THE WALNUT GULCH RAINFALL SIMULATOR: A COMPUTER-CONTROLLED VARIABLE INTENSITY RAINFALL SIMULATOR

G. B. Paige, J. J. Stone, J. R. Smith, J. R. Kennedy

ABSTRACT. *The Walnut Gulch Rainfall Simulator (WGRS) is a portable, computer-controlled, variable intensity rainfall simulator for rainfall-runoff-erosion research on rangelands. The WGRS was developed with the objective to quantify the relationship between rainfall intensity and steady state infiltration rate and to determine how that relationship affects sediment transport by overland flow. The simulator has a single central oscillating boom and applies water over a 2- × 6.1-m area. Two important improvements have been made to the oscillating boom simulator design. First, a computer-controlled stepper motor is used to control the oscillations and minimize the variability of the water application across the plot. Second, the spray time and sequence of nozzle operation are controlled by three-way solenoids to minimize the delay time between oscillations at low application rates. The simulator applies rainfall rates between 13 and 178 mm/h, in 13-mm/h increments, with a coefficient of variability of 11% across the plot. Water use is minimized by recycling the water that is not sprayed directly on the plot. The simulator has been tested in both laboratory and field applications.*

Keywords. *Rainfall simulator, Variable intensity, Infiltration, Runoff, Erosion.*

Rainfall simulators have been used in hydrologic and erosion process studies since the 1930s. They are designed to apply a controlled amount and rate of water on a known area or plot. Rainfall simulators have been used for two major reasons: the difficulty in measuring runoff and erosion resulting from natural rainfall and the need to isolate the major factors that influence those processes. Runoff producing rainfall, particularly on semiarid rangelands, is highly variable in space and time, thus installing and maintaining equipment that can measure rain-fed runoff and sediment on a plot or hillslope scale is difficult and expensive. Rainfall simulation allows for control over the water application rates and initial conditions, and for accurate measurement of runoff and erosion.

Since the 1980s, field experiments with a relatively uniform experimental design have been conducted using a rotating boom rainfall simulator (RBS) at many rangeland sites (Swanson, 1965). The RBS has ten 7.6-m booms that are attached to a hydraulic pedestal mounted on a utility trailer. VeeJet 80100 nozzles are attached to the booms that, in the original design, apply water at a rate of about 60 mm/h on two 3- × 10.7-m plots (Spraying Systems, Inc., Wheaton, Ill.). Subsequent designs (Simanton et al., 1991) added nozzles controlled by two-way solenoids to apply water at 120 and 178 mm/h. Field experiments with the RBS have generated one of the largest runoff and erosion databases for rangelands including studies to parameterize the Universal Soil Loss Equation (Simanton et al., 1986) and the Water Erosion Prediction Project, WEPP (Simanton et al., 1991; Franks et al., 1998).

Although the RBS has been widely used, it does have two distinct disadvantages: the amount of water required for a sequence of runs and the limitation in the range of application rates. For the WEPP rangeland field experiment, 12,000 L of water were required for the simulator runs, necessitating two 6000-L storage tanks. Although the water requirement is simply a matter of logistics, the limitation in the range of applications rates is more consequential because of the spatial variability of infiltration on rangelands.

Hawkins (1982), in analysis of rainfall simulator data, noted that when multiple application rates are used, the apparent steady state infiltration rate, f_a, increases with increasing water application rate, i, where f_a is defined as i – q_{ss}, and q_{ss} is the steady state runoff rate measured at the outlet of a plot. The reason put forth for the increase in f_a is that there is a distribution of infiltration capacity on a given area. At lower rates of i, only those portions of the plot that have a lower infiltration capacity than i contribute to runoff. As i increases, portions of the plot with higher infiltration capacities contribute to runoff, thus increasing f_a. The relationship between i and f_a is conceptualized in figure 1. Before ponding begins, f_a is equal to i because water can only infiltrate at the application rate. After some threshold value of application rate, i_0, the infiltration capacity of a portion of the plot is exceeded and water begins to pond on the soil surface. As the intensity increases runoff will begin with f_a increasing as more of the plot contributes to runoff; when the entire plot is contributing to runoff, f_a will reach a constant value, f_f. This phenomenon implies that for the typical single application rate of simulator experiments, only a portion of the plot may be contributing to runoff. The RBS with three

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The authors are **Ginger Burton Paige**, Assistant Research Scientist, **Jeffry Joel Stone**, Hydrologist, **John Richard Smith**, Supervisory Hydrologic Technician, and **Jeffrey Ronald Kennedy**, Hydrologic Technician, USDA-ARS, Southwest Watershed Research Center, Tucson, Arizona. **Corresponding author:** Ginger Paige, USDA-ARS, 2000 E. Allen Road, Tucson, AZ 85719; phone: 520-670-6381; fax: 520-670-5550; e-mail: gpaige@tucson.ars.ag.gov.

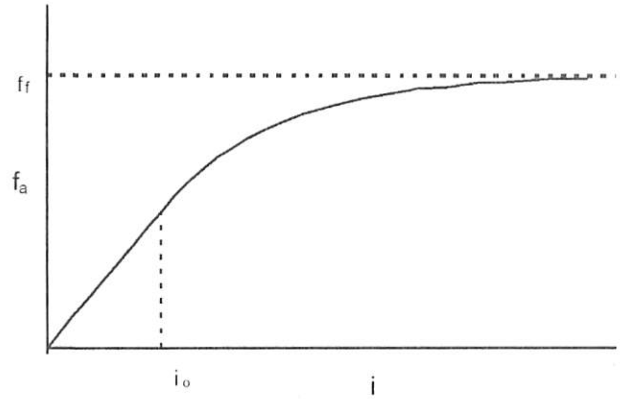

Figure 1. Conceptual relationship between apparent steady state infiltration rate, f_a, and application rate, i. The application rate i_0, is the rate when water begins to pond on the surface and f_f is the apparent infiltration rate when the entire area is contributing to runoff.

application rates could define portions of the curve in figure 1 but not necessarily when ponding or runoff begins or when the steady state infiltration rate becomes constant.

The objective of this article is to present the Walnut Gulch Rainfall Simulator (WGRS), a computer-controlled, variable intensity rainfall simulator that was developed at the USDA-ARS Southwest Watershed Research Center. The goal was to develop a rainfall simulator that would improve our ability to measure infiltration, runoff, and erosion processes on rangelands. The primary objective was to develop a portable, computer-controlled simulator that could apply a large range of rainfall intensities (0 to 200 mm/h) with a low (10% or less) coefficient of variability (CV) of application across the plot. The target was a sprinkler-type simulator designed to cover a large enough area to measure both rill and interrill flow processes. On rangelands, many of the vegetation spatial patterns are spaced on the order of 1 m indicating that at a minimum, a 2-m plot width is necessary to represent those patterns. Therefore, a 2-m wide plot with an adequate length to activate sediment transport by flow (6 m) was needed. The simulator design has been through an extensive development and testing process including laboratory and field experiments; the final design is described in detail below.

Walnut Gulch Rainfall Simulator

The Walnut Gulch Rainfall Simulator design is based in part on existing oscillating rainfall simulator designs including the rainulator (Meyer and McCune, 1958; Meyer and Harmon, 1979), the laboratory rainfall simulator (Bubenzer and Meyer, 1965), the programmable rainfall simulator (Foster et al., 1979; Neibling et al., 1981), and the Norton ladder simulator (Norton, 1998) with some modifications. These simulator designs all use the VeeJet 80100 nozzle, apply a range of rainfall intensities, and control the application rate by changing the delay time between oscillations, the time the nozzles are not spraying on the plot. The shorter the delay time is between oscillations, the higher the application rate. In most cases a single nozzle covers an area that is 1.5 m wide or narrower. In developing the WGRS, modifications were made to: 1) extend the nozzle application area to cover a 2-m wide plot; 2) minimize the delay time between oscillations for the lower intensities; and 3) increase the range of intensities to at least 178 mm/h.

The WGRS (fig. 2) has a single central oscillating boom and is designed to rain on field or laboratory plots with a 2 m width and 6.1 m length. The simulator is portable, and can be assembled in less than an hour. The applied rainfall intensity is computer controlled and can be easily changed using a mechanical knob. The water use is minimized by recycling the water that is not sprayed directly on the plot.

Structural Design

The central oscillating boom is a 6.1-m long aluminum pipe with a 5.08-cm internal diameter. The boom is supported by three sets of telescoping legs welded to 4.6 m lengths of 8-cm wide aluminum channel. The legs are made of 3.81- and 2.54-cm aluminum pipe (10 gage) and can be adjusted by 5-cm increments to a maximum height of 3.3 m. Metal crossbars on the sides and 2.54-cm aluminum square tubing connect the legs across the top for additional stability. A 30-cm high aluminum bracket (with Teflon bearings) is mounted in the center of each aluminum channel to support the central boom. The motor and oscillation drive mechanism are mounted on the first set of legs. Windbreaks encircle three sides of the simulator to minimize the effects of wind on the distribution of rainfall across the plot.

Rainfall Intensity, Energy and Oscillation Control

The VeeJet 80100 nozzle, used on the majority of sprinkler style simulators, was selected for the WGRS to allow comparison of results with results obtained from the RBS. The rainfall intensity applied is determined by the nozzle pressure and the percentage of time that the nozzles spray on the plot. The distribution is controlled by the spacing of the nozzles, the pressure at the nozzle, and the oscillation of the central boom. These factors are all critical in determining the required spraying time needed to apply specific rainfall intensities across the plot.

The VeeJet 80100 nozzle was originally selected for rainfall simulators by Meyer and McCune (1958). Meyer (1958) found the VeeJet 80100 at 41-kPa pressure, a nozzle velocity of 6.8 m/s, and a height 2.4 to 3 m above the ground to be an optimal design with a kinetic energy of 204 kJ/ha-mm (790 ft-ton/acre-in.), approximately 75% of natural rainfall in Northern Mississippi. Based on subsequent testing by Norton (1998), Loch (1997), and our own evaluations, the nozzles are set 2.44 m above the plot and run at a pressure of 55 kPa. This nozzle pressure is greater than the 41 kPa that is often used for these nozzles and was the original operating pressure suggested by Meyer (1958). Therefore it was

Figure 2. Walnut Gulch Rainfall Simulator se up at a field site.

important to determine the effect that this pressure change would have on the drop size distribution and kinetic energy.

The drop size distributions from the VeeJet 80100 nozzle were measured by Spraying Systems, Inc. using a PMS-OAP-2D-GA2 analyzer. The drop size distributions were measured at 41 and 55 kPa from a height of 2.44 m. The volume median diameter measured was 2.985 mm at 41 kPa and 2.857 mm at 55 kPa. The higher application pressure results in a slightly smaller drop size and a slightly larger exit velocity, as expected. The drop sizes ranged from 0.288 to 7.2 mm at 41 kPa and from 0.276 to 6.87 mm at 55 kPa. The larger drop sizes (4.1 mm and greater at 55 kPa) approach but do not attain terminal velocity at a height of 2.44 m. The calculated kinetic energy from the measured drop size distributions is 257 and 271 kJ/ha-mm for 41 and 55 kPa, respectively. These values were calculated using the methodology outlined by Meyer (1958) and the raindrop fall-velocities of Laws (1941). Both of these energy values are very close to the values from natural rainfall in northern Mississippi (McGregor and Mutchler, 1977).

Individual nozzles and the distance between them are critical to the amount of water applied and its distribution across the plot. The four spray nozzle assemblies, spaced 1.52 m apart on the central boom, are attached to the boom using aluminum couplings. The nozzle assemblies, numbered one through four from front to back, are comprised of VeeJet 80100 nozzles and three-way solenoid valves. The spacing of the solenoid-nozzle assemblies was determined based on the nozzle operating pressure and height above the plot surface. The spray shape from the nozzles is a long irregular oval, approximately 2.8 m long at a height of 2.44 m above the plot. The distribution from a single nozzle is not uniform over the entire length of spray; more concentrated spray is directly under the nozzle. The nozzles are spaced along the boom so that the areas of less concentrated spray from the nozzles will overlap (Meyer and McCune, 1958). In addition, the spray shape from each of the VeeJet nozzles is unique so the spray shape from each nozzle was evaluated and the selection and sequence of the nozzles along the boom was determined so as to minimize the coefficient of variability along the length of the plot.

Because the nozzle flow rate is high at 55 kPa (0.29 L/s), the water application has to be intermittent. The percentage of time that a given nozzle should spray on a plot (for each target intensity) is determined by the effective area covered by the nozzle (2×1.52 m) multiplied by the desired intensity and divided by the continuous spray flux (application rate per unit area) for that nozzle at a given pressure. For example, to apply a rainfall intensity of 50 mm/h across a 2-m wide area, the nozzles should only spray on the plot 15.2% of the time. The rainfall intensity (a function of the amount of time the nozzles are spraying on the plot) is therefore controlled by changing the "delay" time, or the length of time between oscillations.

The central boom is oscillated back and forth across the 2-m width of the plot. The long axis (6.1 m) of the plot is set up parallel to the slope. The oscillation of the boom is controlled by a high torque stepper motor (#MH112-FJ-8020, Superior Electric Company, Bristol, Conn.) and a chain and gear-sprocket system (fig. 3). A controller, a high performance microstepper driver and indexer (model HI2, Intelligent Motion Systems, Inc., Marlborough, Conn.), is used to direct the stepper motor. To pass across and off a 2-m wide plot at 2.44 m above the plot, the nozzles have a 50° sweep. When a constant speed motor is used, the application rate will be greater at the center of the plot than at the edges because the nozzles are traveling through an arc but the spray is intersecting a plane. The difference in application rate increases with increasing plot width. For example, on a 1-m wide plot with a nozzle height of 2.44 m, as commonly used in cropland rill studies, the difference is only 2%. For a 2-m wide plot, there is about an 8% difference in application rates from the center to the edge. Therefore, a stepper motor was selected in order to change the speed as the boom oscillates back and forth across the plot. The stepper motor controller can be programmed to vary the speed of the motor and therefore the nozzles, slower on the ends of the oscillation and faster in the middle, as they spray across the plot, thus decreasing the variability of the rainfall intensity across the 2-m distance.

Oscillation Programs

Two different programs are used to control speed and timing of the oscillation of the boom. The oscillation programs are written in a unique controller language as a text file and downloaded into the controller through a COM port using a terminal emulator program. The final oscillation speed and timing was the result of an optimization process. The stepper motor has a maximum speed of 20,000 steps/s. The sprocket gear ratio (9:72) for driving the oscillation of the boom is designed to minimize the steps, and therefore the time required to move the boom. At the maximum speed it would take only 0.064 s to move the 1280 steps required for the nozzles to sweep across the plot. The stepper motor was selected because it had a high holding torque. However, for our application, going a short distance back and forth at high speed, the holding torque was weakened resulting in drift when run at maximum speed. The motor also needs time to: 1) accelerate to final speed; 2) decelerate to a stop; and 3) change directions. In addition, the motor needs to go fast across the middle of the plot and to accelerate and decelerate slowly, to get a uniform distribution across the plot. In order to do this, trip points are programmed into the controller to tell the motor where, in a single sweep, and how fast to accelerate and decelerate.

Figure 3. Stepper motor and gear sprocket system used to control the oscillations of the WGRS.

The controller programs were optimized to: 1) minimize the delay time for the lower intensities (25 to 120 mm/h); 2) maximize the delay time of the higher intensities (130 to 180 mm/h) to give the stepper motor time to stop and change directions; and 3) minimize the variability of rainfall across the width of the plot. The faster the motor moves, the longer it takes to decelerate, stop, and reverse directions. For the lower intensities, the maximum speed across the center of the plot is 4600 steps/s and the spray time for each pass across the plot is 0.30 s. The optimized maximum speed for the higher intensities is 2000 steps/s with a spray time of 0.47 s. The delay between oscillations is intensity dependent as described above. Table 1 shows the calculated percent spray time and the delay times in seconds for each of the intensities.

The delay times for intensities of 76 mm/h and less (table 1) were found to be too long. Preliminary comparisons of steady state runoff generated by the RBS and WGRS at similar field plots at the Walnut Gulch Experimental Watershed showed that at the higher application rates, the runoff rates were comparable, but at the lower application rates, runoff was less with the WGRS. We attributed this difference to the manner in which the two simulators account for the intermittent water application of the VeeJet 80100. With the RBS, any one point on the plot has intermittent application, but there is always water being applied somewhere on the plot so that the run on/runoff process is present. For the WGRS at the lower application rates run on/runoff was not apparent.

Nozzle Spray Time

To minimize the time that water is not being sprayed on the plots, the nozzle spray time on the plot is controlled using three-way solenoid valves that are used to turn the spray at each nozzle off and on during the oscillations. Spraying Systems, Inc. three-way, zero-pressure differential, normally open, 12-V solenoid valves were selected to control the spray times. A three-way solenoid has an inlet port, a bypass port, and two outlet ports. Three-way solenoids are used so that when the nozzles that spray on the plot are turned off, the water is diverted through the second outlet and off of the plot into a drainage system. This system ensures that a constant pressure of 55 kPa is maintained at the nozzle. If two-way (on/off) solenoids are used, there are pressure spikes when the nozzles are first opened and the desired flow rate of 29 L/s is significantly exceeded.

The solenoid valves are attached to the boom using spacers and hose clamps such that the nozzles are centered on the plot (fig. 4). The inlet valve on the solenoid is attached to the aluminum coupling on the boom using PVC elbows and 1.9-cm flexible hose. The bypass port is capped. The nozzles are attached directly to outlet one on the valves.

Table 1. VeeJet 80100 target application rates, % spray times, and delay times.

Application Rate (mm/h)	Spray Time (%)	Spray Time (s)	Delay Time (s)
25	7.6	0.30	3.66
51	15.2	0.30	1.68
76	22.7	0.30	1.03
102	30.3	0.30	0.69
127	37.9	0.30	0.49
152	45.5	0.47	0.57
178	53.0	0.47	0.42

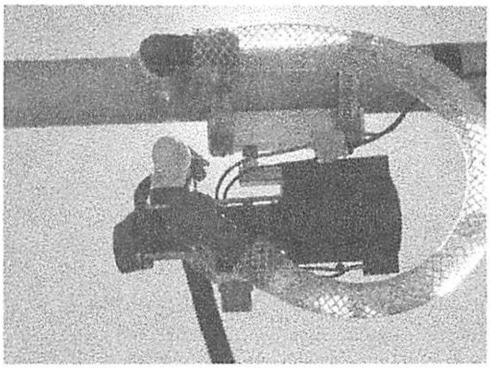

Figure 4. Solenoid and nozzle attached to central oscillating boom.

A second VeeJet nozzle is attached to the second outlet through a 1.27-cm PVC elbow and a flexible hose. An additional flexible hose is attached to the nozzle to direct the water into the drainage system. The second nozzle is necessary to have the same resistance pressure at both outlets; in this manner, a constant pressure of 55 kPa is maintained at the nozzle at all times. The nozzle pressure is checked using pressure gages, one on the fourth nozzle assembly and one mounted directly on the main boom at the universal swivel joint.

The solenoid valves are used in conjunction with the oscillation programs to decrease the time that water is not spraying on the plot for the lower intensities. Three different spray configurations are used. For the higher intensities, 76 to 180 mm/h, all four nozzles are on for each sweep of the boom across the plot. For these intensities, the delay times are the same as those times listed in table 1. The second configuration (64 mm/h) turns on alternate nozzles for each sweep across the plot. For the first pass, the first and third nozzles are on. For the second pass, the second and fourth nozzles are on. This configuration results in a delay of 0.49 s between oscillations, or 0.49 s that water is not being sprayed on the plot. The third spray configuration alternates all four nozzles; only a single nozzle is on for each of four oscillations, followed by a single sweep with all four nozzles on. For the passes with only a single nozzle spraying, the spray order is: nozzle three, nozzle one, nozzle four, and nozzle two. This order was selected to minimize any effect that the spray order might have on surface flow dynamics on the plot. For this spray configuration, the oscillation delay times range from 1.5 to 0.40 s (13 to 51 mm/h). The oscillation and nozzle spray times for the lower intensities are presented in table 2. The "oscillation delay time" is the delay between sweep of the boom and the "nozzle delay time" is the

Table 2. WGRS application rates, individual nozzle delay times, and oscillation delay times for the lower intensities.

Application Rate (mm/h)	Nozzle Delay Time (s)	Oscillation Delay Time (s)
13	4.20[a]	1.50
25	3.35[a]	1.16
38	2.07[a]	0.65
51	1.68	0.43
64	0.98	0.49
76	0.89	0.89

[a] These are average nozzle delay times. For these spray configurations, each nozzle sprays two out of every five oscillations.

delay time for an individual nozzle. For each oscillation, at least one nozzle is spraying on the plot.

Water Delivery and Recycling

The water requirements for the WGRS are much less than that of the RBS, primarily because the water not sprayed on the plot is returned to the water delivery tank. A 1900-L fiberglass water tank is placed near the simulator to deliver water to the main boom and to recycle the captured water that is not sprayed on the plot. A 4-hp gas powered pump is used to deliver water at approximately 172 kPa through a flexible 50.8-mm diameter drainage hose. The hose is connected to a filter and a pressure regulator and attached with a quick release coupling to a 5.08-cm diameter aluminum irrigation pipe mounted to the front leg of the simulator. The aluminum pipe is coupled to a universal swivel joint located at the base of the main boom using a small section of flexible hose (fig. 3). The pressure regulator is used to adjust the water pressure in the delivery system to ensure that the pressure at the nozzles is at 55 kPa.

The system for recycling water not sprayed on the plot was modified from the design used for the programmable rainfall simulator (Neibling et al., 1981). The programmable rainfall simulator has a single trough positioned directly under the main boom that captures and routes the recycled water. For the WGRS, the 1.27-cm flexible hose from the second solenoid outlet nozzle (fig. 4) is connected to a single trough (10-cm diameter pvc pipe) placed to the side of the main boom to capture and route the recycled water. The trough drains into a 7.62-cm diameter flexible suction hose that feeds back into the water tank. The drainage trough is positioned on top of the leg supports, offset from the boom by approximately 15 cm. As discussed previously, this system is designed so that the nozzle pressure can be maintained at 55 kPa to regulate the intensity. The unused water is not wasted, but drained back into the water supply tank.

Simulator Control and Operation

The timing of the oscillations and the nozzle solenoids are controlled using a data logger, relay boards, and knob switch. A Campbell Scientific CR10X data logger is used to signal the controller when to oscillate, which program to run, and at which intensity. A control box was built that contains a mechanical knob and an on/off switch. The intensity is set manually using the mechanical knob which sets a binary switch that is connected to the CR10X data logger. The applied intensity can be changed on the fly, by simply turning the knob. The data logger records the intensities and respective durations. This information can then be output to a file at the end of a simulation run. The solenoids are connected to the CR10X via a four-panel relay board. The sequencing of the nozzles is again determined by the intensity set at the knob and controlled by the CR10X program for that intensity. A laptop computer is used to communicate directly with the motor controller and position the boom before each simulator run. The laptop is not needed while the simulator is running. The laptop can also be used to communicate with the CR10X data logger to download the output file or to reload the program, if necessary.

A schematic of the WGRS control equipment and how it is connected is presented in figure 5. All of the simulator equipment is powered by two 12-V deep cycle batteries,

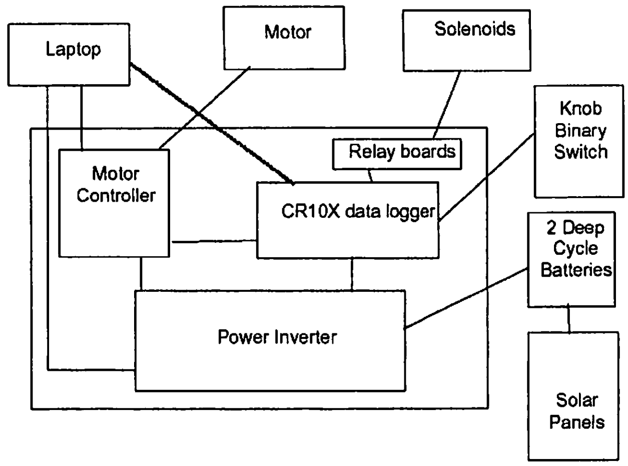

Figure 5. Schematic of the WGRS control equipment.

except for the gas-powered pump. The batteries are connected to a 1200-W sine wave power inverter that powers the controller, motor, laptop, CR10X data logger, relay boards, and solenoids. Two 60-W solar panels are used to maintain the charge on the batteries while the simulator is running.

Evaluation of the WGRS

Evaluation of the WGRS included quantifying the spatial distribution of water applied on a 2- × 6.1-m plot and verifying the application rates. Two different methods were used to measure the distribution and the final application rates. The rainfall distribution across and down the length of the plot was measured using Tru-check, cumulative rain gages. To determine the resulting application rates, plot average application rates were measured. Tru-checks were used in the program and testing processes as well as the final evaluation of the programs. Tru-check gages can measure up to 152 mm of rainfall and are 34 cm tall with a 5.8- × 6.4-cm opening. Two different arrangements of the rain gages were used. To evaluate the spacing of the nozzles along the boom and the optimum pressure to use, Tru-checks were spaced every 0.6 m down the center of the plot. The simulator was raised so that the height of the nozzles was 2.44 m above the opening of the Tru-checks. For the final nozzle configuration, the CV of the rainfall distribution down the length of the plot was 9.5%.

To test the distribution and timing for the two programs, i.e. low and high intensities, in the controller, 28 Tru-checks were arranged across the plot in a 4 × 7 grid with the gages spaced at 30 cm. The distribution across the width of the plot is determined by adjusting the acceleration and deceleration points in the controller program. Because the 28 gages only covered a 1.2- × 2-m area, once the distribution for a given program had a CV of approximately 10% or less, the same program was run with the grid in different locations on the plot. Testing the final program for the low intensities (13 to 130 mm/h), the CV of the measured rainfall distribution was 9%, and the Christiansen coefficient of uniformity (CU, Christiansen, 1942) was 92.7%. For the high intensities (140 to 200 mm/h) the CV of the rainfall distribution was 11% and the CU was 91.6%. The measurement results for the target intensity of 177.8 mm/h are presented in table 3. Though the

Table 3. Rainfall distribution measurements (mm/h) using Tru-checks on a 30-cm grid at three locations on the plot.[a]

Position	Position Across Plot (cm)						
(cm)	10	40	70	100	130	160	190
30	142.24	167.64	193.04	193.04	187.96	167.64	142.24
60	142.24	172.72	180.85	177.80	177.80	177.8	170.69
90	152.40	187.96	193.04	193.04	193.04	193.04	193.04
120	152.40	177.80	177.80	175.79	193.04	193.04	193.04
200	142.24	167.64	167.64	177.80	182.88	193.04	177.80
230	137.16	147.32	166.62	174.75	166.62	162.56	152.40
260	137.16	147.32	177.80	177.80	174.75	177.80	152.40
290	152.40	177.80	181.86	193.04	184.91	177.80	172.72
410	152.40	162.56	167.64	175.77	167.64	185.93	170.69
440	138.18	175.77	198.12	196.09	198.12	172.72	152.40
470	147.32	186.94	197.10	198.12	198.12	195.07	177.80
500	159.51	203.20	208.28	203.20	203.20	195.07	188.98

[a] The target intensity was 177.8 mm/h. The average intensity from the Tru-checks was 175.5 mm/h with a CU of 91.6% (CV of 10.4%).

CV for the higher intensity is slightly higher than our original target of 10%, the distributions are comparable or better than those from other oscillating boom rainfall simulators. Neibling et al. (1981) reported coefficients of uniformity of 87% to 91% for the programmable rainfall simulator for three different 1.2- × 1.7-m measurement locations on a plot. Loch (1997) reported measured CVs of 12.2% to 13.4% on a 2- × 6-m plot.

The application rate is determined by changing the delay time at the end of each oscillation. The relationships between the target application rate and the delay times were presented in tables 1 and 2. To verify the accuracy of the application rates, the rainfall simulator was set up over a 2- × 6.1-m rainfall simulator plot covered with plastic sheeting. Runoff depths were measured at the end of the plot using a pre-calibrated flume attached to a flow depth gauge. The runoff depths were converted to discharge rates using the flume rating curve and the entire plot area (Simanton et al., 1991).

A comparison of the target rates and the measured application rates are presented in table 4. The agreement between the target and the measured application rates was very good. The differences range from 0.2 to 3.71 mm/h, or 0.55% to 3.28%. The depth flow gauge has a measurement accuracy of ±0.882 mm. The differences between the target and measured application rates are within the measurement error of the flow depth gauge.

Table 4. Comparison of target and measured application rates for the WGRS.

Target Rate	Measured Rate	Difference	
(mm/h)	(mm/h)	(mm/h)	(%)
25.40	25.60	-0.20	0.78
38.10	39.35	-1.25	3.28
50.80	51.93	-1.13	2.22
63.50	63.70	-0.20	0.32
76.20	75.78	0.42	0.55
88.90	87.07	1.83	2.06
101.60	100.49	1.11	1.09
114.30	113.16	1.14	1.00
127.00	123.29	3.71	2.92
139.70	139.49	0.21	0.15
152.40	152.90	-0.50	0.33
165.10	162.68	2.42	1.47
177.80	175.84	1.96	1.10

Conclusion

The Walnut Gulch Rainfall Simulator was developed to advance the ability to measure infiltration, runoff, and erosion processes on rangelands. The simulator can apply a large range of rainfall intensities, 13 to 178 mm/h in 13-mm/h increments on a 2- × 6.1-m plot. This ability facilitates the study of the relationships among rainfall intensity, spatial variability of infiltration and runoff and erosion processes. The simulator is portable, and easy to set up and run. Water use is minimized by recycling the water that is not sprayed directly on the plot during a run. The controls developed for the simulator allow the user to easily change among intensities. The coordination between the timing of the oscillations and the nozzle spray time minimizes the time when the nozzles are not spraying on the plot. The simulator has been tested in both laboratory and field applications. The ability to apply a large range in rainfall intensities under controlled conditions has increased and enhanced the knowledge and insights into hydrologic and erosion processes gained from rangeland plot studies.

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