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# Rocks and Rills: The Impact of Rock Fragments on Soil Loss by Concentrated Flow Erosion in Laboratory Experiments

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## ABSTRACT

**In recent times more attention in research has been given to the role rock fragments play in soil erosion. The demand to focus on the interaction between fine particles and rock fragments, and their effects on soil loss, has increased because these types of soils are ubiquitous. Therefore, a study with twenty flume experiments was conducted in which concentrated flow was applied to a Miami Silt Loam, a typical soil of the Midwest of the United States. The study focused on four different treatments: slope (7 and 14%), flow discharge (5.7 and 11.4 L min$^{-1}$), rock fragment content (0, 5, 10, 20, 40% vol) and flow duration. The results show the development of an erosion pavement with time and a surface armoring for soils containing rock fragments. The intensity and the speed of the development of this pavement are dependent on slope, discharge, and initial rock fragment content as well as flow duration. An increase of the rock fragment cover protecting the eroding surface helps to prevent soil loss. The more rock fragments were incorporated with the soil, the less sediment yield was observed in general. Soil surface roughness was evaluated by means of a laser scanner device and a counting method to find an index for the described armoring effect and to identify the increase of cover during the experiments.**

## INTRODUCTION

In the past researchers have given primary attention to the erodible parts of soils that are easily washed or blown away, and less to rock fragments that are less likely to erode and stay in place. However, it is becoming increasingly apparent that larger particles, i.e. rock fragments play an important role in soil erosion. Also, soils containing a significant amount of rock fragments are quite common in many regions. Poesen and Lavee (1994) pointed out that in the Mediterranean region more than 60% of the soils contain a considerable amount of rock fragments. Erosion pavements are found in abundance in semi-arid and arid regions (Mensching 1990). Poesen and Lavee (1994), as well as Brakensiek and Rawls (1994), reported several different effects of rock fragments in soils on soil moisture, plant growth, fertility, runoff, overland flow hydraulics, as well as rill and interrill erosion.

Poesen et al. (1994) discussed the effects of rock fragment to water erosion. They pointed out three key effects of rock fragments in an eroding environment: the protection against raindrop impact and flow detachment (I), the reduction of physical degradation of the eroding surface (II), and retardation of overland flow velocity (III). Lawrence (1996) differentiated the influence of rock fragments for three flow regimes: partially inundated, marginally inundated, and well inundated. Since the frictional resistance of a rock fragment covered surface, is rapidly decreasing with depth of flow.

Other papers concentrated more on overland flow hydraulics of different soil surfaces. Savat (1980) showed for different soil surfaces that log f (where f is the Darcy Weisbach coefficient) decreases with log Nr (where Nr is Reynolds number). Gilley et al. (1992) tested the f-Nr relation for different rock fragment covers glued on a plane surface at varying slopes. They found a negative relation for f-Nr when particles were submerged and a positive relation when larger fragments protruded through the flow. This idea was modeled by Lawrence (1997) who developed the inundation ratio model to describe partially, marginally, and well-inundated flow. Abrahams and Parsons (1991) found that the f-Nr relations varied with the nature of their field experiments. All these authors conducted experiments on non-erodible or fairly stable surfaces, so that their models do not reflect natural conditions i.e. after tillage, as flow energy is not allowed to erode the surface by spending energy for soil detachment and transport processes. Bunte and Poesen (1993) conducted flume studies with rock fragments embedded in the soil surface, but not incorporated in the soil matrix. Reynolds numbers for these experiments were around 200 for the applied shallow overland flow. Past literature has focused on sheet flow conditions; rill flow in combination with rock fragments was not yet studied in laboratory experiments.

This study concentrated on the effects that rock fragments incorporated into the soil body have on concentrated flow hydraulics and erosion as simulated in laboratory experiments. In addition to the rock fragment content, slope and flow discharge were varied. This paper concentrates on qualitative as well as quantitative measures to describe the effects of rock fragments on soil loss observed by the authors.

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## Experiments

Twenty laboratory flume studies were conducted on a Miami silt loam (fine-silty, mixed, mesic Typic Hapludalf). The Miami soil, which contained 25% sand, 52% silt and 23% clay by mass, was taken from an agricultural cornfield 12 miles southwest of West Lafayette, Indiana - USA. Two classes of rock fragments were mixed with the soil. The smaller material had a $D_{50}$ (Median diameter of the intermediate axis of the particle) of 8 mm, the larger a $D_{50}$ of 30 mm. Three parts of the smaller and one part of the larger rock fragments were mixed with the soil that was passed through an 8 mm sieve and air-dried for 2 days. The rock fragments were taken from fluvial deposits from the Wabash River and were sampled 3 miles west of West Lafayette, Indiana - USA.

All experiments were conducted in a 3 m flume that was described earlier by Nearing et al. 1997. The air-dry soil rock fragment mixture was packed loosely in the flume over a sand tension table bed to a "V" shaped surface, the depth of the V being approximately 0.5 cm and the width being 15 cm. The dry bulk density of the soil was 1.27 $gcm^{-3}$; density of the rock fragments was 2.6 $g/cm^{-3}$.

The rock fragments were well-rounded and their flatness index [Leser 1977, p. 203] was found to be 1.75 and 2.0 for the coarser and finer material respectively, given by the ratio of:

$$F = (L+l)*(2E)-1 \qquad (1)$$

where (F) is the flatness index and (L), (l), and (E) are the length of the longest, intermediate, and shortest mutually perpendicular axes of the rock fragments, respectively.

The soil was prewetted from the bottom of the flume through a tension table for 24 hours and then brought to 15 cm tension for 12 hours (Nearing et al., 1997). Drainage from the tension table was then clamped off during the experiment, except for the end drainage hole, which was allowed to drain freely to prevent re-emergent flows at the bottom end of the soil bed during the test. The flume was then raised to the appropriate slope. Slopes used were 7% and 14%. Water flow was added to the top of the flume. Nominal inflow rates were 5.7 and 11.4 L $min^{-1}$. Mean flow velocities were calculated by measuring the velocity of the leading edge of a fluorescent dye and multiplying by a correction factor (Gilley et al., 1990). Flow and rill widths were measured with a ruler during the experiments. The effective rock fragment content by mass was calculated by sampling the soil bed after the run, oven drying the sample, and calculating the ratio of fine earth mass to rock fragment mass after sieving trough a 2 mm sieve. Soil surface roughness and rock coverage were calculated by different methods. Rock fragment cover [%] on the flume surface was estimated by the point count method using a regular grid with 10*10 points on a slide screen using photographs of the soil surface taken before and after each part of an experiment. Photos were made for top, center, and bottom parts of the flume covering the same areas as the laser scans. For a more detailed evaluation of surface roughness, a laser scanner technique was used to visualize erosion and deposition areas as well as having data to define soil surface roughness. The scanner was built by Eltz (1993) reading x, y, and z coordinates of the soil surface to create a three-dimensional model on a computer screen by Kriging interpolation. Quantitative analysis of the scan data was carried out using a semi-variance diagram to illustrate changes in soil surface roughness for different cross sections in the flume at different times during an experiment. The surface elevation plots were mainly used to describe and visualize processes.

## RESULTS

The observed data represented all four flow conditions of (1) sub critical laminar, (2) supercritical laminar, (3) sub critical turbulent, and (4) supercritical turbulent flow (Fig. 1). Froude number (Fr) was calculated as:

$$Fr = v*(g*d)^{-0.5} \qquad (2)$$

where (v) represents the average flow velocity [$m^3s^{-1}$], (g) the acceleration due to gravity [$ms^{-2}$], and (d) the flow depth [m]. The Reynolds number (Nr) was calculated to be:

$$Nr = v*U*\upsilon^{-1} \qquad (3)$$

where (U) is the hydraulic radius and ($\upsilon$ ) the kinematic viscosity of water [$m^2s^{-1}$]. The break line between laminar and turbulent flow conditions in Fig. 1 is estimated at Nr = 600 using the plot of the Darcy-Weisbach coefficient versus Reynolds number (Fig. 2) wherein we observe a difference in behavior at approximately Nr = 600. The Darcy-Weisbach (f) coefficient was calculated as:

$$f = 8g*U*I*v^{-2} \qquad (4)$$

where (I) represents the slope and all other factors are defined before.

Figure 3 shows the development of the soil surfaces with time for runs with two different rock fragment contents. It can clearly be seen that with 0 Vol.% of rock fragments incorporated in the soil matrix, a deep and narrow rill is formed, but with 40 Vol.% rock fragments we observed a wider flow, hence the soil surface shape did not change greatly during the experiment. This result was true in general for the experiment. The greater the rock content, the wider and shallower was the rill formed.

Figure 4 shows relative sediment yield [g $min^{-1}$] versus rock fragment content [mass%]. The figure shows a negative exponential decay in sediment yield with increasing rock fragment content for the lower flow discharge [5.7 L $min^{-1}$], which is consistent with previous results reported in the literature [i.e. Savat, 1990, Gilley et al., 1992, Bunte and Poesen, 1993, Poesen et al., 1994]. For the 11.4 L $min^{-1}$ flow discharge the exponential decay relationship is less evident and in fact the graphs become nearly linear. This difference might be explained by the fact that there are different responses of soil surfaces for higher flow discharges. Also, the experiments with the higher discharge could not be run for a very long time because rills cut more quickly into the 12 cm deep soil bed especially in the case of 0% rock fragments

Figures 5 and 6 show the development of rill cutting depth with time [log-scale]. The average depth of the rill was calculated as a ratio of the sediment collected at the

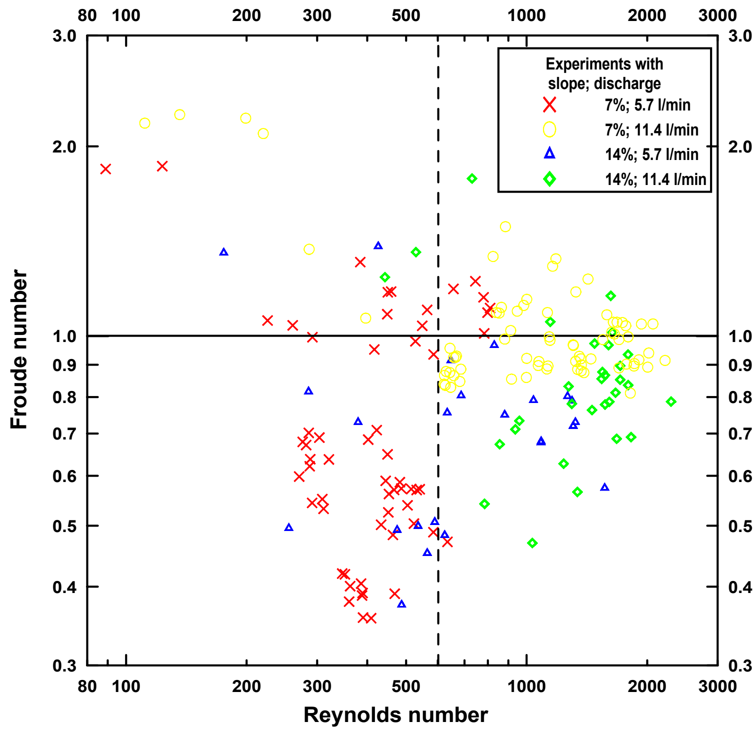


**Figure 1 Hydraulic flow regimes for the experimental data. The dashed line indicates the change between laminar (below 600) and turbulent (above 600) conditions and is set somewhat arbitrarily according to the observations of this experiment. The solid line indicates the change from sub critical to supercritical as defined by a Froude number of below or above 1, respectively.**

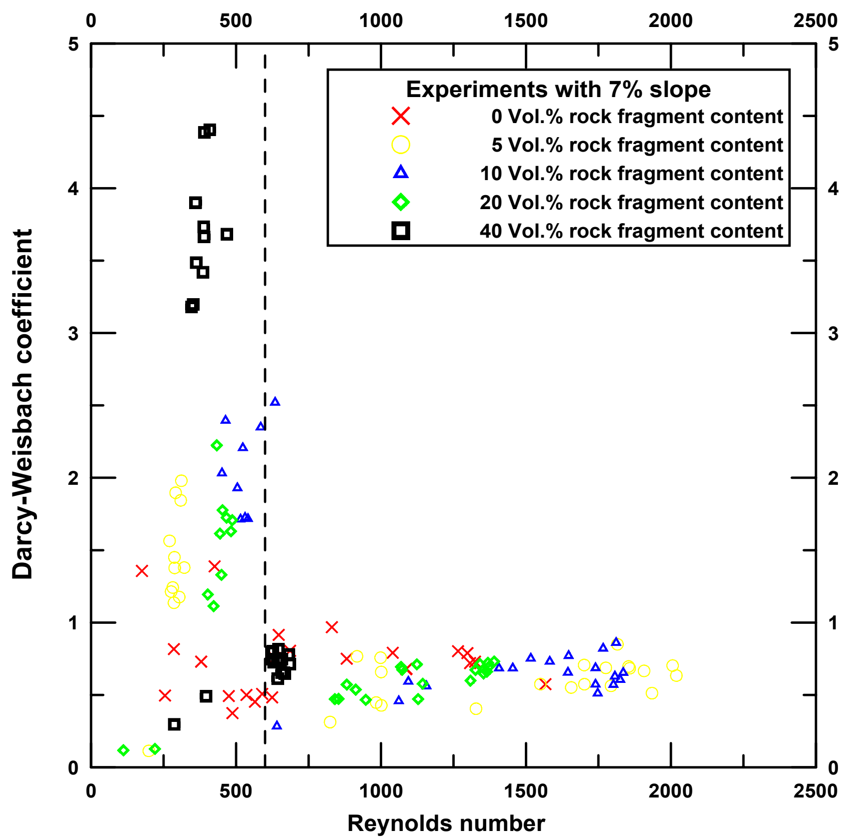


**Figure 2. Darcy-Weisbach factor as a function of Reynolds number for experiments with 75 slope and rock fragment contents varying from 0 – 40 Vol.%. The dashed line indicates the brake between laminar and turbulent conditions.**

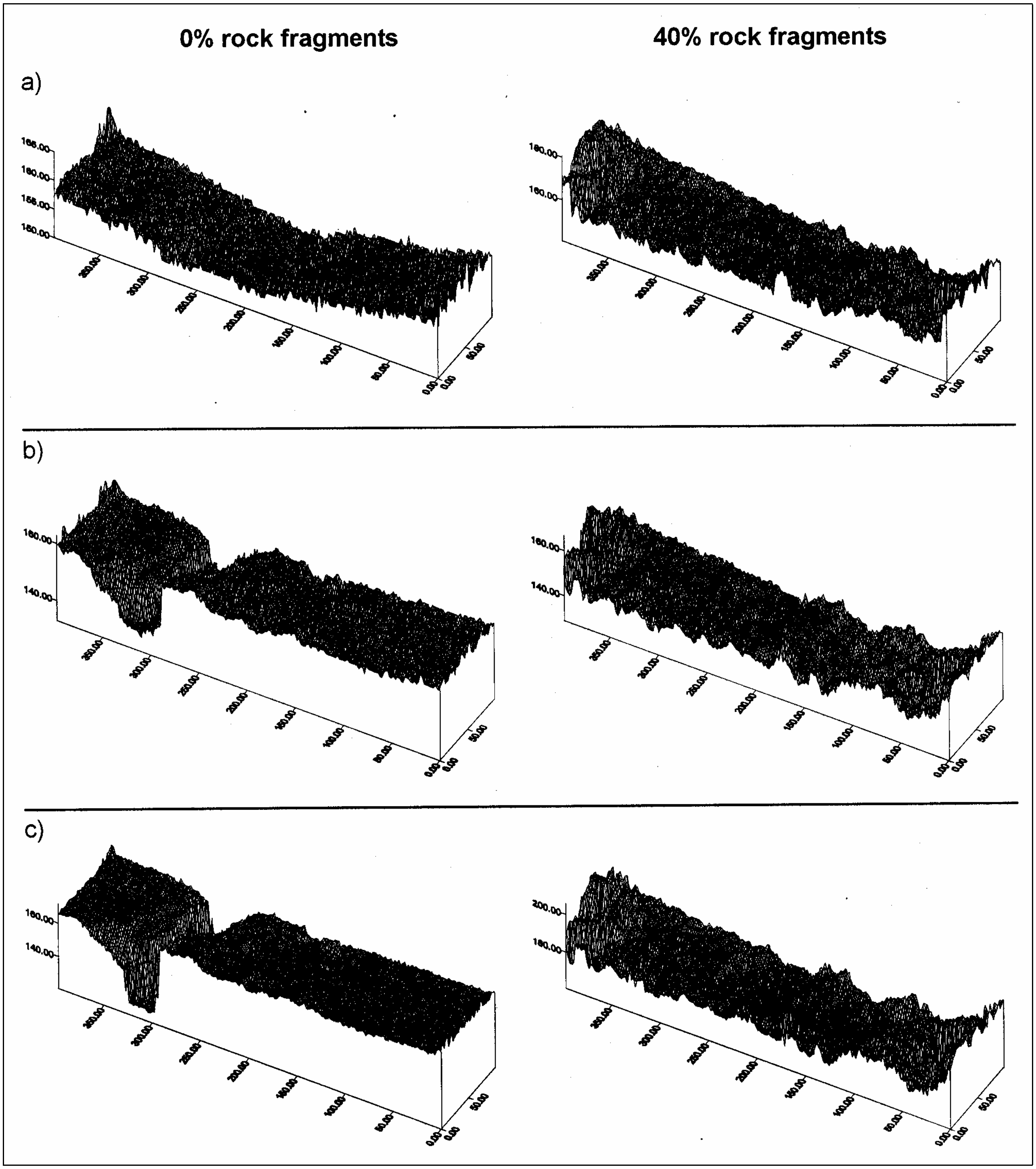


**Figure 3. a) Surface scan before the experiment, extent 10 (in flow direction) * 40 cm²; b) Surface scan after 20 min of running the experiment, same area; c) Surface scan after 40 min of running the experiment, same area. All units on the plots are in mm, slope of the experiment was 14%; discharge 11.4 L $min^{-1}$.**

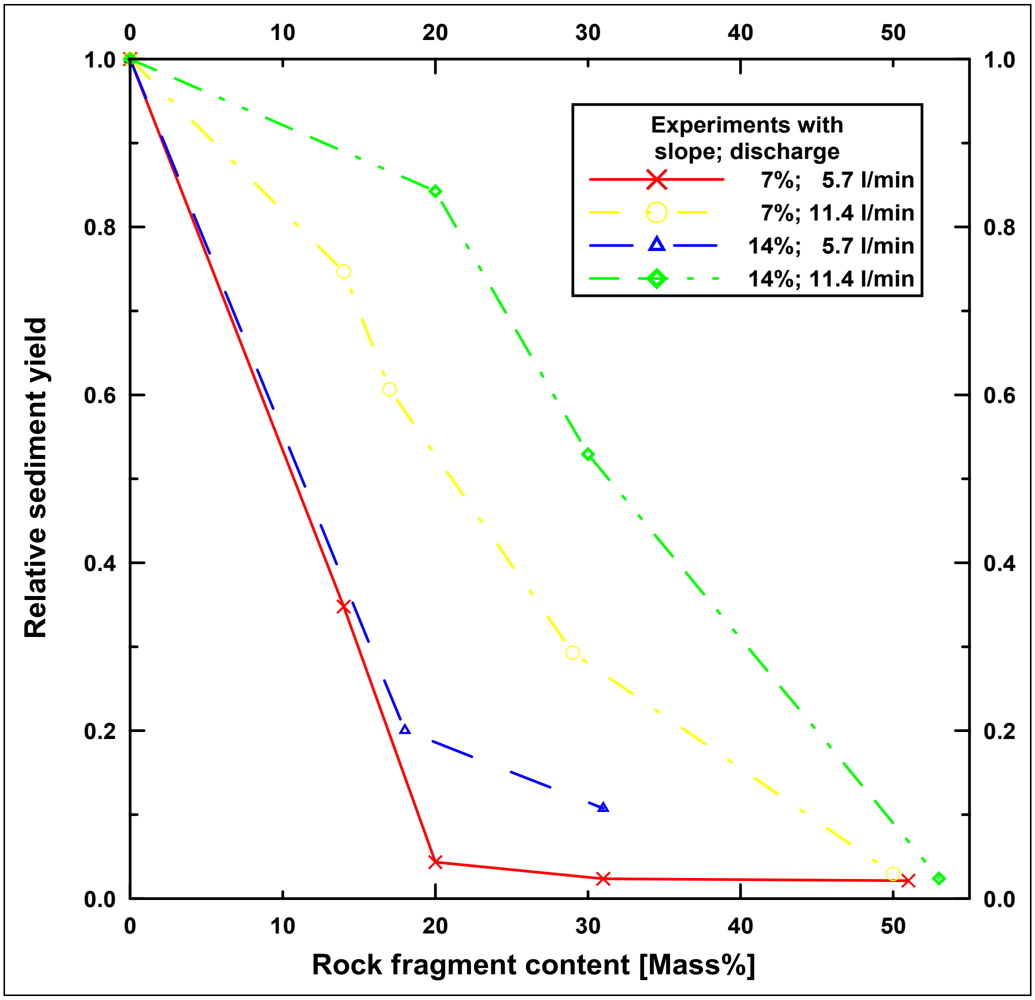


**Figure 4. Relative sediment yield as a function of rock fragment content by mass.**

bottom of the flume and the averaged flow width in the flume for corresponding time intervals. In Fig. 5 it can be seen that the experiment with 0% mass of rock fragments continues to erode and that the rill is cutting deeper with time. For the other treatments of rock amount, we observe near steady state conditions after 10 to 15 minutes. The amount of soil loss is negligible after that time. Figure 6 shows that the armoring process is also dependent on water flow rate. At the greater flow rate of 11.4 L $min^{-1}$, the rill continued to cut after 18 minutes for all but the greatest rock content of 53% mass; thus it appears that there exists an interaction between armoring, flow rate, rock fragment content, and time.

No consistent observations can be made in plotting Reynolds number, flow velocity, or rill width against flow duration. Usually the graphs run parallel to the X-axis, not developing significantly with time, except for rill width and Reynolds number for runs with no rock fragments applied. Here, rills develop narrower and deeper with time and Reynolds number increases with time. The strong relations found by Bunte and Poesen (1993) between various hydraulic parameters could not be observed in this study, probably due to the wide range of flow conditions that were applied in this study.

Hydraulic roughness of the soil surface was evaluated by plotting Darcy Weisbach coefficient against Reynolds number. Fig. 2 shows the graph for all 7% slope data. The graph can be separated into two parts at a Reynolds number of about 600. Below that Reynolds number roughness, as given by the Darcy Weisbach coefficient is higher with higher rock fragment content. Similar observations were made by Savat (1980), Gilley et al. (1992), Bunte and Poesen (1993) as well as Lawrence (1997). For more turbulent conditions (Nr > 600), the data behave approximately the same for all rock fragment contents, which is different from other results reported in the literature. The graph indicates the same roughness effects for all rock fragment contents what could be due to a higher inundation of single particles as described by Lawrence (1997) or due to the fact that we have an eroding surface that changes with time and dissipates energy bye the means of erosion. Due to that more soil loss is observed for runs with less rock fragments embedded in the soil matrix, the development of headcuts in rills is increasing the rills' physical roughness as proposed by Nearing et al. (1997). The differences between concentrated flow in rills and sheet flow for armored surfaces are another difference that could lead to the observed differences in the data.

A simple linear model was fitted to the experimental data to predict sediment yield (Y) [g $min^{-1}$] by flow discharge

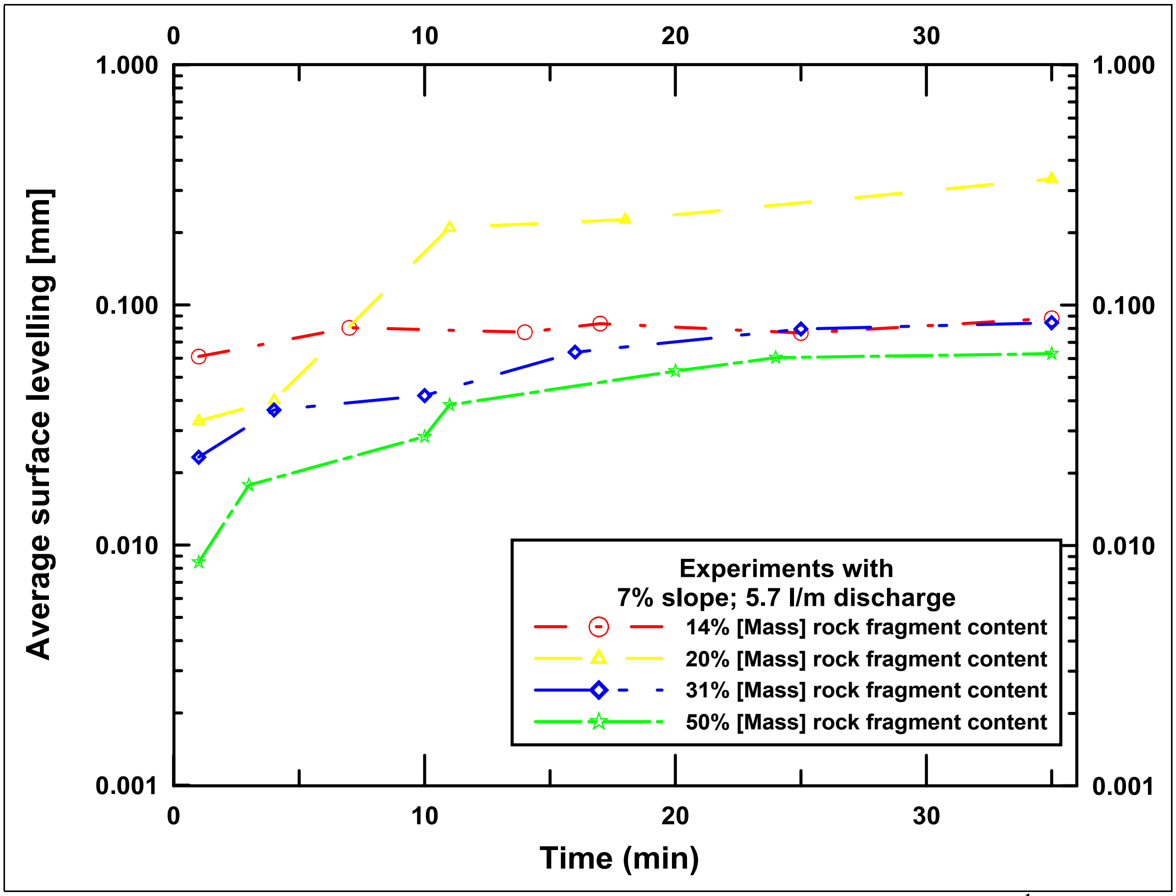


**Figure 5. Average depth of rill as a function of time for experiments with 7% slope and 5.7 L min$^{-1}$ discharges.**

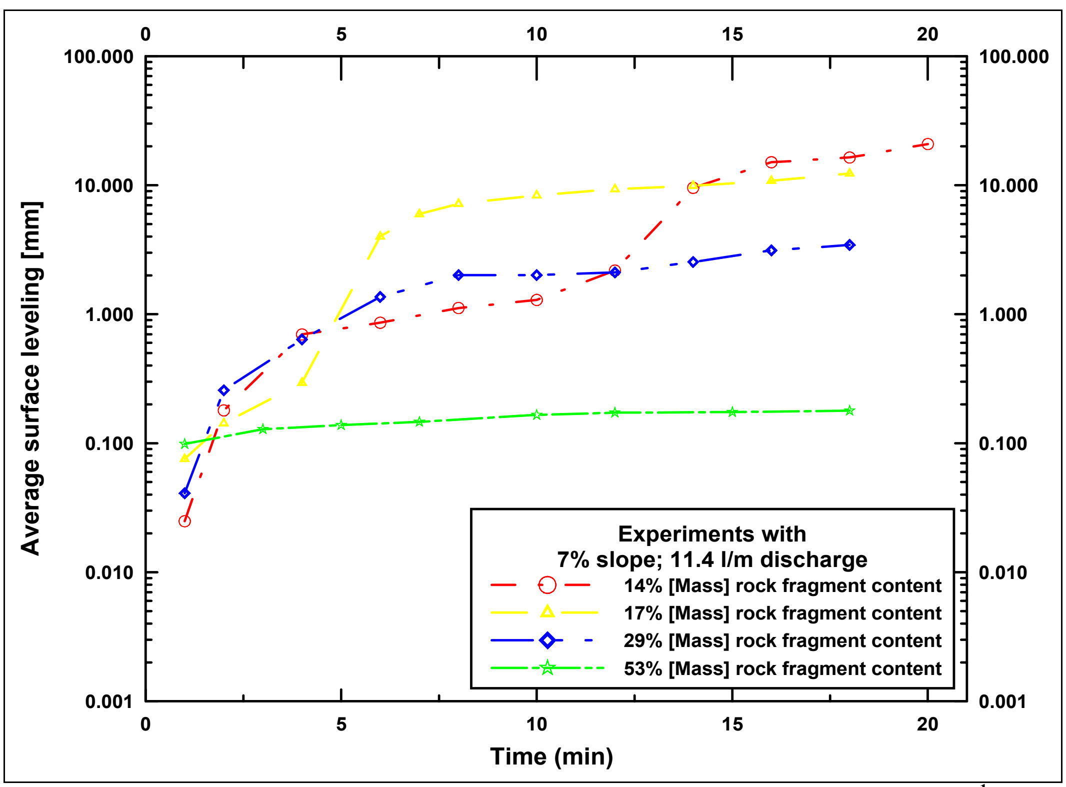


**Figure 6. Average depth of rill as a function of time for experiments with 7% slope and 11.4 L min$^{-1}$ discharge.**

(Q) [L $min^{-1}$], slope (S) [%], and initial rock fragment content (Co) [Vol%]. Slope and initial rock fragment content were treated as class variables. To introduce the effect of time each observation was referenced at point (t) stating the experimental time. The obtained regression function for the natural logarithm of sediment yield explained 72% of the variance within the data set ($r^2$=0.72). The relationship that was found is as follows (e being Euler's number):

$$Y_t = e^{37.70} * Co_t^{-1.04} * Q_t^{3.17} * S_t^{2.87}$$

## CONCLUSIONS

The influence of rock fragments on surface armoring and rill erosion rates was described. We showed that rills form deeper and narrower in soils with fever rock fragments embedded in the matrix, and that armored surfaces tend to produce more shallow overland flow. Sediment yield decreased greatly with increased rock fragment content. Surface armoring was observed to be a time dependent process. Relative sediment yield showed an exponential decay function for the 5.7 L $min^{-1}$ flow discharge experiments, but a more linear decrease for 11.4 L $min^{-1}$ flow discharge.

Hydraulic roughness was found the be related to rock fragment content for low flow conditions, but no differences as a function of rock fragment content were found for flow conditions with a Reynolds number > 600. Statistical analysis showed that 72% of the sediment yields data that could be predicted by a simple linear model using slope, discharge and rock fragment content. The eroding surface used in this study showed a somewhat different behavior than non-eroding surfaces reported in the literature. Future research should focus more on the development of headcuts in the rills, and the differences between shallow interrill and concentrated rill flow to describe the armoring due to rock fragments on an eroding surface.

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