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Factors influencing the velocity–discharge relationship in rills

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Abstract Govers (1992) proposed an empirical relationship to predict flow velocities in rills. Flow velocities in rills were found to be independent of slope. This is probably due to the fact that the effect of increasing slope on flow velocity is compensated for by the formation of a rougher bed surface. New sets of laboratory and field data were analysed in order to evaluate the range of conditions that Govers' relationship can be applied to. For bare unconsolidated soils, where rills are able to adjust their geometry to channel flow, the results are in agreement with Govers' equation. In this situation flow velocity is independent of slope. For soils covered with stones or vegetation flow velocities were lower than predicted from Govers' relationship, but the velocity–discharge relationships were of the same general form. Different results are also obtained when soils are strongly consolidated because rills may then be restricted in their ability to adjust their channel. An effect of slope on the velocity–discharge relationship may be present in such situations.

INTRODUCTION

Flow velocity calculation is a necessary component of all process-based hydrological and soil erosion models. In most models, the Manning equation is applied because of its wide use by engineers and the availability of input data (Morgan *et al.*, submitted). Some models assume that runoff occurs as sheet flow with a uniform flow depth over a model element (pixel, slope segment, e.g. ANSWERS (Beasley *et al.*, 1980)). Recently, more realistic models have been developed which make an explicit distinction between rill and interrill erosion, (e.g. EUROSEM (Morgan *et al.*, submitted)). However, these models also rely on the Manning equation for the calculation of flow depth and velocity albeit that different values of the roughness coefficient (Manning's n) may be used for rill and interrill flow.

Available experimental data suggest that the use of the Manning equation with a fixed roughness coefficient for rill flow may be questioned and that its general use in hydrological and erosion modelling may, in some cases, lead to erroneous results. Using data from the literature and his own experiments, Govers (1992) showed that the flow velocity in rills could well be predicted using the relationship:

$$u = 3.52 \cdot Q^{0.294} \qquad (1)$$

with u = flow velocity (m s^{-1}) and Q = discharge (m^3 s^{-1}). There was no clear slope and/or soil effect. The reasons for this were not clear but it was hypothesized that due to the higher erosion rates on steeper slopes, the rill bed will be rougher, leading to a greater flow resistance. Similarly, rills formed in soils with a low shear strength may be wider but smoother than rill beds formed in very cohesive soils, again leading to similar flow velocities in both cases.

The aim of this study is to determine the range of conditions for which this relationship holds. New sets of laboratory and field experimental data are analysed to evaluate the effect of soil type, slope and stone content on rill flow velocity.

MATERIALS AND METHODS

Data sets

Three data sets were used in this study.

Dataset 1 consists of a series of flume experiments carried out in a flume with a length of 4.25 m, a width of 0.4 m and a depth of 0.6 m. The flume was filled with a sandy loam (collected in the Belgium Loam Belt near Leuven) containing *c.* 17.8% sand, *c.* 70.0% silt and *c.* 12.2% clay (Atterberg). The slopes used were 3°, 5°, 8° and 12° and inflow rates were approximately 0.05, 0.1, 0.3, 0.6 and 0.9 $l\ s^{-1}$. During the experiment samples were collected at the downslope end of the flume to determine water and sediment discharge. The flume was constructed in such a way that the height of the downslope wall could be adapted to the incision of the rill. Mean flow velocity was measured using the dye tracing technique described by Govers (1992).

Dataset 2 was collected using the same experimental procedure. However, the soil material was mixed with stones. The stones had a diameter between 1.7 and 2.7 cm. The mass percentage of stones in the mixture was 0, 7.5, 10, 15.6, 20.0 and 31.1%. The slope of the flume was kept constant at 5°.

Dataset 3 consists of the results of field experiments carried out in two pineapple

Table 1 Slope, pineapple age and the presence of vegetation at the experimental field sites.

Location	Experiment	Slope (degrees)	Pineapple age	Vegetation
Buchanan				
Site 1	B1.1	1.8	16 months	removed
Site 1	B1.2	2.2	16 months	removed
Site 2	B2.1	2.9	33 months	removed
Site 2	B2.2	2.7	33 months	left in place
Site 3	B3.1	2.2	6 months	removed
Site 3	B3.2	2.2	6 months	removed
Walkers				
Site 1	W1	14.6–16.7	1 week	removed
Site 2	W2	14.9–16.9	3 months	removed
Site 3	W3.1	17.2	40 months	removed
Site 3	W3.2	17.0	40 months	left in place
Site 3	W3.3	16.9	40 months	removed
Site 3	W3.4	17.7–18.5	40 months	removed

farms in the Gympie district in southeast Queensland (Ciesiolka *et al.*, 1995). At the Buchanan site the soil was an unconsolidated loamy sand (typic eutropept). The slopes varied from 1.8 to 2.9°. The experiments were conducted in three pineapple crops with an age of 6, 16 and 33 months. Before an experiment, vegetation cover in contact with the soil was removed except for one run, at the location with the oldest pineapples, where the leaves were left in place (*c.* 45% coverage). At the Walkers site the soil was a lithic eutropept, containing up to 40% of mostly small gravel. Slopes at this site were much steeper and varied from 14.6 to 18.5°. The experiments were carried out in pineapple crops of 1 week, 3 months, and 40 months old. Again, leaves were removed before the start of an experiment, except for one run in the oldest pineapples. Some details of the various test sites are given in Table 1. Water was added at the top of an 8-m-long test section located in a furrow between two pineapple ridges. Inflow rates varied from 0.08 to 2.4 l s^{-1}. During the run, samples were taken at the outlet of the test section to determine water and sediment discharge. Flow velocity was measured using the dye tracing technique described by Govers (1992).

RESULTS

The laboratory results for bare soil are presented in Fig. 1. In this figure the relationship found by Govers (1992) is also plotted. In most cases, measured flow velocities agree well with the predictions from equation (1) and the data do not show a clear slope effect on flow velocity. For the lowest or the lowest two discharges in each experiment there was no rill incision: in these cases, measured flow velocities were sometimes significantly higher than predicted.

In Fig. 2 the results of the second series of flume experiments are shown. Again, the velocities for the experiments without stones are predicted well by Govers' equation. However, when stones are added to the soil flow velocities are lower than predicted by equation (1). The relationship between velocity and discharge is of the same general form. Surprisingly, there is no clear relationship between stone content

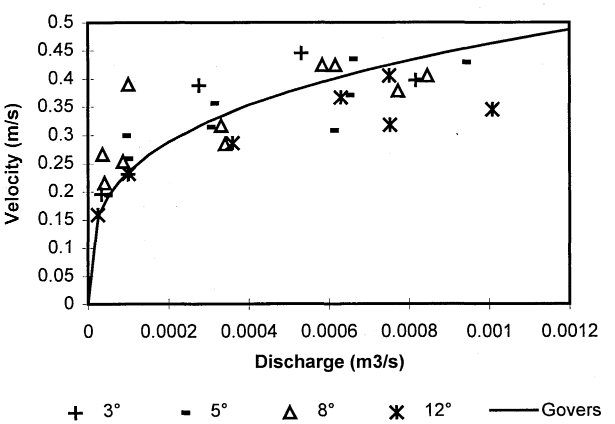

Fig. 1 Velocity-discharge relationship for laboratory experiments with varying slopes (degrees) (data set 1).

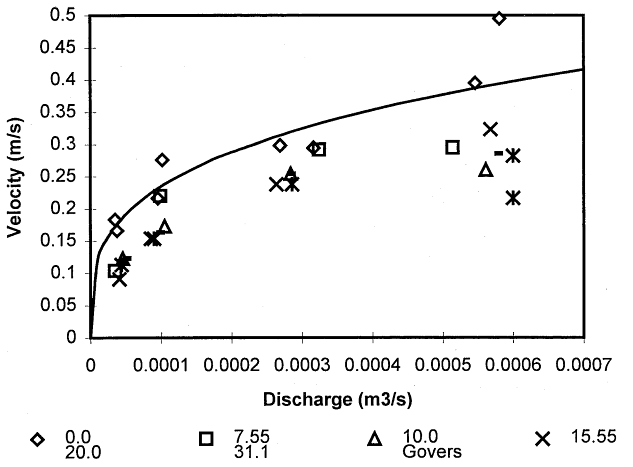

Fig. 2 Velocity–discharge relationship for laboratory experiments with varying stone content (%) (data set 2).

and flow velocity: very similar results were obtained for stone contents between 10 and 31%.

The field data from bare soil on the Buchanan site are in good agreement with Govers' relationship even for discharges much higher than those used by Govers (1992) (Fig. 3). When leaves were left in place (B2.2), the flow velocities were reduced 2–3 times.

Data from the Walkers sites show a more complex situation (Fig. 4). On recently cultivated unconsolidated soil (W1 and W2) data are in agreement with equation (1). At Walkers site 3 the soil was strongly consolidated. Here, velocities were significantly higher than predicted for discharges exceeding 0.0005 $m^3 s^{-1}$. Again, flow velocities dropped by a factor 2–3, where leaves were left in place (W3.2).

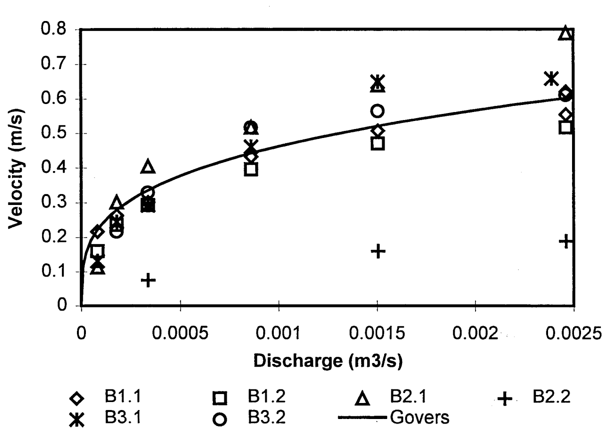

Fig. 3 Velocity–discharge relationship for field experiments at the Buchanan sites (data set 3, Table 1).

DISCUSSION

The experiments presented in this paper confirm earlier findings by Govers (1992): the flow velocity in rills appears to be independent of slope and soil type and can be predicted from discharge alone if the rill is formed in an unconsolidated, non-stony soil. Govers suggested that this independency might be due to an increase of bed roughness with increasing slope. Nearing *et al.* (1997) also found that the flow velocity in rills was slope independent. They reported a significant increase in both number and overfall height of headcuts as rill steepness increased, which is in agreement with the hypothesis of Govers.

The present data show that Govers' (1992) relationship is certainly not universal: in the laboratory lower flow velocities were measured when stones were present in the soil. On the other hand, flow velocities on the Walkers field sites 1 and 2 were similar to those predicted by equation (1), despite the high stone content of the soil. A fundamental difference between the field and the laboratory data sets is that, in the case of the laboratory data, the stones were not transported by the flow and should be considered as static roughness elements. This hampered the flow's ability to adjust its bed. On the field site, the high slope made it possible for the flow to transport rock fragments, even at relatively low flow discharges. In the latter case, the flow could therefore be considered to be competent to adjust fully its own bed.

This ability of the rill to adjust its geometry to the flow appears to be a fundamental requirement for equation (1) to hold. This explains why in several studies conducted on fixed surfaces (Rauws *et al.*, 1988; Foster *et al.*, 1984; and Abrahams *et al.*, 1996) the flow velocity in rills was found to increase as a function of slope.

When the flow has insufficient erosion capacity to adjust its bed, both higher and lower velocities than those predicted by equation (1) may be found and a slope effect on flow velocity may be present. The high velocities measured on Walkers site 3 can be explained by the high slope gradient and the fact that the soil was extremely consolidated and relatively smooth due to the long period between the last tillage operation and the experiments. Despite the high erosivity of the flow, rill incision

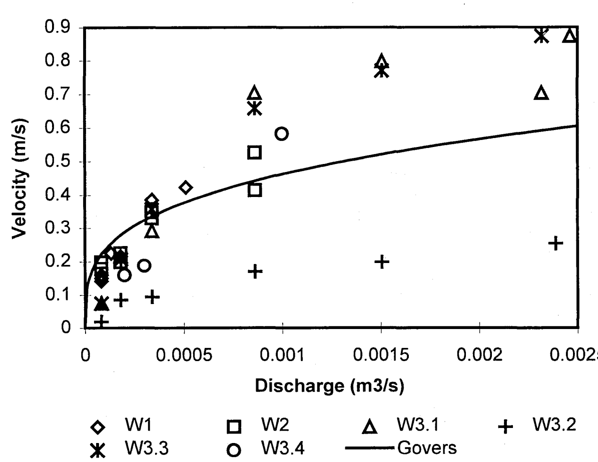

Fig. 4 Velocity–discharge relationship for field experiments at the Walkers sites (data set 3, Table 1).

was very restricted. No or hardly any rill incision occurred in most furrows. As the flow occurred mostly over the smooth, non-incised soil surface, flow velocities up to 50% higher than those predicted by equation (1) were obtained. Similar observations were made during the laboratory experiments (data set 1): flow velocities could be higher than predicted by equation (1) when there was no incision.

On the other hand flow velocities can be much lower than predicted by the Govers relationship if static roughness elements (plants, residue, stones) play a dominant role. This is apparent from the results of the field experiments with vegetation cover as well as from the laboratory data on stony soils (data set 2). The effect of a non-erodible stone cover in combination with low slope gradients may also explain the generally lower flow velocities found by Abrahams *et al.* (1996).

The slope independency of flow velocities in self forming rills implies that the use of the Manning equation is not adequate for the prediction of rill flow velocities, as in this equation flow velocity is related to slope with an exponent of *c.* 0.3. Performance of process-based hydrological and erosion models may be improved by using the Govers' relationships instead of the Manning equation for rill flow, at least if the model is applied to areas where rills are formed in bare, unconsolidated material (Govers, 1992). The applicability of the model to soils with stones and/or vegetation cover needs further investigation. It may still be possible to predict rill flow velocities from a relationship similar to equation (1), but parameterization in function of soil and vegetation characteristics will be necessary.

CONCLUSIONS

The results of this study indicate that there are dynamic relationships between rill flow velocity and discharge. Govers' relationship can be applied to bare soils if the flow is fully capable of adjusting the channel and bed geometry. If this adjustment is not possible both higher and lower velocities may be found depending on slope gradient and the presence of roughness elements (stones, vegetation cover). The results also indicate that the use of the Manning equation for rill flow is not appropriate. The ability of the rills to form and/or adapt its geometry dynamically as a function of discharge and slope has to be accounted for in experimental designs. If the soil bed is artificially fixed before an experiment the obtained results on rill hydraulics may not be realistic.

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