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A multi-purpose rainfall simulator for field infiltration and erosion studies

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Abstract

This paper describes a rainfall simulator developed for field and laboratory studies that gives great flexibility in plot size covered, that is highly portable and able to be used on steep slopes, and that is economical in its water use.

The simulator uses Veejet 80100 nozzles mounted on a manifold, with the nozzles controlled to sweep to and from across a plot width of 1.5 m. Effective rainfall intensity is controlled by the frequency with which the nozzles sweep. Spatial uniformity of rainfall on the plots is high, with coefficients of variation (CV) on the body of the plot being 8–10%. Use of the simulator for erosion and infiltration measurements is discussed.

Additional keywords: calibration, spatial uniformity of rainfall, parameter derivation, rainfall kinetic energy.

Introduction

The rainfall simulator (RFS) design described in this paper was developed primarily for the project ‘Post-mining Landscape Parameters for Erosion and Water Quality Control’, which was jointly funded by the Australian Coal Association Research Programme and BHP Australia Coal Ltd, Callide Coalfields Limited, Capricorn Coal Management Pty Ltd, Curragh Queensland Mining Limited, MIM Holdings Limited, and Pacific Coal Pty Ltd.

In the initial 3 years of the project, field rainfall simulator studies of soil and soil erodibility were carried out on 14 open-cut coal mines and one mining lease, with a geographic spread of sites of approximately 1000 km. In a subsequent 3-year extension of the project, field studies of effects of vegetation and surface roughness were carried out at 6 of the mine sites.

User requirements for the rainfall simulator

Two aspects of the rainfall simulator design were accepted from the outset. The first was that the simulator would use nozzles spraying downwards, to minimise problems with wind blowing ‘rainfall’ off the plots prepared to receive it. The second was that the simulator would use the Veejet 80100 nozzles widely used in previous USDA-ARS and QDPI research

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(Meyer and McCune 1958; Barnett 1977; Loch and Donnollan 1983*a*,1983*b*). There is some variation in reported kinetic energies produced by the nozzles. Perhaps the most accurate assessment comes from Duncan (1972). He used photographic methods to measure both drop size and velocity, and found that with a fall height of 2.4 m, the smaller drops had velocities greater than the terminal velocities of similar-sized drops in still air. Kinetic energy calculated for the Veejet 80100 nozzle on the basis of measured drop size and velocity was 29.49 J/m^2.mm, similar to the kinetic energy reported for natural rain at intensities >40 mm/h by Rosewell (1986). From distrometer measurements that actually counted only 1.96% of the drops, D. M. Silburn and J. L. Foley (pers. comm.) estimated a kinetic energy for the 80100 nozzle of 24 J/m^2.mm. However, this can be expected to be a slight underestimate due to the extremely low proportion of drops counted, and the fact that those drops would have been mainly at the edge of the spray pattern where the drop size distribution is slightly finer (Duncan 1972). Despite these apparent uncertainties, it can be concluded that the 80100 nozzles give reasonable simulation of kinetic energies of intense natural rain.

Other user requirements, based on technical and logistical considerations, were: (*i*) flexibility in use, with ability to vary plot size and hence, the erosion processes studied, and also ability to alter the rainfall intensity applied; (*ii*) suitability for use on steep slopes (up to 40%), with the ability to minimise variation in nozzle pressures as a result of head differences in the manifold to which nozzles were attached being important; (*iii*) high portability, not only from plot to plot, but also for transport from one site to another; (*iv*) economy in water use (as supplies of good quality water were limited in some of the areas visited); (*v*) reliability and ease of repair; and (*vi*) suitability for operation by a field work team of 2 or 3 persons. From these requirements, it was concluded that the simulator should be of a modular design, with a robust structure that was also lightweight and simple in design.

The modular design allows the length of each manifold to which nozzles are attached to be kept short, thus reducing the magnitude of differences in head and of resulting variations in operating pressure at the nozzles. It also enables plot sizes to be varied, as the number of modules joined together to rain on a plot can be varied greatly (within the limitations of resources).

Development from previous rainfall simulator designs

Rainfall simulation has been widely used for erosion/infiltration research in the Darling Downs region of southern Queensland. The initial designs used were a rainulator (McKay and Loch 1978) used for erosion studies (e.g. Loch and Donnollan 1983*a*, 1983*b*; Loch and Thomas 1987; Loch and Donnollan 1988), and a rotating disk rainfall simulator (Morin *et al*. 1967) used for studies of infiltration (e.g. Connolly *et al*. 1991; Foley *et al*. 1991).

Subsequently, a laboratory rainfall simulator was constructed for studies of aggregate breakdown under rainfall wetting (Loch 1989; Loch and Foley 1992). This simulator was based on the design of Bubenzer and Meyer (1965), and used 2 Veejet 80100 nozzles mounted on a manifold that oscillated so that the spray fans swept across the plot. The oscillation of the manifold was driven by an automotive windscreen wiper motor. An electronic control system was built to allow the rate of oscillation of the manifold (and hence, the rainfall intensity) to be varied.

Satisfaction with the performance of the laboratory rainfall simulator led to the construction of a similar unit for field infiltration studies. Using 3 Veejet 80100 flat fan nozzles, the simulator allowed a plot 2.0 by 1.8 m to be studied, or 2 adjacent plots each 0.9 by 2.0 m. The oscillating manifold was supported by an aluminum A-frame structure, and the machine was transported on a trailer fully assembled. It has been used widely

Fig. 1. 6-module RFS, showing modular design, catch troughs, pump, and water delivery and return systems, with control boxes visible at the left of the picture.

throughout southern and central Queensland for studies of soil infiltration properties and nutrient movements (Bridge and Bell 1994; Costantini *et al.* 1995; Loch *et al.* 1995; Bell *et al.* 1997, 1998), and for field days and demonstrations to farmer groups.

The field rainfall simulator using the oscillating manifold formed the basis for the rainfall simulator that is described in the following sections of this paper. Considerable design and development were necessary to ensure that the rainfall simulator met the user requirements outlined in the previous section.

Description of design

Structural design

The RFS frame is constructed as base modules to which additional modules can be connected to increase the length of rainfall simulator plot, depending on experimental requirements (Fig. 1). The base modules can be of either 2-nozzle or 3-nozzle configurations. This corresponds to module lengths of 2 or 3 m, with nozzles set at a 1-m spacing along the manifold, with upslope and downslope nozzles being placed 0.5 m from the ends of each module. (This ensures that the 1-m nozzle spacing is maintained when modules are joined together.) The base module consists of a triangular prism with the sloping sides of equal lengths (see Fig. 2). Additional horizontal members of lighter material are added to enable attachment of the droplet catch trays and the nozzle boom. The module dimensions could be scaled up or down to suit special applications

The frame is constructed from aluminum tubing of 38 mm outside diameter (O.D.) and a 3-mm wall thickness. The bases of the upright tubes are flattened and bent parallel to the ground surface to form feet. Holes drilled in the flattened section enable the unit to be pegged to the ground, if required. Operation on sloping ground may require the module to be guyed to a peg or solid object. Modules are connected by nylon joiners that fit inside the main horizontal frame members. The joiners are machined from solid nylon stock and are about 200 mm in length. Locking pins ensure that the multiple units are securely interconnected.

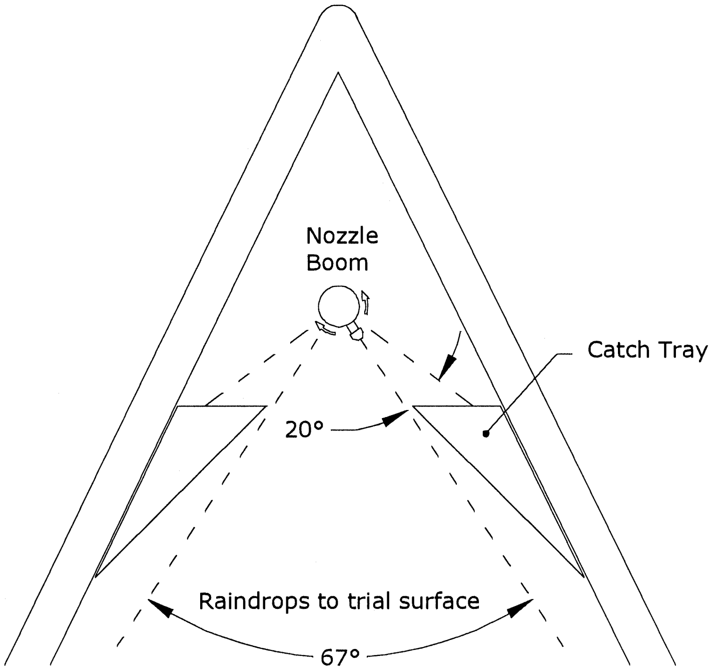

Fig. 2. Operation of nozzle and catch trays.

The nozzle boom consists of a 2-m or 3-m length of 38-mm-O.D. (1.6-mm wall) stainless steel tubing. The boom rotates in 2 plastic bushes (graphite impregnated) that also prevent lateral movement of the boom. Male threaded (1/2" BSPT) unions are welded onto the boom at 1-m spacings. Check valves are threaded onto the bushes to prevent nozzle flow or dripping when the unit is not in use, and Veejet nozzles are fitted to the check valves. The water supply inlet is via a 1¼" BSPT tee fitting attached to the boom opposite to the row of nozzles. A tapping from this fitting provides a connection for a pressure gauge, so that the operating pressure of each module can be monitored.

The operational sequence of this RFS relies on a continuous water flow through the raindrop nozzles. Flow not required (as rainfall on the test surface) is recycled via droplet catch trays on either side of the oscillating nozzles (see Figs 1 and 2). During operation, the nozzles oscillate through ~107°. Of this travel, the middle 67° applies raindrops onto the trial surface, and 20° is used at either end of the travel for overlap into the catch trays. Adjusting the frequency of nozzle oscillation alters rainfall intensity from the RFS. Calibration and performance details of the RFS are given in a subsequent section.

The heavy-duty, geared 12 V DC electric motor used initially provided the oscillating action via a simple Pitman arm and lever system. The current system uses a 1 Amp stepper motor with a 25 : 1 reduction gearbox, operated at 36 V. Advantages of the stepper motor are that it is able to drive at the same speed in both directions, and that it provides repeatable speeds irrespective of operating conditions (load, temperature). A simplified drive using a small roller chain is now used to connect the motor to the manifold. A sprocket is attached to the stepper motor and a drive pin (which fits inside a chain link) is welded to the nozzle boom.

Hydraulic system

Water is supplied to all RFS modules from a single electric, 1500 W water pump (Onga Hi-Flo centrifugal model 142) housed in a steel frame with a 120-L reservoir. The single pump-reservoir unit is located at the base of the slope and recycles return flow from the RFS modules. Its reservoir is topped up, via 75-mm-diameter lay-flat hose and a float valve, from 10000- or 5000-L storage tanks at the head of the slope.

The pressure pipe near the pump is fitted with a non-return valve to prevent back-flow through the pump from the supply line and RFS units when the pump is turned off. A mesh filter is fitted at this point to filter water prior to being pumped to nozzles. A 75-mm cam-lock connects the pump to the main supply line, which consists of 2-m sections of 75-mm aluminum irrigation pipe extending the length of the linked RFS units. Outlets at 2-m spacings are fitted with 38-mm brass ball valves and 32-mm plastic cam-locks to allow individual pressure control to each module. Pressure gauges (0–100 kPa) are mounted on each RFS unit at nozzle level.

Catch trays are used to collect water from the nozzles that is not sprayed onto the plot. The trays have provision for slight adjustment up or down to ensure that the sprays overlap the plot sides sufficiently to ensure even coverage, but wasteful, excessive application is prevented. This also ensures that areas reasonably close to the plots remain dry, assisting the movement of personnel engaged in the trials.

On early versions, catch trays extending the full length of the module were used to collect excess flow from all nozzles on that module. To reduce weight, smaller catch trays fabricated from galvanized tinplate are now used to collect excess flow from individual nozzles. Water collected in the catch trays is gravity fed via flexible hose into a common manifold (100-mm-diam. PVC drainage pipe), and returned to the pump storage tank under gravity.

Control system

The control system is composed of a controller circuit board, a stepper motor power supply and driver module, and a manifold position feedback module.

The controller circuit includes a power supply, a micro-controller (Motorola M68hc11), thumbwheel switches, and transistor switching circuits. The micro-controller runs in single chip mode using only internal random access memory (RAM) and electrically erasable, programmable read-only memory (EEPROM) for data and program storage. The thumbwheel switches set the time period between consecutive sweeps of the spray manifold in 0.1-s increments. The transistor switching circuit is required to provide the correct voltage and current levels to the stepper motor driver module.

The stepper motor power supply provides 36 V DC to the motor driver module. The stepper motor driver module is a commercial unit, with inputs for setting motor direction, step resolution (half or full steps), and motor current setting adjustment.

The manifold position feedback module comprises 2 Hall Effect integrated circuits (ICs) and interface cable mounted on the motor/gearbox assembly. An aluminum disk with 2 small magnets embedded into one surface is attached to the drive sprocket. The magnets are positioned to provide feedback signals indicating the start and end of the manifold movement cycle. The magnet polarities are reversed to eliminate any potential for false triggering resulting in position error.

The software

When powered on, the controller reads the signal from the Hall Effect ICs to determine the manifold's position and if, necessary, moves the manifold to the start position. Five seconds after the unit is switched on, the controller starts to oscillate with a period set by the thumbwheel switches. This period can be changed at any time while the unit is operating, either by changing the thumbwheel setting or via the serial interface to allow multiple RFS units to be controlled simultaneously. This ability to alter rain intensity via computer allows plots to be subjected to rain intensity profiles.

Associated equipment

Plot edgings and runoff collection

Plots are enclosed by metal plate of 3 mm thickness hammered into the soil, usually to a depth of 75 mm. Where a single module is used, the plot edging is constructed in a single piece, occupying the top and sides of the plot, with a separate gutter for collection of runoff at the downslope outlet. For larger plots, the edging is composed of overlapping sheets of steel plate, 1200 mm long and 150 mm wide.

The use of tipping buckets for runoff monitoring and their logging through time by computer are described by Loch *et al.* (1998).

Wind protection

Despite the use of nozzles spraying downwards, in windy conditions there is still a requirement for some form of windbreak to reduce movement of 'rain' from the target plot. The form of windbreak used varies with the size of simulator used. Where several modules are joined together, a shade-cloth wind break (30% open cloth) is erected to run the full length of the RFS. The wind break uses the A-frame of the RFS modules for support in the centre and is pegged to the ground along the windward side. Where only a single module is used, it has been more effective to have the windbreak material sewn and joined to obtain complete enclosure of the RFS.

Transport

A dual-axle fully enclosed trailer was constructed and fitted out to transport the RFS units and associated equipment between trial sites. The 2.0-t trailer measured 1.8 m wide, 2.0 m high, and 3.0 m long. The RFS units were stacked along either side of the trailer with an access walkway through the middle and full width opening doors to the rear. A separate compartment housed a 4 kVA petrol generator, which supplied power for all electrically operated field equipment.

Rainfall simulator performance

Spatial uniformity of intensity

Calibration method

Two modules were joined together to give a 5-m-long RFS covering a plot 4 m long and 1.5 m wide. The RFS was calibrated by measuring volumes of rainfall intercepted by rows of plastic jars located directly under and midway between each nozzle so that each row was 0.5 m apart. Each row consisted of 5 jars, with the centre jar being exactly in the centre of the plot. The outer jars were located so that their outer edge was 0.75 m from the centre of the plot, with the other jars being centred 0.37 m from the centre of the plot. Additional jars were placed on the centre line of the plot, midway between each row. Jar diameters were 10.96 cm. Plastic mesh was placed in the jars to prevent splash losses.

Calibration results

Results obtained after some initial adjustment of the RFS are shown in Tables 1 and 2, which indicate coefficients of variation (CV) of 8–10% for the body of the plot (with the

Table 1. Spatial distribution of measured intensities (mm/h) for a cycle time of 3.5, simulator run for 20 min

Rows in bold were directly under nozzles

Distance downslope (m)	Measured rainfall intensities (mm/h) for distances across plot (m) of:				
	0.05	0.37	0.75	1.12	1.45
0	**32**	**40**	**40**	**38**	**37**
0.25			48		
0.50	38	46	48	48	45
0.75			49		
1.00	**44**	**56**	**57**	**54**	**54**
1.25			52		
1.50	38	45	48	45	44
1.75			46		
2.00	**49**	**59**	**56**	**56**	**52**
2.25			51		
2.50	40	45	47	45	41
2.75			51		
3.00	**45**	**51**	**53**	**51**	**43**
3.25			51		
3.5	43	48	51	48	43
3.75			48		
4.00	**37**	**38**	**48**	**41**	**35**

end rows excluded). When the end rows were included, CVs for the data in Tables 1 and 2 were in the range 12.2–13.4%.

Earlier calibrations by D. N. Orange and B. J. Bridge (unpublished data) for a single module using a windscreen wiper motor drive system gave similar results. For a plot area 2 m long and 2 m wide, the CV ranged from 11.5% to 14.3% for measurements at intensities ranging from 21.5 to 184 mm/h. The greatest variation was noted at the corners of the plots,

Table 2. Spatial distribution of measured intensities (mm/h) for a cycle time of 2.0, simulator run for 9.5 min

Rows in bold were directly under nozzles

Distance downslope (m)	Measured rainfall intensities (mm/h) for distances across plot (m) of:				
	0.05	0.37	0.75	1.12	1.45
0	**60**	**70**	**70**	**67**	**64**
0.25			74		
0.50	74	84	87	80	80
0.75			94		
1.00	**77**	**94**	**97**	**94**	**87**
1.25			100		
1.50	84	94	94	87	87
1.75			87		
2.00	**94**	**98**	**94**	**94**	**87**
2.25			105		
2.50	85	90	94	90	84
2.75			87		
3.00	**80**	**94**	**100**	**94**	**87**
3.25			87		
3.5	74	77	82	80	72
3.75			82		
4.00	**72**	**74**	**78**	**78**	**67**

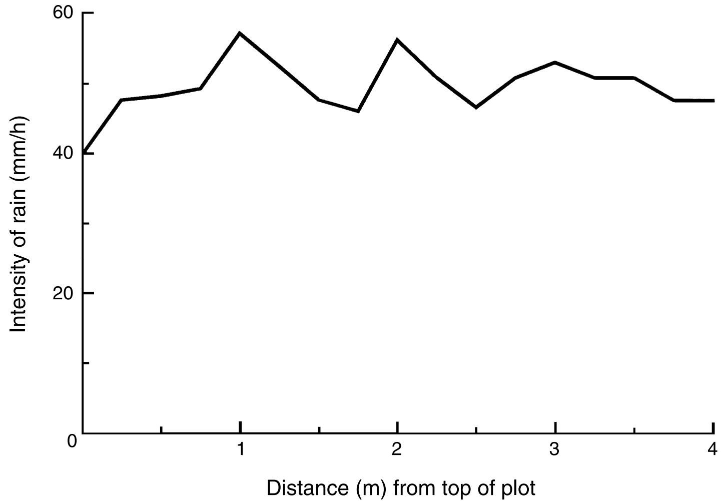

Fig. 3. Intensity variation along the centre of the rainfall simulator plot.

and if those 4 points were deleted from the data, the CV was reduced to 9.4–12.5%. For a central area 1.5 m long and wide, the CV was only 6.3%, illustrating that increasing plot area also increases spatial variability due to inclusion of edge effects. Effects of intensity on the CV were small, with a slight increase in CV as intensity decreased.

This degree of variability is low relative to other simulator types. For example, Marston (1980) reports intensity data for a rotating disc simulator (Morin *et al.* 1967) that show a CV of 24.6% over a plot of only 1 m^2 area. Lascelles *et al.* (2000) report uniformity coefficients largely in the range 0.7–0.85 (roughly equivalent to CVs of 15–30%) for a simulator using 4 full-cone nozzles covering a plot area of 7 m^2.

Because the simulator is based on flat fan nozzles that sweep to and fro across the plot, there is consistent variation in intensity in 2 directions.

The major component of spatial variability is up and down the plot, with peaks under the nozzles and troughs between them. This is minimised by overlap of the nozzles, but still causes consistent variation as shown in Fig. 3.

The minor component of spatial variability is across the plot, with intensity reaching a peak in the centre of the plot, and falling away towards the edges of the plots. This variation can be minimised by adjustment of the catch troughs on the simulator (Fig. 4) to reduce any interception of the sprays until the fan clears the edge of the plot.

For erosion studies, the low variation in intensity across the plots is desirable, as it does not create continuous downslope lines of high rainfall erosivity with increased potential for rill formation. Equally, the repeating pattern of intensity variation down the plot should have a minimal effect on erosion processes associated with downslope accumulation of flow and flow tractive force.

The other main points of intensity variation are at the upper and lower ends of the plot. Intensity falls away at these points because some of the overlapping of nozzles is lost. On longer plots, this has less effect on calculated coefficients of variation than on shorter plots (where its effect on such statistics is greater).

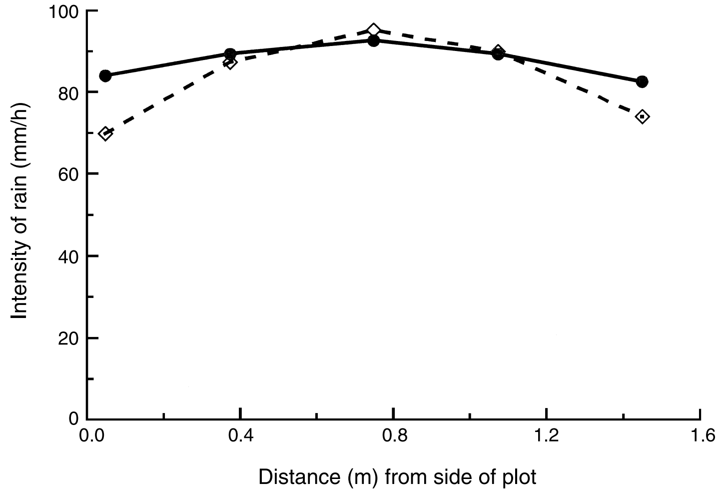

Fig. 4. Effects of trough adjustment on intensity variation across the simulator plot: —●— after adjustments of troughs; – –◇– – before adjustments of troughs.

Control of intensity

The measured relationship between the setting of the control boxes and intensity is shown in Fig. 5. In practice, for a range of reasons, this relationship could be expected to vary slightly, and it should at no time be used as a substitute for adequate monitoring of rainfall intensities during field experimentation.

Use of the simulator for erosion and infiltration studies

Plot size

The size of the simulator and the potential to consider a range of plot sizes have enabled studies to consider inter-rill erosion on short plots (<3 m long), rill plus inter-rill erosion on

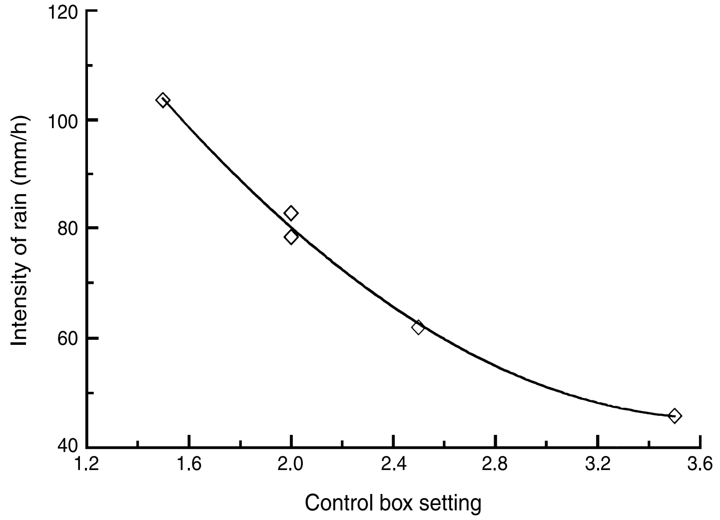

Fig. 5. Relationship between control box settings and intensity.

plots 12 m long, and rill erosion by application of overland flows to the 12-m-long plot. The approach used will naturally depend on the type of soil erosion model for which parameters are to be obtained. Rill and inter-rill processes are considered separately when determining parameters for process-based erosion models, whereas a 12-m-long plot can give reasonable estimates of the Modified Universal Soil Loss Equation (MUSLE) (Onstad and Foster 1975) parameters in situations where the plot length and dominant erosion processes are not unduly different to those found under field conditions. The derivation and application of a range of erosion model parameters from differing plot sizes are illustrated by Loch (2000*b*), and Loch *et al*. (2000).

For infiltration studies, a range of plot sizes have been used, from 18 m^2 to 1.5 m^2. Desirable levels of replication for infiltration studies vary considerably, depending on the spatial variability of the treatment or situation being studied. As well, there are options to use either large plots that cover the range of site variation, or small plots to assess the various components of site variability.

Intermittency of rain

Like many simulators, this machine applies rain in pulses as the nozzles sweep across the plot. Although noting that natural rain seldom occurs in a steady or uniform fashion, it can also be pointed out that the pulsed rainfall application does not appear to affect or distort the parameters obtained. For example, Connolly *et al.* (1991) and Connolly and Silburn (1995) found that infiltration parameters derived from rainfall simulation studies (using a simulator that applied rain intermittently) gave good prediction of observed runoff hydrographs from field catchments. Kinnell (1993) found no difference between continuous and intermittent rain in the time-averaged sediment concentrations carried by inter-rill flows.

Labour requirements

Field studies using 6 modules to cover a plot 12 m long and 1.5 m wide were found to need typically a field crew of 3 staff, and 1 or 2 laboratory technicians. Depending on the range of measurements made and the proximity of plots, an experienced field crew could run 2–3 plots per day. For example, typical 'runs' included raining on a 12-m-long plot for 30 min, followed by inter-rill erosion measurement on a shorter plot, and then overland flow studies on the 12-m-long plot. These measurements are described by Loch (2000*b*).

Automation of runoff measurement and simplification of data recording described by Loch *et al*. (1998) gave some streamlining of operations, usually allowing some of the field crew to prepare a new plot for study while the simulator was still running on an existing plot.

Conclusion

Since its construction in 1993, the 6-module simulator has been used in studies on open cut coal mines in southern and central Queensland (Loch 2000*a*; Sheridan *et al*. 2000), and also in studies on mines in New South Wales (Loch 2000*b*) and Western Australia. It has been used in New South Wales and Queensland for studies of pesticide movement in runoff from irrigated cotton (Silburn *et al*. 1996, 1998; Silburn and Connolly 1998), for studies of erosion and nutrient movement from freshly planted pine plantations, and for studies of movement of nutrients from dairy effluent applied to pastures in southern and northern Queensland. Smaller numbers of modules have been used in laboratory studies (Sheridan *et al*. 2000), and in studies of erosion from forest roads (Costantini *et al*. 1999).

The mobility of the simulator from plot to plot and its ease of transport over large distances have clearly been an advantage. As well, its reliability has been a major factor in enabling efficient use of rainfall simulation in a wide range of environments and locations.

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