*Proceedings of the 20th Annual British Columbia Mine Reclamation Symposium* in Kamloops, BC, 1996.
The Technical and Research Committee on Reclamation

# DESIGN OF A RAINFALL SIMULATOR TO MEASURE EROSION OF RECLAIMED SURFACES

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## ABSTRACT

Rainfall simulation is a useful tool in the analysis of soil erosion. The use of rainfall simulators has become more widespread with the development of automated instrumentation and control systems which offer a physically based system of predicting soil erosion. A variety of simulator designs have been used. This paper describes a rainfall simulator designed for analysis of erosion on steep (2.5H: 1V) reclaimed sand slopes at two oil sand mines near Fort McMurray, Alberta. The rainfall simulator applies artificial rain on a 225 $m^2$ test site divided into two side-by-side test plots.

Most rainfall simulators have used a constant intensity of rainfall throughout a given simulation event. The rainfall simulator designed for this project can vary the rainfall application rate in fifteen discrete rainfall intensity increments. Therefore, it is capable of simulating a variety of non-uniform rainfall hyetographs. The rainfall simulator consists of a system of seven nozzles on each of 27 vertical support pipes. A combination of nozzles was used to simulate a desired uniform or non-uniform rainfall hyetograph with intensities ranging from 10 mm/h to 200 mm/h. The rainfall simulator also successfully simulated extreme historic and synthetic hyetographs.

## INTRODUCTION

A rainfall simulator was designed to assist with examining the erosional sustainability of reclaimed surfaces and provide a means of developing a sound basis for future reclamation planning. The sites consisted of steep, reclaimed sand slopes at two oil sand mines owned by Suncor Inc. and Syncrude Canada Ltd. near Fort McMurray, Alberta.

Estimating erosion and sediment yield is important for designing the sediment carrying capacity of future mine closure drainage systems, for determining the environmental impacts on receiving streams, and for assessing the erosional sustainability of the mine closure landscape. The latter is of particular importance at the oil sand operations because of the very large reclaimed areas and steep (2.5H:1 V) slopes which are being developed.

There are several empirical methods of estimating erosion rates including the well known Universal Soil Loss Equation (USLE). However, erosion estimates based on empirical methods are subject to large errors, arising from uncertainties pertaining to input parameters, particularly at disturbed areas built of highly erodible material.

The most accurate method of estimating soil erosion, resulting from direct rainfall, is by direct measurement of natural events. However, this method does not provide a way of measuring the influence of a wide variation in rainfall parameters such as intensity, duration, and antecedent moisture conditions. In particular, extreme events are rarely monitored because they occur so infrequently. Therefore, investigators have adopted a rainfall simulation approach for the study of soil erosion. The advantages of rainfall simulation over natural rainfall-runoff observation include the ability to control testing, the ability to monitor a range of extreme events in a short time, and cost efficiency.

The design of the rainfall simulator described in this paper incorporates some innovative features which have not been applied previously. Whereas other installations have had limited capability to vary the rainfall application rates, the system for the Suncor and Syncrude simulations was designed to vary the rainfall application with up to 15 discrete rainfall intensities ranging from 10 mm/hi to 200 mm/h.

## APPROACH AND DESIGN CONSIDERATIONS

### Theoretical Considerations

The physical processes governing soil erosion are not well understood despite extensive research (Owoputi and Stolte, 1995). Nevertheless, researchers agree on the overall process of erosion involving soil detachment and sediment transport. Raindrop splash is the primary process governing soil detachment at upstream areas (splash, sheet erosion, interrill areas) and overland flow is the primary process governing soil detachment at downstream areas (rills, gullies, and stream/river areas).

Rainfall simulation can be used to examine the upstream end of the flow path where splash erosion, sheet erosion and interrill erosion govern soil detachment. Often these upstream areas can generate the greatest volume of sediment, particularly in areas of sparse vegetative cover. Vegetative cover and root mass are the main erosion protection measures in the upstream areas. Consequently, the sustainability of reclaimed areas can be examined by observing the ability of the vegetative cover to prevent significant soil detachment. This is determined by measuring runoff and sediment yield from test sites during specific extreme rainfall events.

## Experience of Others

Full scale rainfall-runoff-erosion simulation is not new technology, although its application in Canada is limited. It is currently being used as a research tool by the U.S. Department of Soil Conservation, U.S. Department of Agriculture((USDA) and others (Abrahams *et al,* 1995, Frasier *et al,* 1995). It has also been used by mining companies in the U.S. to assess soil credibility of their reclaimed areas. Some government agencies use small scale 1 $m^2$ rainfall simulators (Nolan *et al,* 1994 and Tossell *et al,* 1987). The design of the rainfall simulator presented in this paper was based on a review of available literature and discussions with investigators in the U.S. who have had direct experience in rainfall simulation.

## Physical Considerations

The reclaimed areas to be tested varied from recently reclaimed weedy cover to grassland vegetation to mature reclamation with trees up to 7 metres in height. Ground slope varied from 17 to 22 degrees. Water was supplied from trucks and/or pumps delivering to a tank situated upslope of the test site to provide a gravity feed. Therefore, a local power source was not required. A maximum water delivery of 200 mm/h for 30 minutes was set as the upper design flow requirement. This allowed simulations to exceed the Probable Maximum Precipitation (PMP) volume and intensities.

## Program Planning Considerations

A full scale physical model was required to adequately simulate the physical conditions which govern the rainfall-runoff-erosion process in the upstream areas. Although rainfall simulation testing is conducted in a limited area and over a relatively short period of time, compromises in size and timespan were adequately accounted for by proper interpretation of the test data in combination with sensitivity tests conducted to assess the impacts of such compromises. Therefore, a range of sensitivity tests were proposed to test the impact of rainfall duration, intensity, antecedent moisture conditions and rainfall distribution in order to support and interpret the rainfall simulation results. The ability to apply a wide range of intensities and durations such that actual design storm events could be tested was a critical requirement of the rainfall simulator design.

## RAINFALL SIMULATOR DESIGN

The rainfall simulator consists of a system of sprinkler nozzles which applies artificial rain on a test plot, as shown on Figure 1.

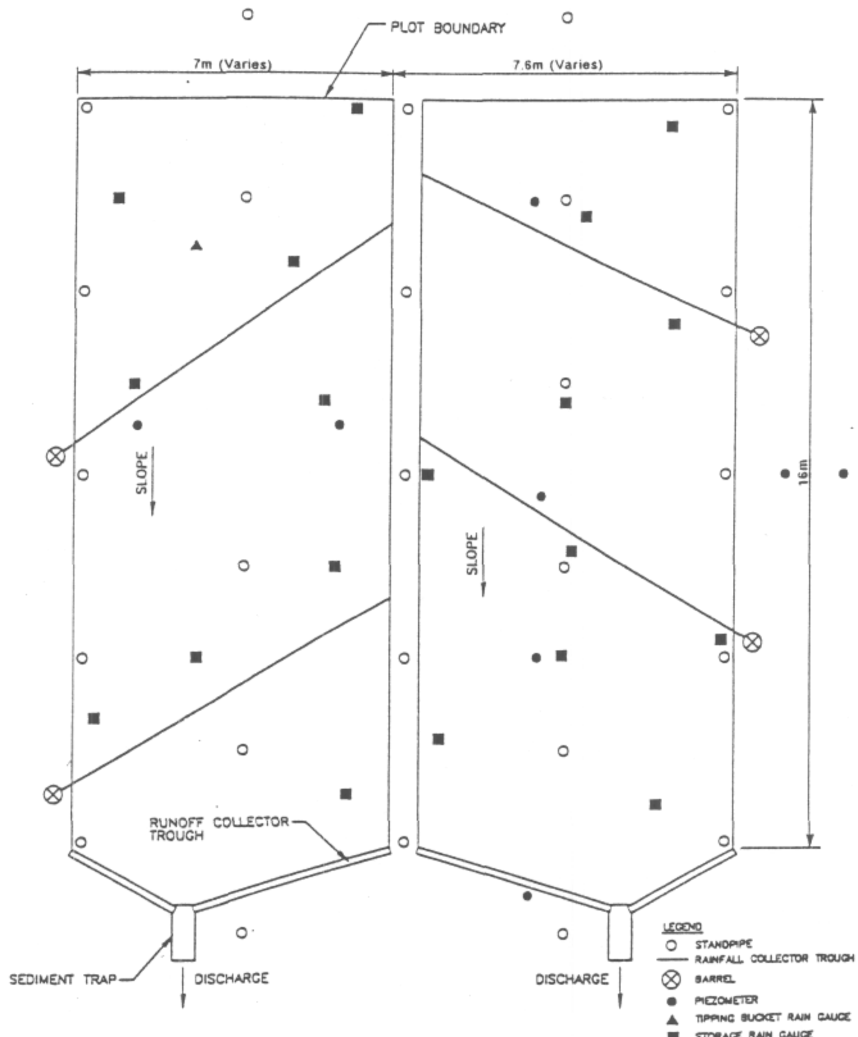


**Figure 1: Rainfall Simulator and Instrumentation Layout**

The system was designed to simulate rainfall intensities up to 200 mm/h over the plot area, which is approximately 16 m square. The simulator should produce rainfall intensities which vary with time but are relatively uniform over the plot, and which mimic the characteristics of natural rainfall as closely as possible. Components of the system designed to meet these objectives are discussed below.

- Large plot size Large scale rainfall simulations were carried out on two side-by-side plots approximately 7 m wide and 16 m long, as shown on Figure 1. This size of test site caused groundwater table mounding. If the site were too small, then the edge effects of the test area might make the simulator unreliable. The selected size was judged to be an appropriate compromise, minimizing cost without causing excessive edge effects. Plot boundaries were constructed of sheet metal and installed along the sides and upper end of each plot. Simulated rainfall extended two metres or more beyond the test area to further reduce edge effects.

Replication There is normally a significant variation in sediment yield from one site to another, even where the cover type and rainfall hyetographs are the same. Therefore, researchers have determined the need to conduct multiple tests on the same type of cover. For this study, two side-by-side plots were used at each site as shown on Figure 1, to check the replicability of the tests and the variation in sediment yield.

Areal uniformity of rainfall Ideally, simulated rainfall should be of fairly uniform areal intensity over the test site at a given point in time. This would replicate actual rainfall which is nearly uniformly distributed over a small area at a given point in time. However, some compromise of this design objective was necessary because of the inherent small variations in areal water distribution by sprinklers. This effect was minimized by choosing sprinklers which offer maximum uniformity in areal distribution, and by using a triangular grid layout of sprinklers.

Ability to control the rainfall time distribution (hyetograph) Most rainfall simulators developed by others use a constant intensity of rainfall because the nozzle requires a constant pressure in order to produce a constant spray pattern. However, it is desirable to be able to vary the rainfall intensity during each test in order to measure the importance of the time distribution of rainfall. Therefore, the simulator was designed with a system of seven nozzles on each vertical support pipe. The nozzles included three different nozzle types, as shown in Table 1. Combinations of nozzles were used to create the desired rainfall intensity. The intensity could be varied during the simulation by control valves at the upstream end of the plot or by valves located at each sprinkler head.

**TABLE 1**
**Nozzle Characteristics**

| Number of Nozzles per Vertical Support Pipe | Nozzle Model No. | Type | Rainfall Intensity[1] At 20 psi |
|---|---|---|---|
| 1 | ½ GG35W | Industrial | 60 mm/h |
| 4 | HS-15 | Turf | 40 mm/h |
| 2 | HS-7 | Turf | 10 mm/h |

[1] Based on a triangular grid with 4 m spacing.

A system of PVC and PE pipe was designed to convey the water to the nozzles. The system consists of a manifold upstream of the plot with five mains to create subsystems to convey the flow down the slope between the two plots and branch lines which carry the discharge laterally across each plot. This layout was selected to minimize differences in pressure between the two plots and between individual nozzles.

Pipe sizes were selected to minimize head losses in the system. Camlock connections were used at strategic points to allow for disassembly and transportation. Flexible hose was used for the connection between the manifold and the mains so that the supply line could easily be connected to the simulator.

The controls include a gate valve at the upstream end of each of the five subsystems, small valves at some of the nozzles, and pressure regulating valves. The pressure regulators were installed between the mains and each lateral branch to compensate for pressure changes along the main line due to friction losses and elevation change. This control system allows the operator to discharge through a single nozzle on each cluster on the plots with equal pressure. Two of the subsystems are equipped with two nozzles of different capacities, each individually controlled at the nozzle. This provides a total of seven nozzles in each cluster, of which a maximum of five can be operated at any one time. This combination provides a total of fifteen discrete rainfall intensities.

## INSTRUMENTATION

- <u>Rainfall Measurement</u> Rainfall intensity was measured by several methods to provide a check of the data. These methods included the following:

  - A turbine meter on the supply line connected to a datalogger measured the total inflow to the simulator and the variation in discharge with time;

  - A network of 20 storage rain gauges to measured the total rainfall during each event and its variability over the plot area;

  - A tipping bucket rain gauge connected to a datalogger measured the variation of rainfall rate at one location in the plot;

- Four rainfall collector troughs captured the rainfall over the entire width of the plot and discharged it to graduated storage barrels to provide automatically averaged areal rainfall measurements.

- Runoff Measurement Runoff was measured by collecting the overland flow in troughs and conveying the water and sediment to a sediment trap equipped with a V-notch weir at its outlet. A float level recorder connected to the datalogger recorded water levels and subsequent discharge from the sediment trap.

- Sediment Yield Measurement A baffle was used to reduce turbulence in the trap and promote sediment settling. Sediment yield was measured by cleaning out the sediment from the sediment trap at the end of each event. Samples of the trap overflow from the V-notch weir were also taken during each test and analyzed for suspended sediment concentrations to complement the sediment trap results.

- Measurement of the surficial groundwater table Nine piezometers were installed to a depth of approximately 1.5 metres inside and adjacent to the plot area to measure the groundwater table before and after each test and at intervals during long tests.

- Visual Documentation Photographic documentation and visual observations of the vegetation cover, runoff and soil erosion were conducted throughout each test.

## ASSESSMENT AND RESULTS

### Rainfall

Rainfall intensities were primarily determined by the network of twenty storage rain gauges in combination with the inflow turbine meter records. The rainfall depths at the ten gauges on each side were averaged to estimate total rainfall depth over each plot. The time distribution of the rainfall was calculated based on the turbine meter observations to establish the shape of the simulated rainfall hyetographs. The tipping bucket was used as a secondary means to verify the shapes of the rainfall hyetographs. The tipping bucket rainfall records were particularly important for simulated events with low rainfall intensities as well as very high peak intensities because of the inaccuracy of the turbine meter at very low flow rates and during short rainfall events.

The rain gauge troughs provided a measure of total rainfall and a check on intensities applied during the tests. Total rainfall based on the troughs and the storage rain gauges were comparable, with differences typically less than ten percent. The storage gauge readings were used for subsequent analysis.

Comparison of the total rainfall measured in each storage gauge indicated typical spatial variations of about 30 percent. However, in some cases, the variations exceeded 100 percent because of wind, vegetation cover, anomalies in the simulation equipment, and occasional plugging of the sprinkler nozzles due to the poor quality of the water supply in one instance. Overall, the rainfall monitoring equipment provided a good measure of the average application amounts over the entire test area and the rainfall simulator provided an adequately uniform areal application that closely matched the desired application rates.

**Raindrop Size and Velocity Impacts**

Raindrop size and velocity can have a significant impact on the rate and amount of erosion that can occur at a site, particularly for non-vegetated conditions.

Drop Size Natural rainfall includes a wide range of drop sizes, and the median drop size increases with increasing rainfall intensity (Laws and Parsons, 1943). For a light rain of 0.25 mm/h, the median drop diameter is approximately 1 mm. During an intense rainfall of 125 mm/h, the median drop diameter increases to 3 mm.

The nozzles used in the rainfall simulator produced two drop sizes. The industrial nozzle (one 1/2 GG35W in each cluster of nozzles) produces a drop size of 3 mm. Drop sizes from the turf irrigation nozzles are noticeably smaller, but the manufacturer could not provide drop diameters. The industrial nozzles were used whenever possible to maximize the median drop diameter of the simulated rainfall.

Sensitivity tests to determine the impact of drop size were conducted at the 1 $m^2$ test sites using the industrial nozzle without the wide spray(l/2 GG35) for the large drop size. A smaller industrial nozzle was used for an intermediate drop size (FL15VS) and the HS-15 turf nozzle was used for the small drop size.

Raindrop Velocity The terminal velocity of falling raindrop increases with increasing drop size. A 3 mm raindrop has a terminal velocity of 8 m/s (Laws, 1941; Gunn and Kinzer, 1949), and a 2 mm raindrop reaches 6.5 m/s. The simulated rainfall, sprayed upward from nozzles mounted 2 m above the ground, does not reach terminal velocity before impact. The fall distance varies depending on whether the point of impact is upslope or downslope from the nozzle. For a typical fall distance of 3 m, a 3 mm drop would reach 75 percent of its terminal velocity, and a 2 mm drop would reach 86 percent of its terminal velocity. Smaller raindrops require less fall distance to reach terminal velocity.

Sensitivity tests at the 1 $m^2$ test sites were conducted to determine the impact of raindrop velocity. The nozzle was aimed downward and water pressure was used to vary the raindrop velocity.

Observations Sediment yield results from the 1 $m^2$ test plots were highly variable using the different nozzles. This was primarily due to initial washing of loose sediment on the ground surface. The large industrial nozzle, however, generally created higher erosion and runoff than the smaller industrial nozzle.

A full scale test was also made at one site to assess the importance of drop size and impact velocity. The hyetograph (60 mtn/h for 1 hour) was simulated twice, once with turf nozzles and once with industrial nozzles. The full scale comparison test produced over three times more runoff using the industrial nozzles. This is partially due to the fact that it was the second test and as a result initial moisture conditions were higher. However, the larger drop size created by the industrial nozzles is also believed to have contributed to the higher runoff. Large drop sizes result in water concentration on the ground reducing allowable infiltration and promoting runoff due to reduced surface friction roughness (Abrahams, Parsons and Wainwright, 1995). Overall, sediment yield was estimated to be approximately 55 percent higher using the industrial large droplet nozzles as opposed to the turf nozzles which produced the smaller raindrop sizes.

The above tests, though not conclusive, tend to support the literature that drop size and velocity can have a significant impact on the erosion potential of a rainfall event. Therefore, sediment yields from the lower intensity rainfall events that relied upon the smaller drop size turf nozzles were factored upward by about 50 percent. For the larger rainfall events that used the industrial nozzles, it is believed that a more representative simulation of actual rainfall was created.

## Runoff and Sediment Yield

As expected, measured runoff and sediment yield results were highly variable. Results of this analysis are presented in a separate paper (Sawatsky *et al* , 1996). The instrumentation and measurements for runoff and sediment yield were considered accurate for the large volume tests conducted. Total runoff volume estimates for the low volume tests that applied less than 50 mm were less reliable because the volumes subtracted to account for the instrumentation and collector troughs accounted for over one half of the total runoff at times. It should be noted that the highly permeable reclaimed sand slopes resulted in minimal runoff until applications exceeded 150 mm and intensities exceeded 100 mm/h.

## CONCLUSIONS

The rainfall simulator described was able to replicate the desired intensities and durations of design rainfall hyetographs. The simulator was also able to produce raindrop sizes and velocities approaching natural rainfall conditions at high intensities. At very low intensities the simulated raindrop sizes tend to be smaller than natural rain, hence the measured erosion is underestimated. This type of rainfall simulator has proven to be a cost effective tool to measure components in the rainfall-runoff-erosion process and to demonstrate the long term sustainability of reclaimed slopes exposed to extreme rainfall events.

Improvements in the rainfall simulator would include the development and use of a greater variety of nozzles to better simulate natural driving rain, a windbreak to extend suitable testing conditions, and automation of control valves. However, increased automation and instrumentation must be weighed against cost if rainfall simulation is to remain a viable tool for mine reclamation planning and design.

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