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A Portable Rainfall Simulator: Techniques for Understanding the Effects of Rainfall on Soil Erodibility

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Introduction

Rainfall simulations are used to help us understand the effects of rainfall on soil properties under various conditions. To study the effects of wildfire on runoff generation and soil erosion during rainstorms, we constructed an effective yet simple rainfall simulator that was inexpensive, portable, and easily operated by two people on steep, forested slopes. The simulator generated results that were useful in understanding runoff and sediment production in burned and unburned forests. This article describes how to construct the simulator and install plots for field data collection.

Background

Studying soil erodibility properties in nature can be extremely difficult because of the natural variability of rainfall intensity, location, frequency, and duration, as well as variable slope and soil conditions. On a small spatial scale, rainfall simulators can be useful tools to help quantify the amount of infiltration excess runoff (Hortonian overland flow) and erosion generated by different rainfall intensities, considering factors such as slope, soil type, burn severity condition, and the type of forest floor. These data can help us understand basic water balance equations and the effects and importance of the forest floor on water storage. The data can be used to generate specific soil parameters such as infiltration, soil erodibility, hydraulic conductivity, and water repellency that can be used to drive erosion process models such as WEPP (Water Erosion Prediction Project) (Flanagan and Nearing 1995).

Various types of rainfall simulators have been built in the United States and Canada for use on agricultural soils (Meyer and Harmon 1979; Shelton et al. 1985; Humphry et al. 2002), on skid trails (Commandeur and Wass 1994; Foltz and Maillard 2003), and for rangeland, forested and burned slopes (Commandeur 1992; Robichaud 2000; Brady et al. 2001; Pierson et al. 2003; Kinner and Moody 2008).

There are two basic designs of rainfall simulators: drip tube and nozzle. The drip tube design consists of a constant-head water reservoir placed at the top of the simulator, which feeds a grid of several hundred capillary tubes (Munn and Huntington 1976; Commandeur and Wass 1994). The nozzle design uses a water source that feeds one or more nozzles at a constant specified pressure. Of the two water application methods, the nozzle design has several advantages in that it is more portable, can produce greater and different intensities, and can create a more random drop pattern similar to natural rain (Kinner and Moody 2008).

The simulator design described here was based on the nozzle-type simulator developed by Humphry et al. (2002). It was altered to fit the specific requirements of a study into the effect of rainfall on runoff and soil erodibility in different wildfire burn severity conditions, and to understand the role of the forest floor in water storage and erosion response in southeastern British Columbia. The simulator needed to produce constant, high-intensity, simulated rainfall for 20-minute intervals, be operated by a 2-person crew on steep forested slopes, and be portable and inexpensive.

Rainfall Simulator Design

The simulator consists of an extendible tripod base that supports a single, fixed spray nozzle above the plot (Figure 1). A small fire pump was used to draw water from a collapsible, 273-L still-well water bladder to supply constant pressure to the nozzle.

The tripod base is constructed of three dry-wall support rods (Task Quick Support Rod) extendable to 3.3 m with flat articulated feet that can be spiked into the ground for stability. The upper portion is a

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Figure 1. Rainfall simulator on a 50% slope.

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rigid frame of three 38-mm angle-aluminium leg extensions (1 m long) supporting a 30-cm square, 19-mm plywood top. The leg extensions ensure the nozzle reaches 3 m high when positioned on a slope up to 60%. Many rainfall simulators are designed with the nozzle at a height of 3 m to replicate the velocity and kinetic energy of natural rain (Meyer and Harmon 1979; Commandeur and Wass 1994; Humphry et al. 2002). A 6-PSI flow regulator and a spray nozzle extend through a hole in the middle of the plywood top. The simulator used a single nozzle (Spraying Systems 1/2HH-30WSQ) to deliver simulated rain over a 1-m^2 plot. Because of the limited water storage capacity of our system, this nozzle is slightly smaller than the nozzle used by Humphry et al. (2002) (1/2HH-50WSQ). A level and a hook for a plumb bob were attached to the nozzle for levelling and centring the nozzle over the plot. The height was set by adjusting and positioning the legs so that the hanging plumb bob touched the centre of the plot when the level bubble was centred.

A small pump (Shindawa GP25) delivered water from the water bladder to the simulator through a 12.7-mm garden hose (Figure 2). An adjustable valve at the base of the simulator, along with a pressure gauge at the outlet of the pump and one at the nozzle, were used to achieve the desired nozzle pressure.

Four collapsible water bladders were used for water supply. Three of these were filled in the truck from a nearby creek using a large pump (Mark 26) and 3.8-cm fire hose. The water from one of the bladders in the truck was then transferred to the fourth bladder located approximately 5 m vertically upslope from the simulator for each 20-minute simulation. These water bladders were compact and portable making them ideal for transport.

Rainfall Characteristics

Intensity

The rainfall simulator described in this article was designed to simulate high-intensity, short-duration rainfall similar to that generated by convective rainstorms. This type of rainfall (as opposed to rain-on-snow or snowmelt) causes the dislocation and transport of surface soil particles and is the leading cause of post-fire erosion events in the United States (Gartner et al. 2005). The simulator generated an average rainfall intensity of 74 ±3 mm per hour for 20 minutes, which is similar to the maximum 100-year storm intensity (73 ±24 mm per hour) for a 15-minute period near Castlegar, BC (Environment Canada 2008). An intensity of this magnitude was necessary to generate runoff on unburned forest floors and thereby show a comparison with runoff from burned sites (P. Robichaud, pers. comm., July 2007). Depending on the objectives of the study, simulated rainfall intensity and duration can be varied by altering the nozzle type and water pressure. The rainfall intensity we achieved was the maximum possible with our simulator setup; however, a larger water source and different nozzle types could be used to generate greater intensities. Other, more complex rainfall simulators are also available that can produce higher intensities (Robichaud 2000; Pierson et al. 2003).

Figure 2. Still-well bladder and small pump supplying water to simulator downslope.

Drop Size and Velocity

We assessed the drop characteristics to ensure comparability with other rain simulation studies. A tripod-mounted digital camera was used to photograph the raindrops at 1/500 second shutter speed against a 10 × 10-cm grid backdrop. To calculate fall velocity and diameter of drops, the length and width of 200 drops falling closest to the grid were measured directly from 10 consecutive photographs. Figure 3 illustrates the distribution of drop sizes.

Because of our simulator's smaller nozzle size, the median drop size of 1.4 mm was approximately three-quarters of that measured by Humphry et al. (2002). Drop-size distribution fell between 0 mm and 6 mm, with the majority falling between 0 mm and 3 mm. In comparison, Cerda (1997) observed raindrop sizes in natural, high-intensity rainstorms (maximum 120 mm per hour) to range from

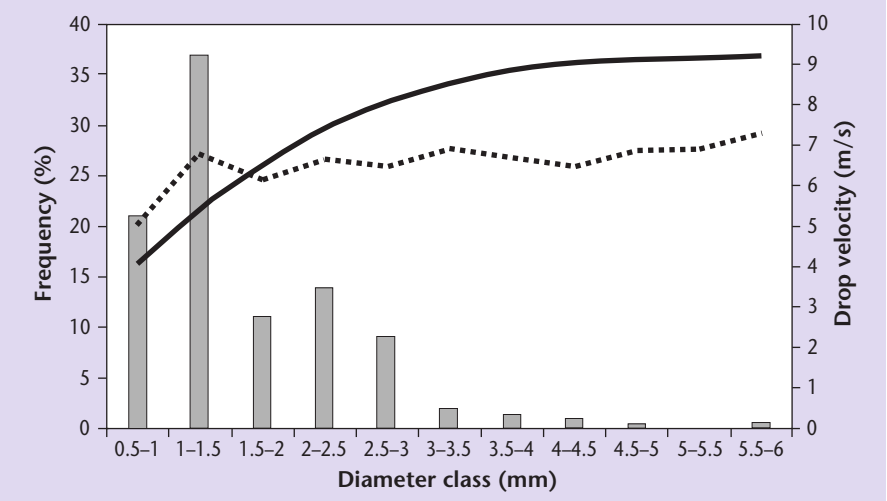

Figure 3. Drop-size distribution (bars) shown with the average measured drop velocity (dotted line) for each diameter class. Terminal velocity values (solid line) for drops of various diameter classes are shown for comparison (Epema and Riezebos 1983).

0 mm to 3.87 mm from measurements taken over a 7-month period in the Mediterranean, which is also comparable to measurements in the United States.

The velocity for the median drop size of 1.4 mm was estimated at approximately 6.9 mm per hour, which is 7% higher than terminal velocity of drops measured by Epema and Riezebos (1983). The less frequent, larger drops in the 1.5–3 mm range fell 5% slower than similar-sized drops at terminal velocity. Drops greater than 3 mm fell at approximately 75% of terminal velocity. Epema and Riezebos (1983) found that drops greater than 3 mm require a fall distance of approximately 13 m to reach terminal velocity, which is difficult to achieve with this apparatus; however, only 6% of drops generated by this simulator were greater than 3 mm.

Plot Setup

For our study, a sample of five 1-m^2 plots was grouped in each study site (e.g., high burn severity, moderate burn severity, and unburned). Because of the time needed to set up the plots and equipment, the plots were grouped together so that minimal movement of the equipment was necessary.

A 1-m^2 steel plot border, constructed of 3-mm steel plate with 10-cm sides was installed for each plot. These borders were pounded into the soil approximately 5 cm deep leaving 5 cm above ground to prevent inflow and outflow of water from the plot. The downslope edge of the border was level with the ground surface so the surface runoff and sediment flow directly into a trough (Figure 4). The trough is a PVC gutter pipe with a cap at one end and an open valve at the other. The trough was set into the ground below the lower lip of the plot border, and placed on a slight slope so that the runoff and sediment from the plot drained from it into sample bottles. A plexiglas shield was placed over the trough to ensure that only runoff, and no rainfall, entered the trough.

This style of trough did not provide enough of a gradient, resulting in a significant amount of sediment settling in the bottom and leading to an underestimation of sediment in each minute (~25% per bottle); however, the settled sediment was collected at the end of the 20-minute simulation and added to the total sediment value. A more precise method uses a funnel-shaped collector (Commandeur and Wass 1994).

Wind blowing during simulations can change the amount of rainfall reaching the plot. As a preventative measure, a tarpaulin could be draped over some bamboo poles around the simulator.

Operation

After the plot border was installed, the simulator was centred over the plot using the level and plumb bob to achieve the correct height and position. A calibration was then done to ensure the correct rainfall intensity.

For the calibration, a 1-m^2 waterproof tray was placed over the plot border to catch the rainfall and to keep the plot dry during calibration. The pump at the water bladder and pressure at the nozzle were set to the desired level for one minute. The water captured in the tray was measured in a 1000-ml graduated cylinder to determine the resulting rainfall intensity. If the intensity was incorrect, the pressure was adjusted

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Figure 4. Collecting a sample on a 1-m^2 plot in a high severity burn; note the white collection trough covered by the plexiglas shield.

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and the calibration re-run until the volume reached the desired amount for the simulation.

After calibration, the plot cover was removed, the timer started, and the valve was opened to start the simulation. The time for runoff to start was recorded when the first drip entered the first 1-L sample bottle. Individual sample bottles were used to collect a 30-second sample of runoff and sediment for every minute of the 20-minute experiment. After the rain was turned off, another bottle was immediately placed under the nozzle until runoff ended. A final bottle was used to collect the remaining sediment from the trough, resulting in a total of 22 bottles per simulation.

Following the field experiments, each 30-second sample was dried and weighed in the laboratory to determine the runoff rate (millimetres per hour) and sediment yield (grams per hour) for each minute of the simulation. Figures 5 and 6 provide examples of the results for runoff and sediment yield.

Time and Costs

The time required to install plot borders, set up the simulator, run a calibration and a simulation can range from 45 minutes to 1.5 hours depending on the conditions of the site and proximity of plots. Additional time is needed to establish sites and bring water and equipment to the site. In an average 9-hour day, our two-person crew could complete three simulations if the plots were adjacent (within several metres) to each other.

The final cost of the simulator, and associated equipment, was approximately $1300; $500 of this amount was for two steel plot borders. This simulator was designed to be inexpensive and simple to use and operate. Our costs were greatly reduced by our ability to borrow pumps, bladders, and hoses from the Wildfire Management Branch of the BC Forest Service. If purchased, the cost of the pumps, hoses, and bladders used would be approximately $7000; however, a similar system could be set up for lower cost if different pumps were used or if equipment could be rented.

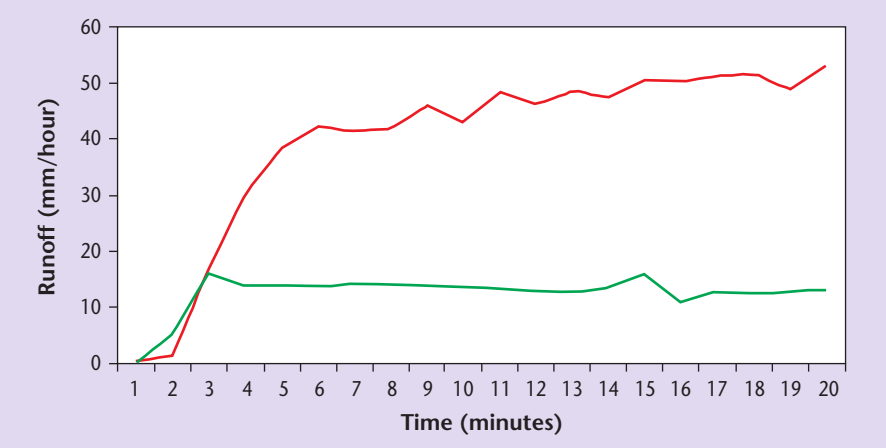

Figure 5. Example of runoff rate over a 20-minute simulation for high-severity (red) and unburned (green) plots. Graphs show average values for three simulation plots.

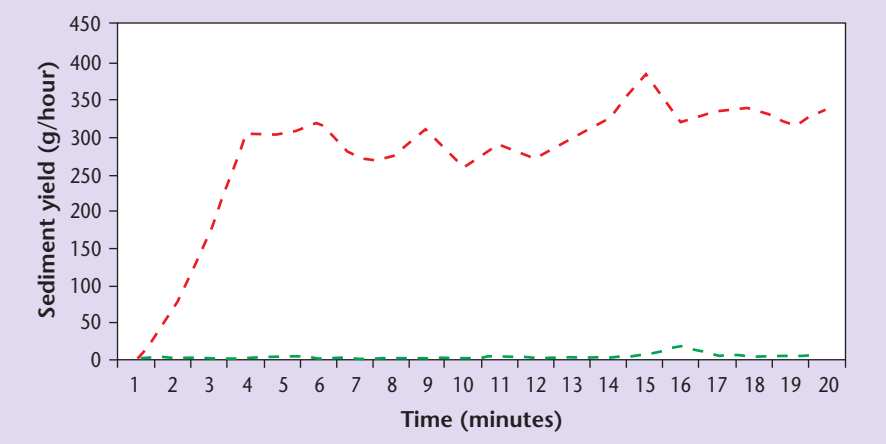

Figure 6. Example of sediment yield over a 20-minute simulation for high-severity (red) and unburned (green) plots. Graphs show average values for three simulation plots.

Other Potential Research Applications

Rainfall simulators have been used for many different types of applied research. The simulator designed for this project can be altered for different rainfall intensities and rainfall characteristics. Our research compared runoff and erosion rates between unburned forests and burns of varying severity. However, adjustments to the nozzle and pressure could be used to:

- examine the threshold for rainfall intensity that generates erosion on different slopes;
- examine the different water-holding capacities of different forest floor types and depths;
- test the infiltration rates for different soil types;
- test the effectiveness of different hillslope stabilization techniques; or
- observe the difference in erodibility between wet and dry soils.

Conclusion

This article is intended to help in the construction and application of a rainfall simulator for use in forested environments. The overall design of the simulator presented here is simple, lightweight, inexpensive, and versatile enough to be modified to achieve various objectives. The simulator generated sufficient rainfall characteristics and intensity to assess the relative difference in runoff and sediment yield in different burned and unburned conditions. The resulting data can be used to help understand soil erosivity and to aid forest management applications such as risk assessment and prescription of mitigation treatments.

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