Deposition Processes in a Simulated Rill

T.A. Cochrane and D.C. Flanagan

Abstract

The processes that govern deposition of sediment within a rill are fundamental to the study of erosion mechanics and subsequently our ability to accurately predict erosion with process-based models such as WEPP. An experimental laboratory apparatus, named the rill simulator, was used to study deposition in a 25cm wide rill that was set up under laboratory rainfall simulators. Sediment feeders were used to add sediment and water to the top of the rill as well as to the sides of the rill to simulate conditions of interrill erosion contribution as would occur in natural conditions. A laser scanner was used to quantify the amount of deposition that occurred after each experiment. Water flow velocity measurements and sediment concentration samples from the outlet of the rill were also taken during the experimental runs to quantify the deposition and sediment transport in the rill. The experiments were conducted using silica sand, glass beads, and artificial plastic/glass aggregates with average diameters of 330µm, 150µm, and 3mm and specific gravities of 2.65, 2.5, and 1.25 respectively. Combinations of different flow rates, rainfall intensities, and sediment feed rates were studied for each sediment type at low slopes. The objective of these studies was to determine if shallow water flow as influenced by rainfall intensity and incoming sediment concentration had a significant effect on the deposition of sediment in a rill. Results showed that the interaction of rainfall intensity and flow depths had a more significant effect on deposition of particles of low specific gravity. It was also shown that under no rainfall and high intensity rainfall deposition was limited whereas under medium intensity rainfall deposition was greater.

Keywords. Soil erosion, Deposition, Erosion mechanics, Sediment transport, WEPP.

Introduction

Soil erosion by water is a complex mechanism, which depends on various land use, weather, hydrologic, topographic, and soil properties. The combination of these factors dictates the rates at which sediment detachment, transport, and deposition occur. Although there has been much study in most of the aspects of soil erosion, the overall picture is not complete. One area that needs further study is the effect of rainfall and flow depth on sediment deposition in rills. This is especially important for parameterization of deposition equations in physically based erosion models such as the Water Erosion Prediction Project (WEPP) developed by the United States Department of Agriculture (Flanagan and Nearing, 1995). Of particular interest for this study are the erosion equations used in WEPP for sediment deposition in a rill. These equations are derived from the continuity equation for sediment transport and are presented as follows (Foster et al., 1995):

\[
\frac{dG}{dx} = D_r + q_s \quad \text{where} \quad D_r = \alpha(T_c - G) \quad \text{and} \quad \alpha = \frac{\beta V_s}{q}
\]

where \(G\) is defined as the sediment load per unit width (ML\(^{-1}\)T\(^{-1}\)), \(x\) is the distance along the channel (L), \(D_r\) is the net deposition rate in rills (ML\(^{-2}\)T\(^{-1}\)), \(q_s\) is the lateral sediment inflow from adjacent contributing broad shallow flow areas (ML\(^{-2}\)T\(^{-1}\)), \(T_c\) is the transport capacity (ML\(^{-1}\)T\(^{-1}\)), and \(\alpha\) is a first-order reaction coefficient (L\(^{-1}\)) which is computed for a single particle size distribution (Foster, 1982) with the following parameters: \(V_s\) is the effective particle fall velocity (LT\(^{-1}\)), \(q\) is the flow rate per unit rill channel width (L\(^2\)T\(^{-1}\)), and finally \(\beta\) being a dimensionless turbulence parameter.

The \(\beta\) constant is a gather all parameter that includes the turbulence of the rainfall and other such turbulence and is defined to range from zero for shallow flows and high turbulence to one for deep flows and low turbulence, but is usually set to 0.5 for shallow flow under rainfall in a rill. This is a parameter that could be improved by taking into account different sources of turbulence. The experiments in this study are designed to help in the understanding of the turbulent effects of rainfall intensity and flow depth on deposition of sediments and therefore to improve the representation of this parameter.

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Materials and Methods

Experimental Setup

An experimental setup was designed to simulate conditions in an agricultural rill. The setup included a 3.6 m long by 0.25 m wide flume with sediment feeders that added sediment to the top and sides of the rill, rainfall simulators, and a laser scanner. The experimental setup was named the rill simulator (Figure 1) and was designed to study the effects of different parameters such as slope, rill width, sediment input from the top and sides, infiltration, sediment type, flow depth, and rainfall intensity on deposition in a rill. The laser scanner was used as a tool to measure the surface of the sediment bed before and after each experimental run and obtain a digital image of the deposition and detachment that had occurred as a result of the experimental treatment.

Figure 1. Rill simulator used to conduct experiments of deposition in rills.

A variety of rainfall intensities ranging from 0 to 160mm/hr, two flow rates and a few sediment feed rates were studied. Slopes, water inflow rates, and sediment feed rate conditions were selected accordingly to obtain shallow flows and to reach a depositional stage for the specific sediment being studied. The experiments were conducted using silica sand, glass beads, and plastic/glass aggregates. These sediments vary in their sizes, densities, and fall velocities as shown in Figure 2(a). It is also important to note that silica sand and glass beads erode in a similar way as natural sand and that an experiment conducted by mixing a small fraction of the plastic/glass aggregates with a Cincinnati series soil resulted in similar erosion rates as shown Figure 2(b). It was therefore possible to study the effect of sediment size and density on deposition as influenced by rainfall intensity and flow depth.

a) Sediment physical properties

<table>
<thead>
<tr>
<th>Sediment type</th>
<th>Specific gravity</th>
<th>Average diameter (mm)</th>
<th>Experimental Fall Velocity (m/s)*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silica sand</td>
<td>2.65</td>
<td>0.330</td>
<td>0.0557</td>
</tr>
<tr>
<td>Glass beads</td>
<td>2.50</td>
<td>0.150</td>
<td>0.0211</td>
</tr>
<tr>
<td>Plastic/Glass aggregates</td>
<td>1.25</td>
<td>3.175</td>
<td>0.0986</td>
</tr>
</tbody>
</table>

*The fall velocity was calculated experimentally using the Griffith Tube (Hairsine and McTainsh, 1986).

b) Erodibility of plastic/glass aggregates when mixed with Cincinnati series soil.

Figure 2. Physical properties of sediment used in experiments (a) and erodibility of plastic/glass aggregates when mixed with Cincinnati series soil on a 10% slope erodible rill (b).

Two types of results were obtained, sediment leaving the bed and sediment being deposited on the bed. Sediment leaving the bed was measured by collecting outflow samples every minute during the 10-minute runs
and sediment deposition on the bed was measured by using a laser scanner. Topographic laser scans were taken before and after each experiment run and deposition quantities in control volumes along the rill for each experiment were calculated from the difference between initial and final laser scans (Cochrane and Flanagan, 1997).

Deposition Modeling

The deposition in a rill was modeled by using the WEPP deposition equations presented earlier. These equations were solved using a finite difference approach, which allows the estimation of deposition in control volumes down the rill. Deposition in each control volume as defined by the laser scans would be dependent on the sediment concentration flowing in from the adjacent control volume, the sediment fall velocity, the flow rate, the turbulence, and the transport capacity in the volume.

\[
G_{out} = G_{in} + (X_{out} - X_{in}) \cdot \left( \frac{\beta \mu_f}{q} \right) \cdot (T_c - G)
\]

Where \( G_{out} \) and \( G_{in} \) are the sediment load going in and out of interval (kg/m·s), \( X_{out} \) and \( X_{in} \) represent distance down slope (m), \( \beta \) is the dimensionless turbulence parameter, \( \mu_f \) is the particle fall velocity (m/s), \( q \) is the flow rate per unit channel width (m²/s), and \( T_c \) is the transport capacity (kg/m·s). The \( \beta \) factor is used to adjust the prediction for greater turbulence induced by a rainfall intensity and flow depth relationship, which may also be linked to particle size or density.

Results and Discussion

The results from the deposition studies with sand and glass beads showed that rainfall intensity did not have a significant effect on either deposition in the rill or sediment discharge from the end of the rill for different ranges of slopes, sediment feed rates, and flow depths. In other words, the interaction between flow depth and rainfall as it affects deposition was not observed with the sands and glass beads. Meyer et al. (1983) obtained comparable results for similar conditions (flow rates, rainfalls, and sand sediments of similar size) and alluded that these conditions resulted in a transition phase in which rainfall intensity did not have an effect on sediment transport. Additionally, another explanation stems from visual observations of the experiments involving sands, where it was observed that most of the sediment moved as bed load transport. Foster (1982) mentions that for bed load transport the deposition equation could possibly be ignored, but may be significant for the transport and deposition of fine particles. However, using finer particles, such as glass beads, did not change the results significantly either, but low-density particles such as the plastic/glass aggregates were influenced by rainfall intensity and flow depths (Figure 3).

![Figure 3. Deposition/detachment changes with rainfall intensity for plastic/glass beads during 10-minute runs. Error bars show one standard deviation range for 3 to 4 repetitions each.](image-url)
For these low-density particles, no rainfall and high intensity rainfall diminish deposition, whereas at medium rainfall intensities deposition is greater. This effect is also seen in the detachment regime, but it is more pronounced on deposition as seen in Figure 3. Additionally, shallower flow depths (at 20L/s flow rate) show a greater deposition at medium intensity rainfall, relative the no rainfall and high rainfall intensity, than at deeper flow depths (at 30 L/s flow rate). A possible explanation for this is that meandering and concentration of water flow were seen in the deposition study when rainfall was not present. This meandering could have decreased the deposition by concentrating the water flow and increasing the transport capacity. Rainfall had a definite effect on the surface of the bed. When either the medium or high rainfall intensity was applied to the flow, the bed of the rill kept a uniformly flat surface. Meandering of flow and formation of bed forms were significantly reduced and in most cases eliminated. Deposition areas were still present, but visual determination of these areas was difficult and could only be accounted for with laser scans. The high intensity rainfall is thought to have increased turbulence thus limiting deposition.

Modeling of deposition was attempted using the deposition equations used in the WEPP model (Equation 2). The results showed that a turbulence factor $\beta$ equal to 0.5, as used in the WEPP model for flow in rill with influence of rainfall, did not adequately predict the deposition on the bed for the experiments. Alternate $\beta$ values were calculated and found to be in the range of 0.02 to 0.2 for different flow depths ranging from 3 mm to 6 mm. Rainfall intensity did not seem to have a significant effect on the calculation of the $\beta$ value for the sands and glass beads, but there was observable influence of rainfall intensity and flow depth on the calculation of $\beta$ using plastic/glass artificial aggregates.

**Conclusions**

A series of laboratory experiments were conducted to study the influence of rainfall intensity and flow depth on deposition in a rill. The deposition of sands and glass beads in the rill was not significantly altered with different rainfall intensities or flow depths. However, a significant effect of rainfall intensity on deposition in shallow flow depths was seen in the experiments carried out using the less dense plastic/glass artificial aggregates. Modeling with the WEPP deposition equations suggested that the turbulence factor $\beta$ could be adjusted to account for sediment size/density, rainfall intensity, and flow depths. Alternate bed load equations should be examined and adjusted to predict deposition in conditions of shallow and turbulent flow for sands and dense particles. Further experiments with smaller sized particles of different densities and different flow conditions should be performed in order to obtain a better understanding of the relationships of flow depth, sediment size/density, and rainfall intensity on estimating values of $\beta$.

**References**


