficulty and manpower. Runoff studies (using rainfall simulators; Edwards et al., 1992) to relate extractable soil P–to–P losses in runoff have been successful (Pote, 1996); however, these simulators were not portable, were designed for large plot situations, and required several nozzles per simulator resulting in high water usage. Our research has focused on developing a small, lightweight, portable simulator easily moved from location to location while exhibiting acceptable rainfall characteristics.

To ensure our simulator meets these requirements our objectives were to develop a simulator that produces 1) acceptable median drop size, velocities, and kinetic energy over the plot area, 2) intensities sufficient to generate runoff, 3) acceptable uniformity over the plot area, and 4) near continuous flow. Additionally, the simulator must be readily transported, use a minimum amount of water, and be affordable. This article describes the construction, operation, and testing of a portable rainfall simulator.

Materials and Methods

Design and Construction

The simulator is designed to be lightweight, portable, and emphasizes the use of inexpensive and readily available materials requiring minimal construction and operation expense. As discussed below, the design is based on a field plot size of 1.5 × 2.0 m (4.9 × 6.6 ft). The frame of the simulator (fig. 1) is constructed from 32–mm (1.25 in.) diameter aluminum pipe. The top of the simulator is permanently assembled, but the legs and braces are detachable. The aluminum pipe frame is connected with Nu–Rail® fittings manufactured by Hollaender® Manufacturing Co. (Cincinnati, Ohio). Adjustable angle fittings are used to attach the legs and side braces. To make the simulator easy to disassemble and reassemble, the swivel pins in the adjustable angle fittings are drilled out and replaced with larger, removable locking pins (fig. 2). With these quick coupling fittings attached to the legs and braces, the simulator can be dismantled/assembled by maneuvering the pin. The fittings are numbered to insure proper alignment upon re–assembly.

The frame is constructed so that windscreens are attached to each side and secured at the top and bottom so as not to affect rainfall simulation. Windscreens made from PVC

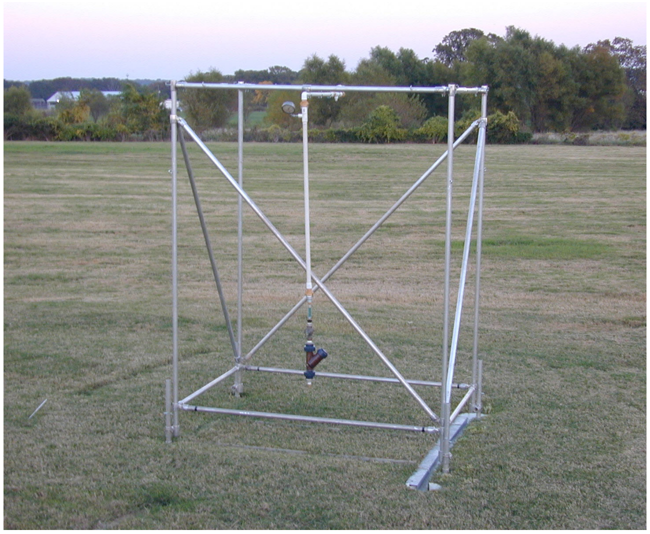

Figure 1. Portable rainfall simulator shown over 1.5– × 2.0–m plot.

plastic tarps are easily attached and detached for transport. The frame is sturdy and can withstand windy conditions using four stakes and tie–down straps positioned at each leg of the simulator.

The nozzle assembly used on the simulator is a single Spraying Systems Fulljet HH50WSQ nozzle, described previously by Shelton et al. (1985). The nozzle is centered at the top of the frame 3 m (9.8 ft) high and is threaded directly into a 13–mm (0.5–in.) PVC tee. The tee, connected to a 25–mm (1–in.) diameter PVC water supply pipe, is attached to the aluminum frame via 25–mm (1–in.) conduit hangers. A low pressure regulator is used in combination with a liquid–filled pressure gauge to insure that a 28–kPa (4.1–psi) nozzle pressure is maintained. An in–line filter is placed in the flow stream to prevent foreign particles from clogging the regulator and the nozzle. A garden hose supplies water to the simulator.

Drop–Size Distribution

Drop–size distribution was determined by the oil method of Eigel and Moore (1983). This method consists of catching raindrops in a petri dish containing a 2:1 ratio mixture of STP® Oil Treatment (First Brands Corporation, Danbury, Conn.) and mineral oil. Single petri dishes were positioned at 13 locations within the plot area and exposed to the simulated rainfall using a shutter device as described by Eigel and Moore (1983). This exposure process was conducted in random order and replicated twice. The less dense, more viscous oil mixture suspends the water droplets in a sphere. A digital image was taken of the petri dish with a scale in the background, the image enlarged, and the drop diameters measured. Drop–size distribution was determined by counting the number of drops in 0.5–mm (0.02–in.) intervals ranging from 1.0–1.5 to 4.0–4.5 mm (0.04–0.06 to 0.16–0.18 in.). Raindrops smaller than 1.0 mm (0.04 in.) were not measured due to the physical difficulty and their insignificance in terms of kinetic energy compared to the larger droplets. No droplets larger than 4.5 mm (0.18 in.) were obtained.

Since the droplets were captured in the oil as spheres, median drop size was calculated on a volume basis from the distribution ($v = \pi[d^3]/6$). The total volume of droplets caught was summed across all petri dishes and replications and divided by the total number of drops counted to yield a median droplet volume. The median drop size was then calculated by manipulating the equation above to solve for *d*, where *d* is the median drop size and *v* is the median volume of a droplet.

Figure 2. Removable locking pins attached to braces that allow rapid assembly or disassembly of the simulator.

Kinetic Energy

According to Shelton et al. (1985), a 50WSQ nozzle placed 3 m (9.8 ft) high at a 28–kPa (4.1–psi) operating nozzle pressure produces drops within 2% of terminal velocity. Terminal velocities given by Gunn and Kinzer (1949) were used for each drop–size interval to calculate kinetic energy (KE). The distribution of kinetic energy was calculated using the equation

$$KE = 1/2mv^2$$

where *m* is the mass of the mean drop size in each size interval and *v* is the corresponding raindrop velocity. The kinetic energy calculated for each drop–size interval was summed across all drop–size intervals, and then averaged for each petri dish location and replication. The resulting 26 KE values (13 locations × 2 replication) where averaged to yield an average KE energy value for the plot.

Intensity

A sheet–metal pan, having the same dimensions as the field plots (1.5 × 2.0 m), was placed under the simulator to measure intensity. The pan had a gutter attached to the down–slope end and was oriented with a slight slope to catch runoff. Replicated aliquots of the runoff were collected for approximately 30 s and the final volume recorded. Runoff volume was then divided by the plot dimensions to give depth of runoff over time.

Uniformity

Two hundred and twenty–one 100–mm (3.9–in.) diameter cups were placed under the simulator on a 1.5– × 2.0–m grid at spacings of 0.125 m (4.9 in.). Rainfall was collected in the cups for approximately 30–min of continuous flow from the simulator. The individual cups were weighed, yielding a volume at each location on the grid. The coefficient of uniformity (CU) was then determined using Christiansen's (1942) method which expresses CU as a percentage with the formula CU = 100(1.0–Σ*d*/*mn*) where *d* is the standard deviation of individual observations from the mean value *m*, and *n* is the number of observations.

Results and Discussion

Kinetic Energy – Drop Size and Velocity

The distribution of the kinetic energy over a plot area is dependent on the drop–size distribution and their respective velocities. Drop–size distribution measured in duplicate at the 13 locations over the 1.5– × 2.0–m plot area yielded a median volumetric drop diameter of 1.9 mm (0.075 in.). This drop size is consistent with diameters of 1.8 mm (0.071 in.) reported by Shelton et al. (1985) and 1.75 mm (0.069 in.) by Lascano et al. (1997) using the same 50WSQ nozzle. Raindrop velocities were assumed to be at terminal velocity based on the location (elevated 3 m) and operating pressure (28 kPa) of the nozzle (Foster et al., 1982; Shelton et al., 1985). Terminal velocity data from Gunn and Kinzer (1949) was used to obtain an average value for each drop–size interval. Although both drop–size distribution and velocity are important parameters to be considered, the resulting KE offers a better way to compare simulated and natural rainfall.

Kinetic energy calculated from the individual drop–size distributions and the corresponding terminal velocities ranged from 17.5 to 40.7 J m^{-2} mm^{-1} (100 to 232 ft–lb ft^{-2} $in.^{-2}$; fig. 3), with an overall mean of 24.6 J m^{-2} mm^{-1} (141 ft–lb ft^{-2} $in.^{-1}$). These KE values are comparable to the KE reported for natural rainfall at similar intensities and geographic locations (Hudson, 1995; Carter et al., 1974). The observed mean value of 24.6 J m^{-2} mm^{-1} was approximately 87% of the KE reported by Hudson (1995) for natural rainfall and approximately 82% of that reported by Carter et al. (1974).

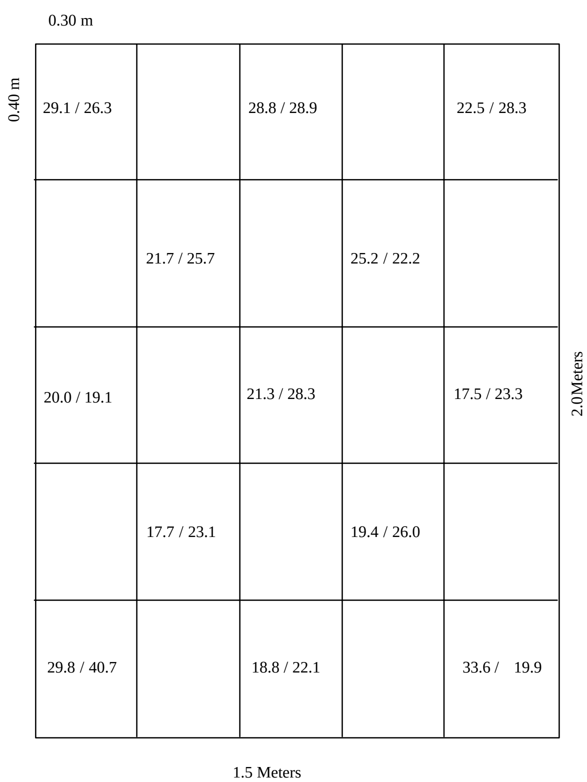

Figure 3. Kinetic energy distribution (J m^{-2} mm^{-1}, measured in duplicate) of simulated rainfall on a 1.5– × 2.0–m plot under a single nozzle simulator (50 WSQ nozzle at 28 kPa).

The kinetic energy appeared to be slightly greater at distances farthest from the nozzles, indicating that the spray pattern produced larger drops at these locations. The bottom two locations had the largest differences between the two replications. However, the high and low readings for these two locations where not recorded in the same replication, indicating the variable nature of the measurements recorded. The kinetic energy therefore appears to be variable across the plot with little dependence on location or replication.

Intensity

Previous researchers have controlled intensity by either oscillating the nozzles over the plot (Bubenzer and Meyer, 1965; Foster et al., 1982; Moore et al., 1983), injecting air into the water stream (Shelton et al., 1985), or using solenoids to produce intermittent application (Miller, 1987; Lascano et al., 1997). To our knowledge, up until this point, a simulator producing acceptable drop sizes, uniformity, and intensity did not utilize continuous flow techniques. By utilizing a plot of 1.5– × 2.0–m, this simulator is capable of producing a continuous flow rain event with an intensity of 70 mm h^{-1} (2.8 in. h^{-1}). This intensity was sufficient to generate runoff and thus met our needs, since we were comparing relative differences between the relationship of soil phosphorus and surface runoff phosphorus among different soil series. Operating the simulator at continuous flow is advantageous because it does not require the use of solenoid–operated valves, is sufficient to generate runoff, and more accurately simulates natural rainfall. For these reasons, all investigators on the Project used the 70–mm h^{-1} intensity. A solenoid–operated valve similar to that described by Miller (1987) can be attached if an intensity lower than 70 mm h^{-1} is desired. However, when using a valve to regulate the water flow through the 50WSQ nozzle, a spike occurs in the distribution of rainfall directly under the nozzle. Water trapped between the valve and the nozzle tip forms a large drop when the valve is closed resulting in excessive drop sizes directly below the nozzle. This large drop size may not be such a severe problem when used in pasture situations, but when used on tilled ground the large drops would have a significant impact on the kinetic energy hitting the soil resulting in excessive cratering and erosion. Miller (1987) noted a similar problem when using a solenoid to regulate water flow through the 30WSQ nozzles and corrected the problem by placing a siphon hose between the valve and the nozzle, which kept the droplet from falling when the nozzle closed. We had little success using a siphon hose on the 50WSQ nozzle, possibly due to the larger orifice of the nozzle that prevented the siphon hose from having enough negative suction to hold the droplet. Another possible solution to overcome this problem could be to insert a small piece of a furnace filter or other such material directly below the nozzle that would disperse and absorb the energy of the drop while compromising an insignificantly small area of the plot.

UNIFORMITY

Using one nozzle (50WSQ) centered over the plot produced a 93% coefficient of uniformity (CU) as shown in figure 4. Miller (1987) reported CU values above 90% using a single 30WSQ nozzle and found that using more than one nozzle decreased CU due to uneven overlap of the spray patterns. Cerda et al. (1997) also reported a CU of 93% using a single nozzle (HARDI–1553–10) over a very small plot area [0.24 m^2 (0.62 ft^2)]. Simulators using multiple nozzles are capable of producing higher intensities over larger plot areas, but often sacrifice uniformity and portability.

PLOT SIZE

A plot size of 1.5– × 2.0–m may not be appropriate for all research applications and is not intended to represent edge of field values from a large watershed, but this approach does allow relative comparisons and was sufficient in preliminary runoff studies for relating soil P and runoff P. Green and Sawtell (1992) successfully used a small mobile rainfall simulator on 1–m^2 (10.8–ft^2) plots for soil erosion studies. The plot area should be of sufficient size for satisfactory representation of treatments and erosion conditions (Meyer, 1965). The 1.5– × 2.0–m plot is adequate for basic or mechanistic runoff studies relating soil P to runoff P.

PORTABILITY

The simulator is constructed from lightweight aluminum allowing two people to carry the assembled simulator from plot to plot. When the simulator must be moved from one location to another, it can be completely disassembled for travel in 10 min. Likewise, the simulator can be reassembled within 10 min upon arrival at the next location. The locking pins holding the legs and braces together can be easily removed and inserted. Since the simulator only employs the use of one nozzle, water use is a minimum. At the operating nozzle pressure of 28 kPa, the simulator uses about 0.21 L s^{-1} (3.4 gpm). This low water requirement is extremely important when conducting rain simulations in remote areas where water must be hauled.

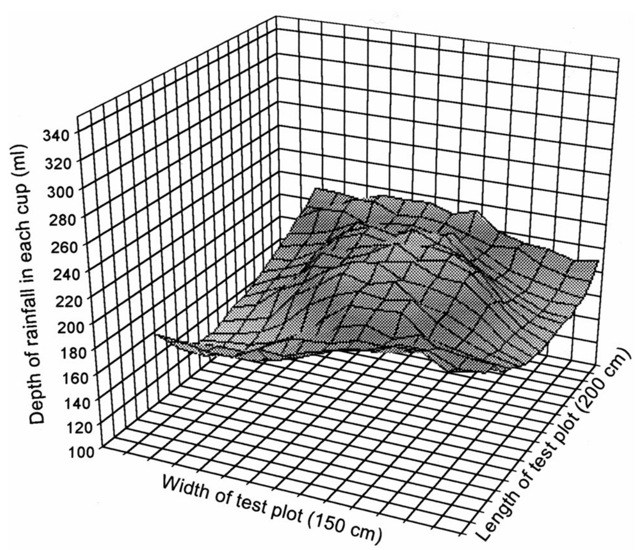

Figure 4. Distribution of simulated rainfall depths over 1.5– × 2.0–m plot area (30–min rainfall duration).

NOTES ON FIELD USE

This simulator was used to collect runoff data from four different sites possessing different soil series. Each site had three runoff plots installed into a pasture that was accessible by vehicle. The simulator was transported disassembled on a flatbed trailer or in the back of a truck to each site. Upon reaching the site, the simulator was assembled in approximately 10 min. Once assembled, the simulator was positioned over a plot for the simulation. Following rainfall simulations, two people moved the simulator intact from plot to plot.

Windscreens were attached to the frame on all four sides and secured at the top and bottom. The windscreens were effective in blocking winds and no visible distortion of the spray pattern was noted. With the windscreens on, the simulator must be secured to prevent tipping or sliding when the wind is blowing. Tie–down straps connected to each leg and to stakes driven in the ground were effective in stabilizing the simulator. Since the simulator is carried from plot to plot by two people, and thus not staked down, excessive wind can make the process extremely difficult. Personal discretion should be used as to when the wind is blowing hard enough that handling and setting up the simulator become too laborious and cumbersome.

None of the sites where our plots were located had water or electricity. To accommodate rain simulations in such remote areas, a trailer outfitted with a tank, gas generator, cord and hose reels, and electric pump was used. The gas generator was used to power a small pump (Jacuzzi Bros.) that supplied water from the 6180 L (1635–gal) water tank to the simulator through a garden hose. A hose reel mounted to the trailer contained the garden hose. Cord reels were also used to hold extension cords used to power sampling pumps. The hose and cord reels helped tremendously in preventing tangles and keeping the study site in an orderly condition.

Rainfall simulations were conducted for approximately 1 h/plot. Because the rainfall simulator uses 0.21 L s^{-1} (3.4 gpm) of water we were able to conduct rainfall simulations at two locations (six plots) with less than one tank of water.

CONCLUSIONS

This simulator was developed to produce simulated rain on a 1.5– × 2.0–m (4.9– × 6.6–ft) plot in remote locations for runoff studies. Ease in operation and portability are the advantages of this simulator design. Because the simulator utilizes continuous flow from a single nozzle, the only requirement to operate the simulator is a water supply capable of producing 28–kPa (4.06–psi) nozzle pressure. The design of the simulator allows two researchers to conduct runoff studies in locations that lack access to water and electricity. In locations where there is no access to water or electricity, a trailer outfitted with a water tank, a gas generator, and hose reels is required to operate the simulator. When traveling from site to site, two people can disassemble/assemble the simulator within 10 minutes.

The performance of this simulator is comparable to other simulators using a wide–square spray nozzle that utilized air injection (Shelton et al., 1985) and solenoid–operated valves (Miller, 1987) to control intensity. The greatest advantages of this simulator are the portability and the capability of operating at continuous flow requiring no complex mechanisms to control intensity. Materials required to build the entire simulator cost about $1,500 with a minimal amount of labor required in construction.

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