# A New Rainfall Simulator for Use in Low-energy Rainfall Areas

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**Abstract.** *A sound assessment of hydrologic and erosional responses in wildland and agricultural ecosystems to rainfall requires that rainfall simulators mimic natural rainfall. The accuracy and usefulness of the assessment improves with increased similarity between natural and simulated rainfall. Some characteristics of natural rainfall important to rainfall simulation include rainfall energy, intensity, distribution, drop size distribution, time or season of application, and plot size. Our purpose for constructing a new rainfall simulator was to improve an old design with current technology. This equipment is especially needed for research in regions with low energy rainfall and convectional storms are not the primary source of excess rainfall and subsequent erosion. We developed a new rainfall simulator to simulate low energy rainfall under a wide range of ambient weather conditions. The simulator consists of four structures. Each structure simulates rainfall onto a 1.5 m wide × 9.1 m long plot, and consists of a frame for structural support and wind screening, three rotating disk-single nozzle modules, and control systems. The nozzle modules produce rainfall at five discrete intensities; 4.5, 9.0, 13.4, 17.9, and 35.8 mm/h. At the control center, water pressure at each nozzle is monitored and controlled to insure consistent rainfall over all treatments. Data loggers record water and air temperature in each structure during rainfall simulations. We tested uniformity of rainfall distribution and rainfall intensity. The coefficient of application uniformity for rainfall distribution within each structure is greater than 76, and rainfall intensity does not vary significantly (± 1 standard deviation) between structures. For our purposes, we developed this simulator for the evaluation of residue management, tillage methods, and farming systems. We used the simulator in subfreezing weather to evaluate residue management practices and concluded that the simulator is operable for data collection during all seasons and temperatures ranging from –5°C to 40°C. Rainfall simulation continues to be an important tool in efforts to understand how wildland ecosystems function and how agricultural practices might be improved. This rainfall simulator is an appropriate tool for hydrologic and erosion research in low energy rainfall regions.*

***Keywords.** Erosion, Rain simulator, Runoff, Interrill erosion, Rill erosion.*

The purpose of rainfall simulation is to create rainfall characteristics typical to the region of use. Rainfall simulators developed in the mid and southwestern United States (U.S.) produce high energy rainfall typical of the erosive convective storms common in that region. These storms have large diameter raindrops, produce considerable kinetic energy, and generally occur at high intensity. Low energy rainfall is typical in areas where storms originate as warm marine frontal systems and move inland, as in western North America, Ireland, England, and northern Europe. In the Pacific Northwest (PNW) U.S., 95% of the storms are < 4 mm/h (Columbia Plateau Conservation Research Center (CPCRC) records), with small drop size of 1.7 mm median diameter, $D_{90}$ = 2.6 mm (Bubenzer et al., 1985), and a mean depth and duration of 1.5 mm and 3 h, respectively (Zuzel et al., 1993). Because of the small drop size and slow rate of delivery, there is insufficient energy to cause splash erosion. Most of the erosion from these storms does not result from soil particle dislodgement by raindrop impact. Rather, between 30 to 86% of erosion results from rain or snowmelt water that is unable to infiltrate frozen cropland soils (Zuzel et al., 1982; McCool et al., 1995). Erosion occurs as rills develop in saturated surface soils in the approximately 1.8 million ha annually planted to winter wheat (*Triticum aestivum* L.) following summer fallow (Smiley, 1991; McCool et al., 1993). Forest and rangeland sites also are subject to erosion as a result of the freeze/thaw cycle, particularly in circumstances where vegetation has been lost to fire or mismanagement. Under these conditions, land management plays a crucial role in the temporal variability of erosion events (Zuzel et al., 1993). This article introduces a rainfall simulator capable of mimicking natural low energy rainfall for the evaluation of soil and water conservation effectiveness of land management practices.

## Rainfall Simulator Criteria

Low energy rainfall simulators have received relatively little research and development attention (Amerman et al., 1970; Bubenzer et al., 1985) compared to high energy simulators, e.g., Byars et al., 1996;

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Edwards et al., 1992; Foster et al., 1982; Meyer and Harmon, 1979; Radke, 1995; Swanson, 1965; or Wilcox et al., 1986. Two design features, more than any others, distinguish between high and low energy rainfall simulators: choice of nozzle and the method of regulating rainfall intensity (depth per unit time).

Nozzles chosen for high energy rainfall produce large droplets at relatively low nozzle pressure (41 kPa). High energy rainfall simulators have used Spraying System Vee Jet nozzles since 1958 (Foster et al., 1979). These nozzles produce a fan spray at a large angle of exit from the orifice. A sweeping motion is needed to cover a meter square area or larger. The fan is swept across an opening in the simulator body and the frequency of sweep determines rainfall intensity. A more extensive description of Vee Jet based simulator designs can be found in Neff et al. (1979).

Nozzles chosen for low energy rainfall require a nozzle pressure (100 kPa) to produce small droplets. The high pressure, although producing the required small drop size, also delivers rainfall in excess of the desired low intensity. Nozzles producing the prerequisite small drop size create square or round spray patterns with a low angle of exit from the orifice. To regulate rainfall intensity from these nozzles, Morin et al. (1967) developed the rotating disk rainfall simulator. Its most touted advantage over the sweep system was that it produced a nearly continuous rain compared to the sweep method used for the Vee Jet nozzles. Amerman et al. (1970) improved the rotating disk design by developing a system to vary rainfall intensity. With the choice of Spraying Systems 1/4HH-SS14SQW and additional modifications, Bubenzer et al. (1985) introduced the Palouse Rainfall Simulator specifically for use in the PNW (U.S.).

Additional changes by Bubenzer et al. (1985) to the Amerman et al. (1970) design included suspending two simulator modules (rotating disk and nozzle assembly) by booms anchored on a small utility trailer. With this design, the trailer could be pulled into a field, positioned between two 1 m × 1 m plots, the booms and modules extended, and rainfall simulation research conducted. The 1 m × 1 m plot size is suitable for rapid treatment comparisons of interrill erosion. However, the plot size is not adequate for the study of rill formation and development. Multiple units of the Palouse simulator were expected to be linked together to increase plot length. Unfortunately, proper nozzle placement for uniform rainfall distribution was not attainable. Furthermore, because the simulators are attached to trailers, wet and thawing fields limit the movement and positioning of the simulator to sites very near roadways, or to periods when the soil is frozen.

## The New Simulator

Our purpose for designing a new rainfall simulator was to solve the problems associated with linking multiple modules of the Palouse simulator. We decided that the new simulator, (Pacific Northwest Rainfall Simulator ~ PNRS) must be capable of covering plots long enough for rills to form (greater than two meters). In doing so, it must provide uniform distribution of drop sizes and depth across the plot area, and produce energy and intensity commensurate with natural rainfall. Furthermore, it must work on slopes up to 25 to 30%, in temperatures ranging from −5°C to 40°C, in winds up to 30 km/h, and provide uninterrupted rainfall for up to four hours. For quality control of data collection, any improvement to the simulator needed to include monitoring devices for air and water temperature, and nozzle pressure.

To overcome the problems of linking multiple Palouse simulators, we designed the PNRS to simulate rainfall onto 1.5 m wide × 9 m long plots (figs. 1 and 2). A 3 m wide × 12 m long frame was adopted from a manufactured portable garage. Each frame disassembles into to two 6 m long halves for moving within a field from plot to plot. The frame supports nozzle modules and a wind guard to prevent the wind from blowing raindrops away from runoff plots. The cover material purchased with portable garage was adequate to prevent droplet disturbance by light winds, but was prohibitively heavy for rapid disassembly and assembly. We eliminated this problem by replacing the heavy material with 1.7 mm mesh rip resistant fabric. The frame width allows passageway between wind guard and plot. Anchoring the frames with rope to steel fence posts driven into the soil allows use of the simulator in winds up to 30 km/h. We decreased plot width from the 1.8 m, used

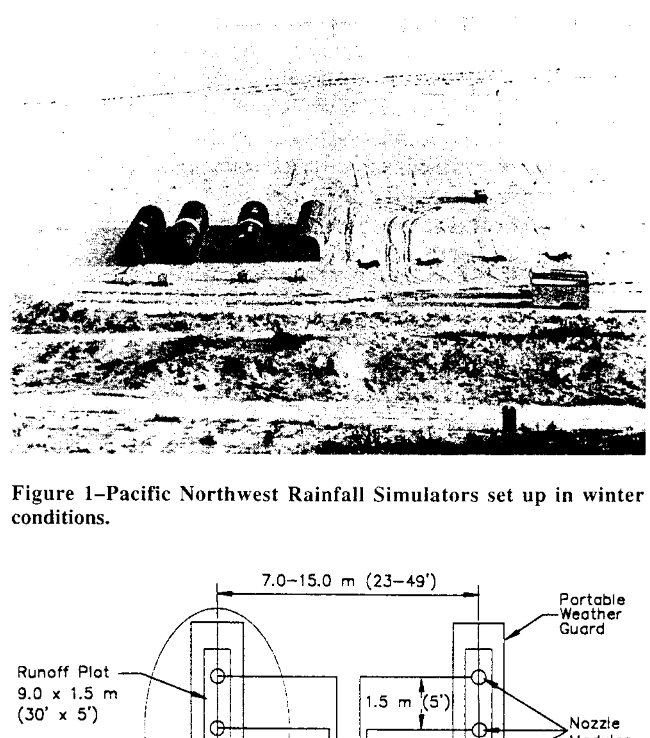

**Figure 1–Pacific Northwest Rainfall Simulators set up in winter conditions.**

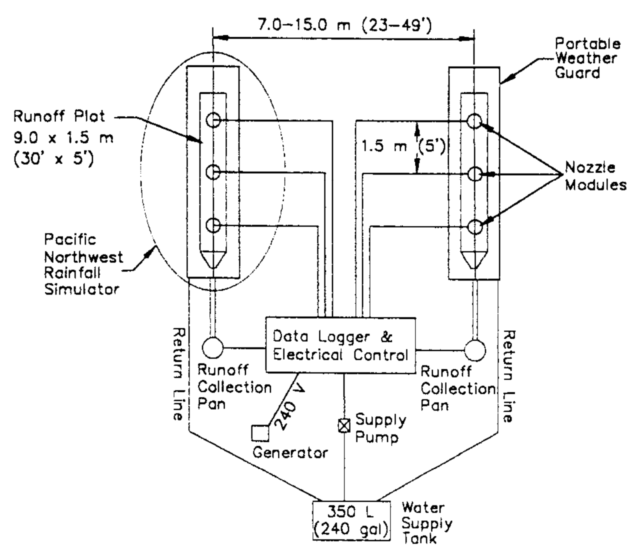


**Figure 2–Layout of two Pacific Rainfall Simulators with power sources, control center, and water supply.**

with the Palouse simulator, to improve uniformity of rainfall across the plot while marginally sacrificing distribution down slope (fig. 3).

Portability, or ease of relocation, is one of the most important characteristics of a rainfall simulator. A major impediment to the portability of this rainfall simulator is the rotating disk modules. We attempted to eliminate this component through the use of a solenoid activated valve system to reduce flow to natural rainfall levels. This method successfully reduced flow, but did not create the instantaneous pressure changes necessary to maintain droplet development and even droplet distribution. Our use of a solenoid valve system resulted in a very poorly distributed, cone-shaped rainfall pattern. We concluded that the rotating disk remains the most effective method of regulating rainfall intensity and maintaining droplet distribution. We tested a much smaller version of the rotating disk, but found that minimum disk size is determined by the angle and pressure of water flow from the nozzle. Disks with a diameter smaller than 700 mm were judged unacceptable due to disruption of the spray pattern and excessive splash resulting in large drops immediately beneath the nozzle.

Each frame contains one set of three rotating disk nozzle modules suspended 2.5 m above the plot from a 3 m × 10 m hoop frame positioned lengthwise with the plot (fig. 4). The Palouse simulator used Spraying Systems 1/4HH-SS14SQW nozzles, also mounted in rotating disk modules and producing 2 $m^2$ wetted areas per nozzle. After discussing droplet and distribution characteristics with the manufacturer, two nozzles (1/4HH-SS14SQW and 1/4HH-SS14.5SQ) appeared to meet our requirements. The 14SQW consistently produced a more even distribution pattern and remains the preferred nozzle. This nozzle, at a pressure of 100 kPa, creates a distribution of drop sizes approximating natural rainfall (Bubenzer et al., 1985), with similar raindrop impact energy; i.e., 260 kJ/mm·ha (nozzle) and 240 kJ/mm·ha (natural).

An aluminum rotating disk module supports each nozzle (fig. 5) and is smaller and lighter than the rotating disk module of the Palouse design. The disk module hangs from the simulator frame and supports the nozzle, rotating disk, and a 120 V, 75 W gearmotor to rotate the disk. A pan suspended from the frame collects and returns excess water to the supply tank. Aluminum mesh screens, added to flat surfaces of rotor disks, and sharpened metal edges eliminate splash and large drops, and reduce drip points. More detailed diagrams are available upon request.

We designed the modules to produce rainfall at five discrete intensities:4.5, 9.0, 13.4, 17.9, and 35.8 mm/h. The lowest application rate is equal to or greater than 95% of the rainfall recorded at CPCRC between 1982 and 1995 in one-hour periods. The second lowest intensity is expected to reoccur every 10 years. The third, fourth, and fifth intensities are available for studying the influence of high intensity, low energy rainfall on infiltration, runoff, and erosion. Each disk has four equally sized open slots, equaling one-half of the disk area. Rainfall intensity is changed by inserting pans to close the open slots. The rotating disk must be stopped to insert or remove the pans. Rainfall intensity changes require less than five minutes per simulator (set of three nozzles).

A control center for each set of two simulator frames consists of a Campbell Scientific 21X data logger, a manifold to supply and control water pressure to individual nozzles, and a 120/240 V power supply box controlled by ground-fault interrupter circuit breakers. The power supply

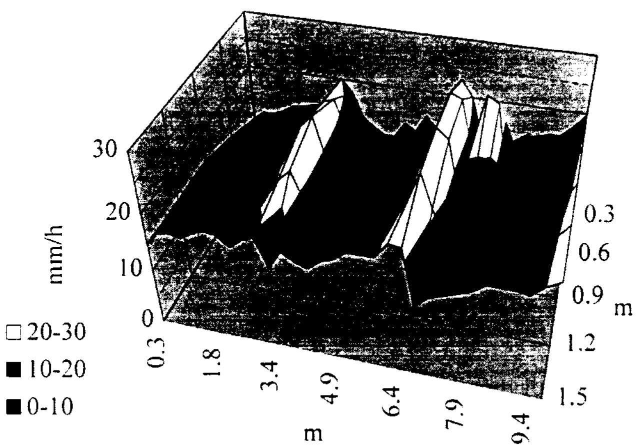


**Figure 3–Rainfall distribution over plot surface. The peaks in the 20 to 60 mm/h range are areas of nozzle overlap.**

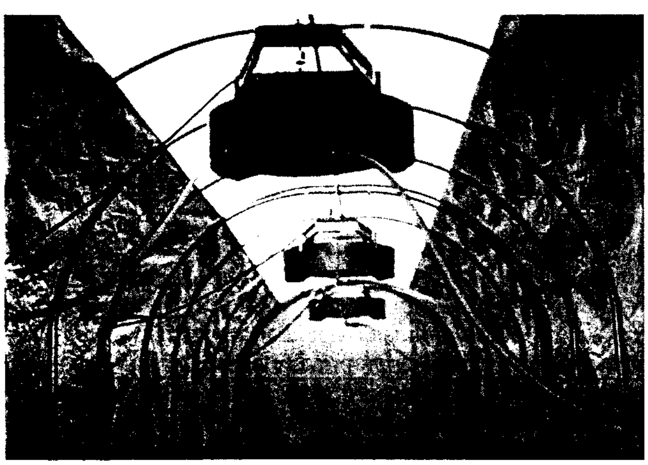

**Figure 4–Nozzle modules suspended in frame with wind guard in place.**

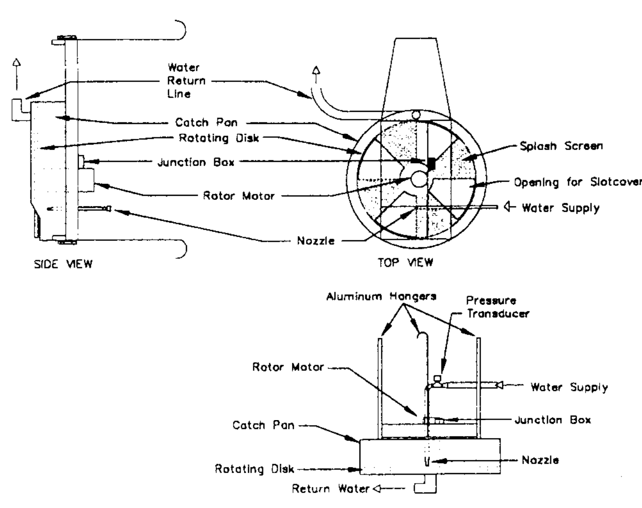


**Figure 5–Nozzle module used to support nozzle, rotating disk assembly, and catch pan assembly.**

box is grounded by driving a 1 m brass rod at least 500 mm into the earth. Twist-lock plugs were used on all electrical lines to insure secure and waterproof connections. A 6 kW, 120/240 V, 50/25 Ω portable generator supplies power for two units. Nozzle pressure, air, soil and water temperature, and runoff data are recorded by the data logger. The data logger reads the in-line pressure transducer at each nozzle every 10 s, and records and provides a visual readout every 60 s to aid in continuous pressure adjustment and control. Pressure corrections for individual nozzles are made using gate valves at the manifold. Individual nozzles can be disconnected from the power and water supplies in the event of plugging or other service needs.

Water is transported to a research site in a 15 kL semi-tank trailer. One nurse tank (350L) supplies each set of two simulator frames. Water is supplied by a 240 V, 7.5 kW pump from the nurse tank via 51 mm braided plastic hose to the control manifold. From the control manifold, 19 mm braided plastic hose supplies water to the nozzles and 38 mm lines return excess water caught by the disk module pan to the nurse tank. To facilitate rapid assembly, all hose fittings were of a cam-lock design.

When disassembled, the four simulators and support equipment fit in three trailers for transportation. The frames and tanks travel on a "goose-neck" flatbed trailer and the rest of the system fits in two six-meter cargo trailers. Borders for runoff plots can either be metal sheeting or fabric. We use fabric borders and install them using a border installation device (Warn et al., 1981).

The simulator is usable in subfreezing weather if adequate care is taken to drain the pump and all water lines at the end of each simulation. Nozzles, manifolds, and pumps are stored in a heated building between simulations to prevent damage by freezing.

Four simulator units can be readied for use in 7 h by four persons. A minimum of 10 persons are required to operate the four simulator structures; one person per control unit (2), one person per plot to collect runoff and erosion samples (4), and two persons maintaining the water supply, two persons to maintain plot borders, catch troughs and change rotor opening settings for intensity changes.

## Simulator Uniformity Testing

Four rainfall simulator units were constructed and calibrated to produce equal intensity rainfall that is evenly and consistently distributed. We calculated rainfall intensity in each of the simulator units by collecting rainfall for three 30-min periods in 132 evenly spaced soil tins within a 1.5 m × 9 m area. We measured the water volume in each can, and converted it to a depth value (mm/h) to obtain intensity and distribution values (table 1 and 2). To evaluate depth distribution, we used the Christiansen coefficient (Cu) of application uniformity (eq. 1, Christiansen, 1942):

$$\mathrm{Cu} = \left(1 - \frac{\text{average deviation from mean}}{\text{mean depth of applied water}}\right) \times 100 \quad (1)$$

A uniform depth distribution generates a Cu = 100.

**Table 1. Rainfall intensities at 100 kPa**

| Disk Area | Open Slot(s) | Intensity, mm/h | (in./h) |
|---|---|---|---|
| 1/8 | 1 | 4.5 | (0.18) |
| 1/4 | 2 | 9.0 | (0.35) |
| 3/8 | 3 | 13.4 | (0.53) |
| 1/2 | 4 | 17.9 | (0.71) |
| Disk stopped | Open slot | 35.8 | (1.41) |

**Table 2. Rainfall intensity and Christiansen coefficient of application values for each of the four simulators calculated from four 30-min runs**

| Simulator | Intensity, mm/h (in./h) Mean | | Standard Error | | Christiansen Coefficient Cu |
|---|---|---|---|---|---|
| 1 | 17.7 | (0.70) | 0.7 | (0.03) | 78 |
| 2 | 18.0 | (0.71) | 0.6 | (0.03) | 81 |
| 3 | 17.6 | (0.69) | 0.4 | (0.02) | 76 |
| 4 | 18.3 | (0.72) | 0.2 | (0.01) | 80 |

**Table 3. Nozzle pressures within one simulator, measured under laboratory conditions at one-minute intervals for 30 min**

| Nozzle | Pressure Mean kPa | (psi) | Standard Error | |
|---|---|---|---|---|
| 1 | 104.0 | (15.07) | 0.2 | (0.03) |
| 2 | 104.0 | (15.07) | 0.2 | (0.03) |
| 3 | 104.1 | (15.09) | 0.2 | (0.03) |

The Christiansen coefficient for each simulator unit of three nozzles, calculated by running each simulator four (4) times at 1/2 disk opening (17.9 mm/h), compares favorably with the value of 80 obtained for single nozzles at low intensity (6 mm/h) by Bubenzer et al. (1985) (table 2). Based on Bubenzer et al. (1985), we expect the Cu to be slightly lower for the lower intensities. Average rainfall intensity did not differ significantly between simulator structures in four calibration runs (SAS, 1995).

Rainfall distribution is not measurable during soil and water conservation experiments, thus nozzle pressure becomes the measure of simulator performance. During uniformity testing, we found no significant differences in pressure between nozzles of individual simulator units (table 3). We collected nozzle pressure data during field use for quality control of runoff and erosion data and for further evaluation of the simulators. Rainfall was simulated at air temperatures of –4°C and frozen soil and continued until air temperatures increased to 4°C and the soil had thawed. The coefficient of variation for these data, 292 h recorded each minute, was 5.3 kPa (0.77 psi) and demonstrates the high degree of control available for application of uniform and consistent rainfall.

Further analysis of the pressure data collected indicates a consistently lower reading [–2.6 kPa (–0.38 psi)] at the furthermost nozzle upslope. Although this difference is physically minor, simulator operators should be aware of it and compensate with appropriately higher pressure settings. In the field data acquisition runs, average nozzle pressure between rainfall simulators varied within the coefficient of variation. To overcome any systematic errors in data collection, simulators should be rotated among treatments.

## Notes on Field Use

We used the PNRS to collect data runoff and erosion data during five rapid thawing periods over the course of two winters. Each time, the simulators were assembled during temperatures of –10°C or less on 15 to 25% slopes. All rainfall simulations were begun at temperatures ranging from –5°C to 0°C. Following rainfall simulations, we were able to move the simulators from one set of plots to the next during thaw periods, an impossible task for the trailer-mounted Palouse Simulator. It was in the process of disassembling, moving, and reassembling the simulators on the steepest slopes that we reached our decision to use lighter material for the wind guards. Changing to the lighter material decreased the setup and takedown time by approximately one hour for each simulator.

Based on our original power requirement calculations and simulator performance on an approximately 5% slope during uniformity testing, we began the field work with two 5 kW, 120/240 V, 42/21 Ω generators, one generator for each set of two simulators. These generators did not provide sufficient power to the pumps to maintain the required nozzles pressure. This problem can be solved by using the 6 kW, 120/240 V, 50/25 Ω portable generators, as recommended above.

The rapid thawing conditions were accompanied by recorded light winds up to 25 kph. Isolating the plots inside of the wind guards effectively prevented the wind from blowing the simulated rain from the plots. Additionally, the wind guard served as a rainout shelter, during one day of simulation noted for the intense natural rainstorm that occurred, preventing the addition of uncontrolled natural rainfall to our experimental plots.

Although we were successful in our efforts to use the PNRS for runoff and erosion data collection, the mobility of the units could stand improvement. Our greatest difficulty in moving the simulators was encountered on the steep slopes. Even disassembled and only 6 m long, a minimum of six persons was required to lift, carry, and position the frames over the next set of plots. This problem could be considerably lessened by the development of an alternative to the nozzle modules containing the rotating disks.

## Summary

The Pacific Northwest Rainfall Simulator was developed to apply low energy, low intensity rainfall to 1.5 m × 9 m plots under a variety of weather conditions. The increased plot length provides the opportunity to study rill formation and development under rainfall conditions. Uniformity test results conducted on four rainfall simulators show that the design produces consistent and evenly distributed rainfall. We collected nozzle pressure data during uniformity testing and soil and water conservation experiments conducted in subfreezing temperatures. From the analysis of these data, we demonstrated the high degree to which rainfall application can be controlled with this simulator.

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