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Estimating Manning's *n* for steep slopes

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Abstract

Hydrological and soil erosion models require calculations of flow velocity, for which either the Darcy-Weisbach or the Manning equation is generally used. A series of field experiments was carried out in a small catchment on the Chinese Loess Plateau to obtain reliable values of Manning's *n*. The soils are typically erodible loess soils. The experiments were conducted for a range of land uses as well as for different slope angles (6–64%). Measurements were performed on a 2.5 × 0.4 m plot, on which flow was allowed to find its own path. Water was evenly applied to the top of the plot and discharge, surface velocity, flow width and slope were measured. The results show that Manning's *n* can, just like Darcy-Weisbach *f*, be estimated from Reynolds number. Furthermore, for croplands, there is an apparent linear increase in Manning's *n* (and *f*) with increasing slope angle ($R^2 = 0.70$). As Manning's *n* is usually assumed to be constant, this must mean that either velocity increases with slope or hydraulic radius decreases. The measurements showed virtually no increase in velocity and a minor increase in hydraulic radius with slope, as flow was more concentrated on steeper slopes. Possible explanations for this lack of increase in velocity include increased roughness [Water Resour. Res. 37 (2001) 791], decreased effective slope angle because of the development of vertical head cuts and a shift in energy use. All three hypotheses only apply to situations involving erosion. The trend of Manning's *n* with slope implies that, in soil erosion models using Manning's equation (or Darcy-Weisbach), the value of *n* (or *f*) should be a function of the slope for erodible soils. For non-erodible soil (as in woodland), no increase in Manning's *n* with slope was observed.

Keywords: Manning's *n*; Darcy-Weisbach *f*; Erodible soils; Chinese Loess Plateau

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1. Introduction

Hydrological and soil erosion models need to calculate the flow velocity to be able to simulate the flow of water over the land surface. These models generally use a separate water balance for each spatial element, in which the water depth available for runoff is calculated by subtracting interception, infiltration and surface storage from precipitation. Several equations are available to calculate overland flow velocity from this water depth. The most widely used of these equations are the Darcy-Weisbach and Manning equations.

Most field and laboratory studies on overland flow seem to use the Darcy-Weisbach f, whilst most studies of channel flow use Manning's n. This division, however, is not clear-cut, as the choice for either formula is also influenced by personal preference. Furthermore, there is no reason to assume major differences in results between the two methods. Both are calculated from the same variables and both suffer from the limitations of having to characterise flow patterns that are highly variable in space and time. On hill slopes, overland flow will occur as a shallow sheet of water, with faster flowing, diverging and converging flow threads around obstacles. Flow depth and velocity will therefore be highly variable in space. Abrahams et al. (1990) studied Darcy-Weisbach f for desert hill slopes and found that it varies with the rate of flow. Since the rate of flow is highly variable in space, so too is f. Resistance to flow will also be variable in time, as it depends on continuously changing flow conditions. This dependence is often expressed by developing relationships between the Darcy-Weisbach f and Reynolds number (e.g., Abrahams et al., 1990; Gilley et al., 1992). As Takken and Govers (2000) have noted, Manning's n is likely to behave in the same way as f. Likewise, Emmett (1970) showed that there are not only relationships between Re and f, but also between Re and n and between Re and Chezy C. The flow will also tend to concentrate in the downslope direction, which is likely to decrease resistance to flow in that direction (Abrahams et al., 1990).

Contrary to field studies, most hydrological and soil erosion models use Manning's n, probably because the literature provides more data for n than for f. Another reason could be that the use of Manning's equation for overland flow is more or less accepted, while Darcy-Weisbach appears not to have been used for streamflow. It is obviously preferable to use only one equation for any one model application, and the choice for Manning's equation in modelling is therefore generally accepted.

The Danangou catchment is a typical small (3.5 km^2) Loess Plateau catchment in Northern China, with steep slopes and a loess thickness of close to 200 m. The climate is semi-arid, with occasional heavy thunderstorms in summer. At Ansai town, 5 km from the Danangou catchment, total average annual rainfall was 513 mm over the period 1971–1998 (data from Ansai County Meteorological Station), with most of the rain (72%) falling in the period of June to September. Vegetation cover is generally low, even in croplands, and as the loess soils are susceptible to crusting, very high erosion rates can prevail during these summer storms. High erosion rates are also promoted by steep slopes. Gully walls in the catchment have angles up to about 250% (70°) and croplands on slopes in excess of 50% are common. Research into the flow resistance on such steep slopes has been scant. Abrahams et al. (1990) measured f values on slopes of 6–33°, but they focussed on soil roughness effects and did not investigate the effect of slope itself.

The aims of the research project described in this paper were the following. (1) To evaluate the use of Manning's equation for steep slopes. For this purpose, Manning's *n* was measured on slopes ranging from 6% to 64%. (2) To find out if Manning's equation can be used or if the Darcy-Weisbach equation is more suitable because of its relationship with Reynolds number. (3) To obtain values of Manning's *n* for different types of land use in the Danangou catchment. The values obtained for different land uses and slopes were intended to be used as input for soil erosion models.

2. Experimental set-up

Manning's *n* was measured using 2.5 × 0.4 m plots. The set-up of the measurements is shown in Fig. 1. Water was evenly applied to the top of the plot using a small, horizontally placed gutter. Discharge could be regulated using the tap on the bucket above the gutter. The water level in the bucket (and hence the discharge) could be kept reasonably constant with the help of two Mariotte bottles with a volume of 25 l each. Discharge was measured at the bottom of the plot by recording the water level in a bucket every 15 s. Low earthen walls were used as the boundaries of the plot, since these disturb the natural water flow less than metal sheets, which tend to result in concentrated flow along the boundaries of the plot. Water velocity was measured over a 2-m stretch, either every 30 s or every minute (depending on the velocity), using dye tracer. The leading edge of the dye cloud was used, so that the

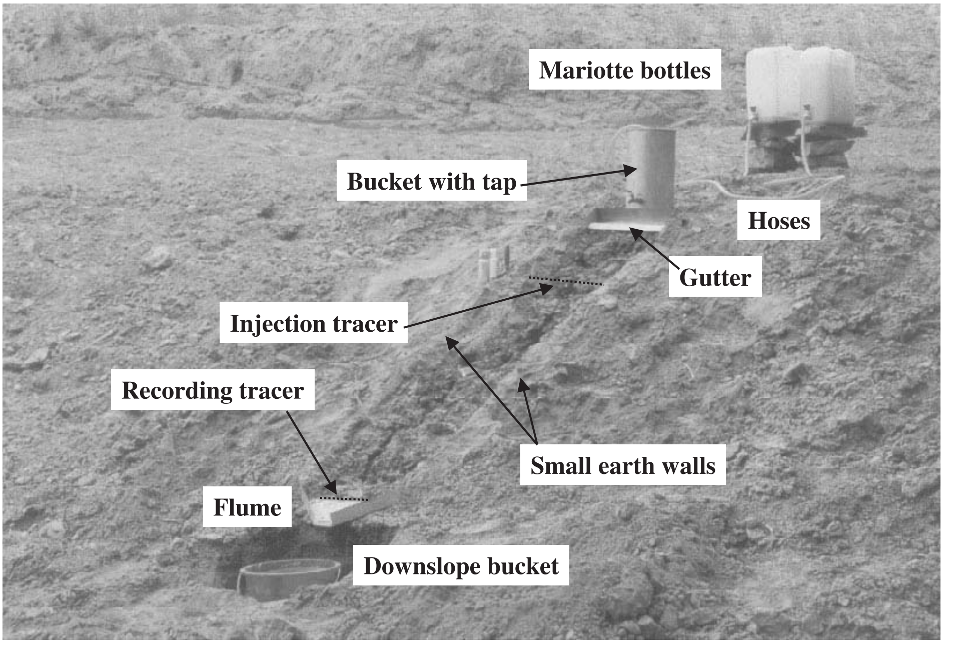

Fig. 1. Set-up of measurement 3 of the second series (2000). See Table 1 for plot characteristics.

Table 1
Plot characteristics

Land use	Crop type	Plot number	Slope (%)	Cover (%)	Comments
First series (1999)					
Cropland	Maize and bean	3a	19	30	
Cropland	Maize and bean	3b	40	30	
Cropland	Sunflower and bean	5a	25	6	
Cropland	Sunflower and bean	5b	13	10	
Cropland	Foxtail millet	6a	14	4	weeding
Cropland	Foxtail millet	6b	30	8	weeding
Cropland	Potato	7a	55	4	
Cropland	Potato	7b	28	5	
Cropland	Soy bean	8a	27	10	
Cropland	Soy bean	8b	13	5	
Cropland	Pearl millet	10a	38	10	weeding
Cropland	Pearl millet	10b	46	10	weeding
Cropland	Potato	11a	36	8	weeding
Cropland	Potato	11b	47	5	weeding
Cropland	Foxtail millet	12a	6	3	weeding
Cropland	Foxtail millet	12b	7	5	weeding
Fallow		9a	27	2	
Fallow		9b	44	1	
Orchard		2a	34	5	
Orchard		2b	34	4	
Wasteland		4a	62	25	
Wasteland		4b	62	20	
Wasteland		14a	54	25	
Wasteland		14b	54	35	
Woodland		1a	34	42	
Woodland		1b	34	44	
Woodland		13a	22	86	
Woodland		13b	23	44	
Second series (2000)					
Cropland	Pearl millet	3	44	0	thin crust
Cropland	Pearl millet	4	9	1	thin crust
Cropland	Maize	6	19	1	
Cropland	Maize	8	56	1.5	
Cropland	Maize	9	32	5	
Cropland	Maize	12	40	5.5	
Cropland	Maize	13	46	5.5	
Cropland	Pearl millet and bean	14	25	32	weeding
Cropland	Pearl millet and bean	15	13	7	weeding
Cropland	Pearl millet	16	51	4.5	
Cropland	Pearl millet	25	11	4	
Cropland	Pearl millet	26	9	7.5	
Cropland	Maize	29	15	5.5	
Cropland	Maize	30	29	8.5	
Cropland	Potato	31	36	15.5	
Cropland	Potato	32	62	15	
Cropland	Potato	33	7	5.5	weeding
Cropland	Pearl millet	34	7	1	

Table 1 (*continued*)

Second series (2000)					
Land use	Crop type	Plot number	Slope (%)	Cover (%)	Comments
Fallow		19	33	5.5	
Fallow		20	42	6	
Fallow		22	16	61	
Fallow		23	8	32	
Orchard		21	52	3	
Wasteland		18	44	26	
Wasteland		27	57	21	
Wasteland		28	61	30.5	
Woodland		1	64	15.5	
Woodland		2	52	5	
Woodland		5	38	46	
Woodland		7	18	27.8	
Woodland		10	22	36.2	
Woodland		11	30	7	
Woodland		17	55	1.5	
Woodland		24	62	31	

The soil surface for the cropland plots showed slight crusting, unless otherwise stated.

resulting measurement represented surface water velocity. Measuring over a stretch of 2 m was necessary to achieve sufficiently accurate time measurements. The actual flow width was measured with a ruler at several cross-sections along the length of the plot. The measurement required three people: one to check time and record the measurements, a second to inject the tracer and to keep track of its progress and a third to watch the water level in the bucket. The first person could generally also check the performance of the Mariotte bottles.

As one of the aims of the present study was to obtain input values of Manning's n for use in modelling, the plots were left intact as much as possible. No vegetation or litter was removed, as these would also be present in natural conditions during rainstorms.

Before measurements started, the plot was prewetted until the wetted area of the plot no longer changed visibly. This was necessary to ensure a steady state flow during the measurement. Each measurement consisted of three runs, each lasting 10 min. About 40 l of water were normally used in each run. As long as the water did not become too dirty from sediment and tracer, some of it was recycled for the next run. Nevertheless, the distance from available water sources limited the selection of possible locations for measurement. Total plot erosion could also be determined by measuring the sediment levels in the buckets at the lower end of the plot after the experiment had been completed.

Manning's n was calculated whenever the velocity was available, using running 1-min averages of discharges. As the runs lasted 10 min each, only velocity measurements between 30 s after the start of the run and 30 s before the end of the run could be used. Manning's n was calculated in the following way:

$$n = \frac{R^{2/3} \cdot S^{1/2}}{v} \tag{1}$$

where R = hydraulic radius (area (A)/wetted perimeter (P)) in metres, S = slope (sine of slope angle), v = average velocity (m/s).

Darcy-Weisbach f can be calculated from the following equation:

$$f = \frac{8gRS}{v^2} \tag{2}$$

where g = acceleration due to gravity (m/s^2).

The area (A) is given by discharge divided by mean velocity. Dividing A by the measured width gives the water depth (h). P is equal to the sum of the width and twice the water depth. To calculate mean velocity, measured velocities are usually corrected as the dye measurements indicate surface velocity, rather than average velocity (see, e.g., Emmett, 1970; Abrahams et al., 1986; Takken and Govers, 2000). Calculated Reynolds numbers suggested that the flow was transitional in most cases. In accordance with Abrahams et al. (1986), measured velocities were therefore multiplied by 0.7 to obtain mean velocities. Thus, 7–18 values for Manning's n were usually obtained for each run. The differences between the runs were usually small, so the final Manning's n for the plot was calculated by taking the average of all values.

In 1999, Manning's n was measured on 28 plots, 16 of which were croplands. In most cases, two measurements were conducted in each field, using plots with different slope angles. This was done to investigate the effect of slope angle on flow resistance. In some cases, two plots of different lengths (2.5 and 1 m) but with the same slope angle were used. This was done for two reasons: to try and limit water use and to find out if flow concentration on the longer plots would result in lower values of Manning's n. In 2000, an additional series of measurements was conducted on 34 plots, 18 of which were croplands. Since the 1999 measurements had yielded no differences for different plot lengths, all experiments in 2000 were conducted on 2.5 m plots. The 1999 and 2000 measurements are referred to below as the first and second series, respectively. Table 1 summarises the plot characteristics.

Plant cover was estimated from a vertical viewpoint. It therefore included leaf cover for ground vegetation (but not for trees). Plant cover is not equal to cover at ground level, which is much lower because the cover of plant stems is lower than that of the leaves. The number of individual plants on the cropland plots (all 1 m^2) was generally below 10 and at these concentrations the presence of plants did not seem to impede flow. The soil surface of the cropland plots had been ploughed some weeks before measurement and a slight crust had formed in most cases. On a few plots, weeds had been recently removed (Table 1) and, in these cases, the crust had been broken locally. The orchard plot had been weeded, but not ploughed. The other plots had remained undisturbed. Litter cover was incorporated in the soil cover estimations.

The second series of experiments, carried out in 2000, was conducted in much the same way as the first series had been in 1999. The only differences were that in 2000 flow width was measured more accurately and more attention was paid to erosion on the plot. The second series of results therefore gives a little more information than the first series.

3. Results

The data collected on the plots were used to calculate Manning's n, Darcy-Weisbach f and Reynolds number. As shown in Fig. 2, both n and f increased with increasing

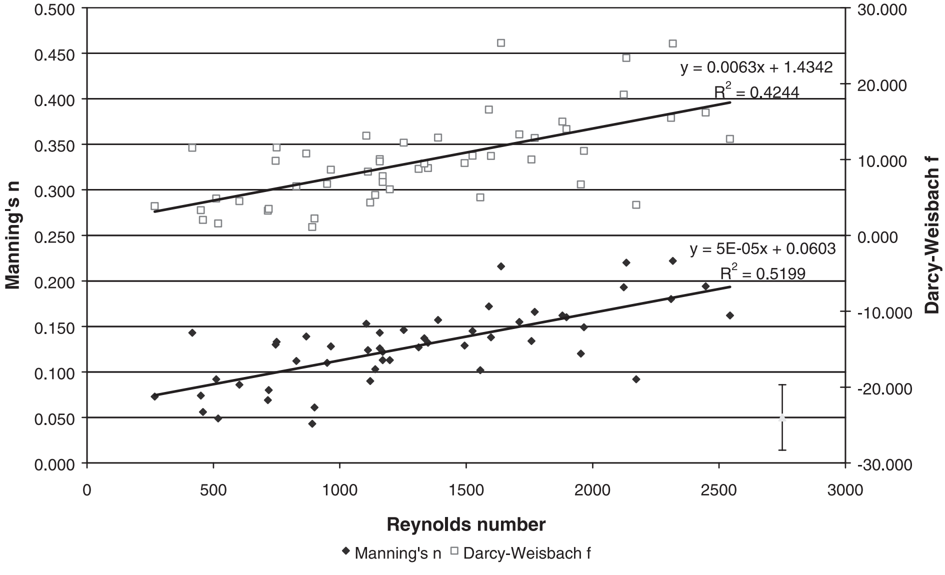

Fig. 2. Manning's n and Darcy-Weisbach f as functions of Reynolds number. Data for all cropland runs of the second series. The bar in the lower right-hand corner shows the average error about the mean of two standard deviations.

Reynolds number (*Re*). Linear regression showed that R^2 was slightly higher for the n–*Re* relationship than for the f–*Re* relationship (0.52 versus 0.42). This shows that the approach of developing relationships to calculate f from *Re* is just as valid for n. In the remainder of this paper, only Manning's n is used.

The calculated values of Manning's n, averaged for the various types of land use, are given in Table 2, which is based on the first data series (1999), as this series studied a larger variety of land uses than that in 2000. The value found for woodland is much higher than for all other land uses. This is caused by the presence in some places of dense undergrowth of herbs, together with litter. Fallow land includes both short-term fallow (which should be similar to cropland) and long-term fallow (which can be expected to resemble wasteland). All cropland plots were combined because no differences were found between the various crops. Instead, the Manning's n values calculated for cropland show a clear relationship with slope angle. This is shown in Fig. 3, which shows combined data for 1999 and 2000. Fig. 3 also suggests that, for the lower slope angles, the values found

Table 2
Average values of Manning's n for the first (1999) series

Land use	Manning's n	Standard deviation	N	Number of plots
Cropland	0.104	0.052	375	16
Fallow	0.076	0.016	49	2
Orchard	0.090	0.023	50	2
Woodland	0.211	0.083	58	4
Wasteland	0.084	0.025	92	4

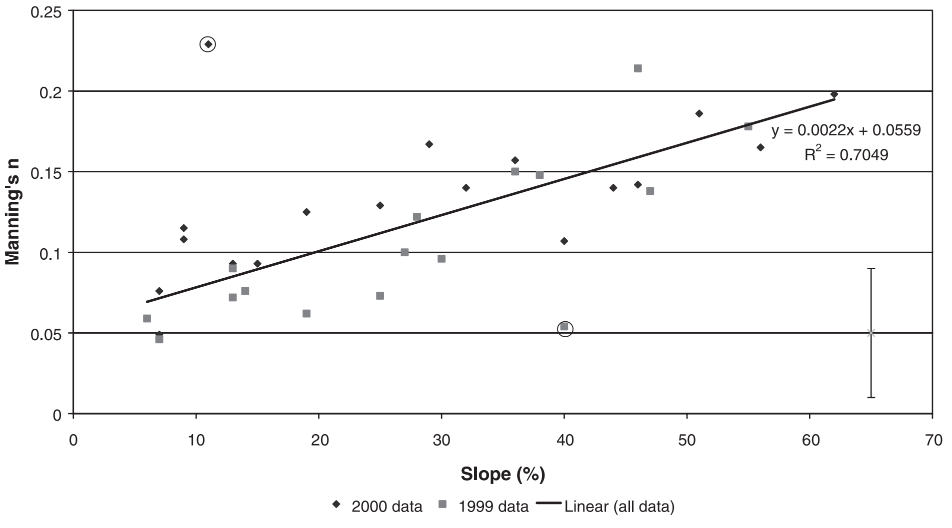

Fig. 3. Cropland Manning's *n* as a function of slope, data per plot. Data for 1999 and 2000 combined. The circled points have been omitted from the regression. The bar in the lower right-hand corner shows the average error about the mean of two standard deviations.

for Manning's *n* were lower in 1999 than in 2000. This might be caused by a more accurate measurement of flow width in 2000. In 2000, only water that actually flowed was measured, while in 1999 standing water was also measured. Since there is only standing water at low slope angles, this might explain the above observation. Despite the small difference in method between 1999 and 2000, the data for the 2 years are very similar and a single regression equation can therefore be used.

The fitted linear regression line has the equation:

$$n = 0.0559 + 0.0022S \tag{3}$$

where S is expressed in percent. The value for R^2 is 0.70. The circled data points in Fig. 3 were omitted from the regression for the following reasons.

The data point at slope 11% and Manning's *n* 0.230 (measurement 25 in 2000) was on a very gentle slope with pronounced furrows across the slope. Many pools (6) with standing water were formed and the velocity was therefore much lower than is normally the case. Since the experiment forced the water across the plough ridges, one can argue that it is not representative, as it does not reflect the natural flow direction. Obviously, plough ridges and furrows can play an important role in determining the direction of water flow on gentle slopes. Before applying Eq. (2) to a gentle slope one should therefore make sure that the flow is indeed in the direction of the steepest plot level gradient.

The point at slope 40% and Manning's *n* 0.06 (measurement 3b of 1999) differed from all other plots because no erosion was observed, despite the considerable slope. This plot was located very close to (and downslope of) a zone of water seepage, and it seems possible that this seepage had resulted in stabilisation of the loess through hydro-consolidation.

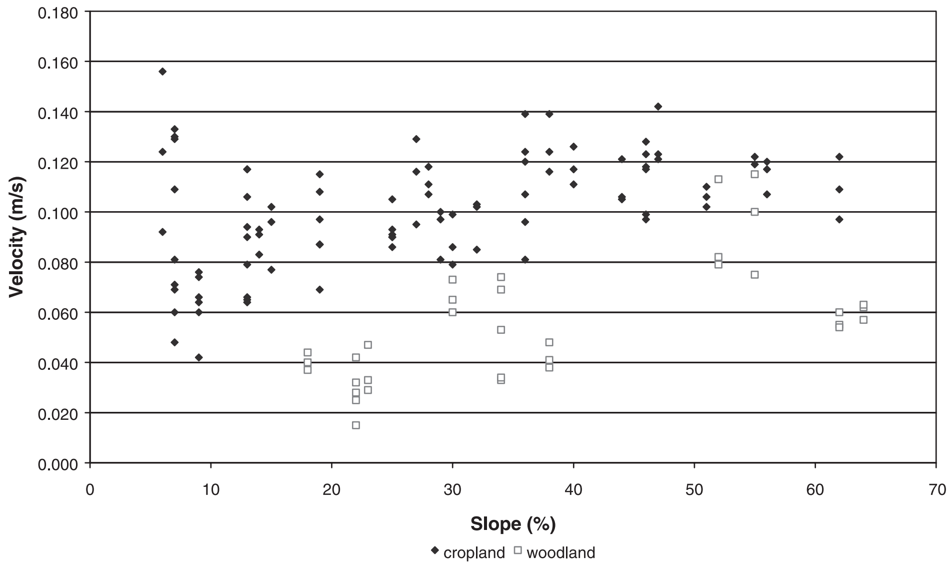

Fig. 4. Velocity as a function of slope for cropland and woodland, all data.

Using the data for all runs instead of those for all plots (Fig. 3) reduces R^2 to 0.57. These results show that slope is a slightly better predictor of Manning's *n* for cropland in the Danangou catchment than Reynolds number, since Fig. 2 shows that the Manning's *n*–Reynolds number relationship has a slightly lower R^2.

Because of the relationship with slope, the cropland values given in Table 2 should be interpreted with caution.

Contrary to cropland, no relationship between Manning's *n* and slope was found for woodland. On the other hand, the woodland plots showed a clearer relationship between velocity and slope than the cropland plots. Fig. 4 shows velocity as a function of slope. Since discharge is different from run to run and velocity is related to discharge, Fig. 4 shows a considerable spread in velocity. Nevertheless, it can be seen that there was no clear increase in velocity with increasing slope for cropland, while a more pronounced increase was found for woodland.

4. Discussion

4.1. Slope versus Reynolds number

The data show that slope was a slightly better predictor of Manning's *n* for croplands in the Danangou catchment than Reynolds number, since the R^2 values for these relationships were 0.57 and 0.51, respectively. Although slope is much easier to determine than Reynolds number, predicting Manning's *n* from a combination of slope and Reynolds number could be a worthwhile approach, because slope only results in a spatial variation in Manning's n, while Reynolds number results in a temporal variation when used in simulations (since Reynolds number depends on changing flow conditions). Further research into this is needed.

4.2. Effects of steep slopes

Manning's n is usually considered a constant, so the question arises what caused this apparent increase of Manning's n with slope. For n to remain constant at increasing slopes, either R has to decrease or velocity has to increase according to Eq. (1). Observations during the experiments showed that, on steeper slopes, the flow concentrated and rill erosion occurred. At the range of discharges used in the experiments, this resulted in an increased value of R because of flow concentration. The erosion rates clearly increased with increasing slope angles. Furthermore, it was observed that flow velocity hardly increased with increasing slope angles (Fig. 4). This has already been observed for eroding rills by several other authors (e.g., Govers, 1992; Nearing et al., 1997; Takken et al., 1998; Giménez and Govers, 2001). One could think of several possible causes.

4.2.1. Increased roughness

This is the most commonly proposed explanation for the observed lack of velocity increase with slope angle. According to Govers (1992), roughness can play an important role in this situation because of two effects:

- Rill beds in cohesive materials are very irregular and are hydraulically rough. The effect of slope might be reduced for hydraulically rough surfaces.
- An increased erosion rate with increasing slope might result in increased bed roughness.

In subsequent research, Giménez and Govers (2001) used laser measurements to show that, for eroding rills, both roughness amplitude and frequency of roughness elements on rill beds increase with increasing slope angle. There is thus a real increase in roughness with increasing slope angles, but their experiments do not show whether or not this increase is sufficient to explain the lack of increase in velocity with slope angle.

4.2.2. Slope decrease

Our experiments found that erosion rates were higher for greater slope angles and that small vertical headcuts developed. The number and size of these headcuts can be expected to increase with increasing erosion rates, and thus with the slope angle. The effect of these headcuts will be to decrease the effective slope angle and thus the flow velocity. During the second year of measurements, these small headcuts were measured and the slope angle corrected. The lower line in Fig. 5 shows that the dependence of Manning's n on slope has decreased, but not disappeared. The slope dependence in the equation has decreased by about 25%. The headcuts could therefore be a partial explanation of the observed relationship between n and slope.

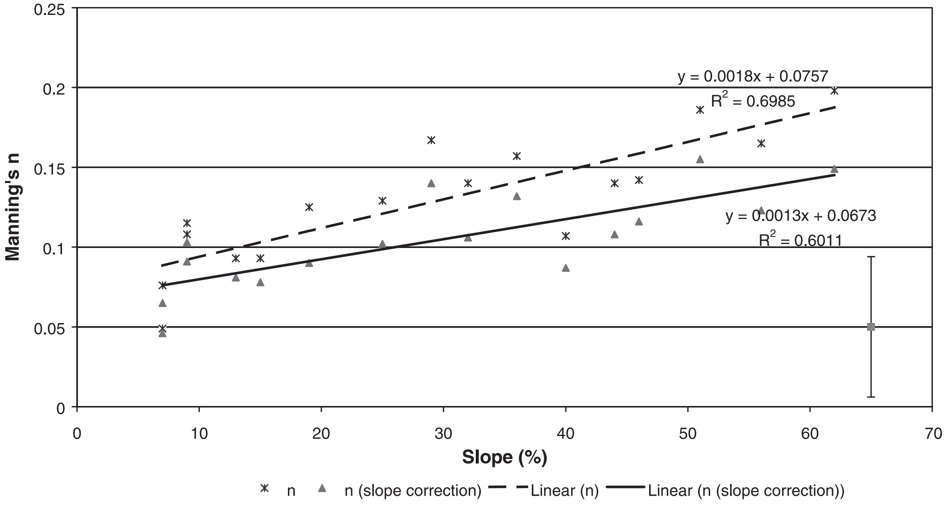

Fig. 5. Manning's *n* as a function of slope for croplands, data of second series. The squares represent the original data, the triangles the data with slope correction. The bar in the lower right-hand corner shows the average error about the mean of two standard deviations.

4.2.3. Energy-based approach

The third explanation for the lack of velocity increase with slope is the result of what might be called an energy-based approach. It was observed that rill erosion rates increased with increasing slope angle. This implies that more energy is used for erosion and transport of sediment than on more gentle slopes and this energy cannot therefore be used for increasing velocity. Both water flow and sediment transport are driven by the one available energy source: potential energy (ignoring raindrop impact energy). This potential energy drives the flow of water, which in turn plays a large role in erosion. With increasing slope angle, potential energy increases but, as was observed, so does erosion (and transport) of soil, and the net effect might be that no more energy is available for water flow than on gentler slopes. Summer and Zhang (1998) use more or less the same line of argumentation to explain the inverse relationship between turbulence and sediment concentration.

Such an energy-based approach is further complicated by the fact that eroded material entering the flow also has potential energy. Erosion therefore not only uses energy from the flow, but also adds energy to the flow. As a result, part of the energy used for erosion will return to the flow. Sediment entering the flow will also alter flow properties like density and viscosity. With increasing sediment content, internal friction will increase and more energy will be needed to overcome this friction. It is therefore perhaps more appropriate to argue that fluid velocity does not increase even though more energy might be used for it. Such a shift in the use of available energy could explain the lack of increase in velocity at greater slope angles. This, in turn, inevitably leads to an increase in apparent Manning's *n* with increasing slope angle.

Although the exact mechanisms and energy uses of all these erosion-related effects cannot be studied with the present field experiments, some indication might be obtained from the quantities of sediment in the bucket at the lower end of the plot. These amounts were recorded in 2000 and if the hypothesis explained above were true, one would expect an increase in Manning's *n* with increasing sediment volume in the bucket. Fig. 6 shows the results obtained.

Fig. 6 shows a weak positive correlation between sediment volume and Manning's *n*, but the data are inconclusive. One has to bear in mind that the field observations showed that erosion rates increased with slope angle. It is therefore difficult to be certain whether an observed relationship between sediment volume and Manning's *n* is a causal relationship or just the consequence of both depending on slope. Also, sediment volume might be significantly influenced by other parameters such as discharge and cohesion. Finally, it was observed that when two consecutive runs with comparable discharge were conducted, the second one generally produced less sediment, but no reduction in the calculated Manning's *n*. The data therefore do not seem to support the hypothesis of a shift in energy use. Clearly, more research is needed.

4.3. Consequences for modelling

In hydrological and erosion modelling, there are several ways to overcome the problem posed by the dependence of Manning's *n* on slope. The most radical method would be to use a different equation altogether. Another solution would be to allow Manning's *n* to change with slope. These methods will now be discussed briefly.

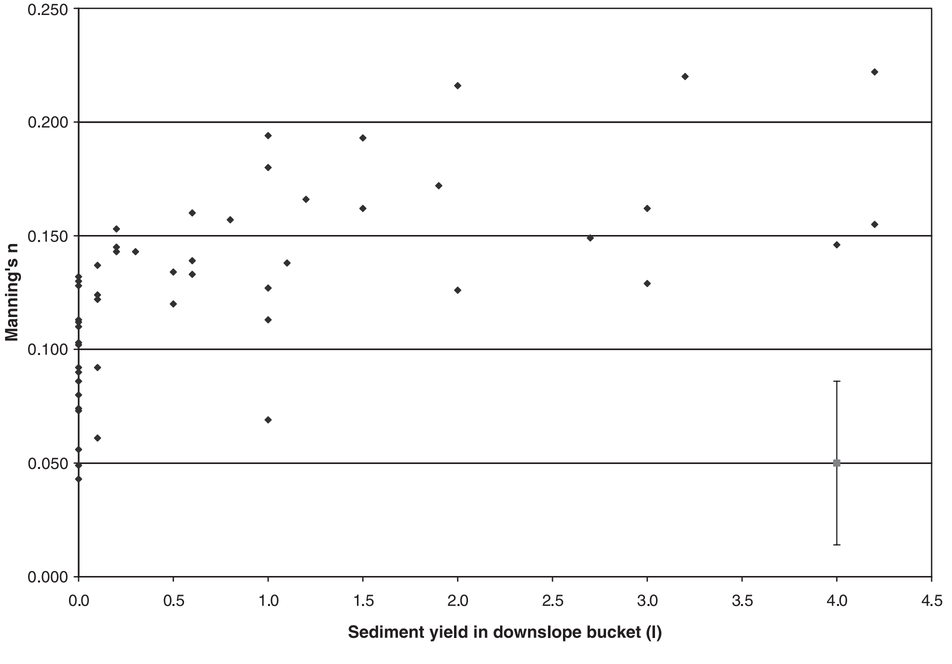

Fig. 6. Manning's *n* versus sediment volume in the bucket at the downstream end of the plot. Data for the second series are shown. The bar in the lower right-hand corner shows the average error about the mean of two standard deviations.

Govers (1992) developed an empirical equation to calculate mean velocity in eroding rills from discharge alone. The equation is:

$$v = 3.52Q^{0.294} \tag{4}$$

Takken et al. (1998) found that this equation can be used in circumstances where the rills can freely change their shape (i.e., in bare, unconsolidated, stone-free soils). They suggest using Eq. (4) instead of Manning's equation to calculate flow velocity in eroding rills.

Flow in cropland rills in the Danangou catchment can be assumed to meet these requirements. Vegetation cover is low; the soil consists of unconsolidated loess and contains no stones in its upper layers. The conditions mentioned by Takken et al. (1998) are, however, not met for most other land uses in the Danangou catchment. In woodland, for example, the soil is usually not bare and it is also much more consolidated than in cropland, making it impossible to apply Eq. (4). Fig. 7 shows the results of the cropland measurements described in the present paper, together with the equation developed by Govers (1992). The equation clearly overpredicts velocity in this case. It should be noted that Fig. 7 shows all measurements, not only those that had eroding rills. To be able to calculate a relationship of the same form as that given by Govers, these data points would have to be removed first, at least according to theory. It should be noted that the discharges used in the present study are much lower than those used by Govers. It is tempting to conclude from Fig. 7 that Govers' (1992) equation is not universally applicable in the case of eroding rills. However, if no velocity correction for the dye tracer is applied, our measured data match the equation developed by Govers

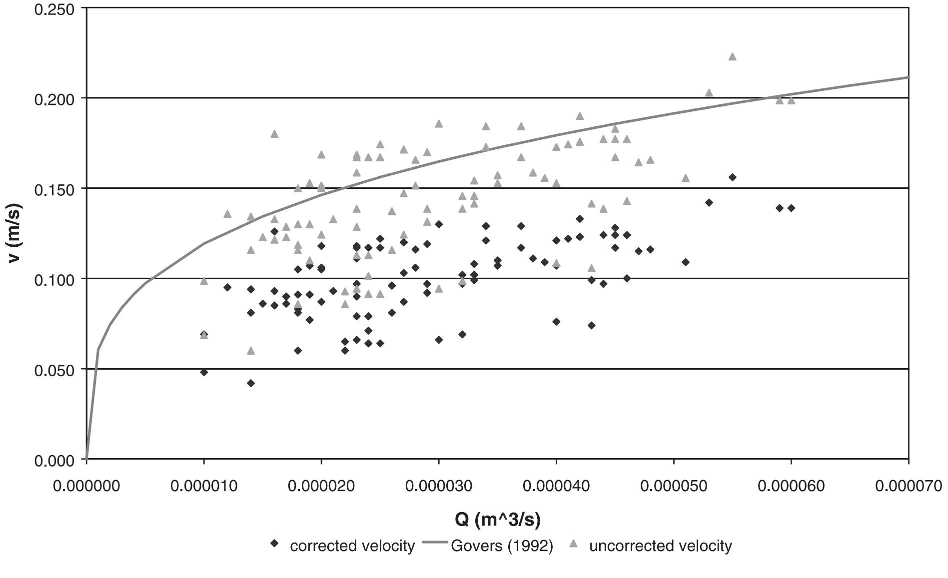

Fig. 7. Velocity as a function of discharge. Measurements are compared with the relationship developed by Govers (1992) and given in Eq. (4). Data for all cropland runs of 1999 and 2000 are shown.

reasonably well (Fig. 7). Since Eq. (4) can only be used for channels freely able to change their shape, it is less well suited for catchment-wide modelling. Using Eq. (4) in erosion models would involve the use of several velocity equations within the model area. Since the position of eroding rills is not likely to remain constant during a storm, the use of different equations would also have to change in time, with the expansion and contraction of the eroding rill network.

The easiest and most practical solution to overcome the modelling problems posed by a variable Manning's *n* is to use Manning's equation with a slope-dependent value of Manning's *n*. This avoids the problem of having to use different velocity equations in different parts of the model area. It can be assumed that Eq. (3) can be used for other Loess Plateau catchments as well as those catchments that have similar characteristics of steep slopes and erodible materials. For other regions, different equations might be necessary.

The values of Manning's *n* obtained seem to be rather high compared to the data published, for example, by Engman (1986), Ven Te Chow et al. (1988) and Morgan et al. (1998). A possible explanation could be that the velocity correction of 0.7 that was applied decreases velocity too much. If no correction is applied; the calculated values of Manning's *n* decrease by about 40%, so a value of, for example, 0.1 is reduced to about 0.06. It is also evident from Fig. 7 that not applying any correction on measured velocity produces much better agreement with the data presented by Govers (1992). The results therefore raise some doubts about the value of the velocity correction factor, at least for field measurements on highly erodible soils.

5. Conclusions

Manning's *n* measurements in a small Loess Plateau catchment showed that Manning's *n* can, just like Darcy-Weisbach *f*, be estimated from Reynolds number. For croplands, Manning's *n* was found to increase with slope angle. This was caused by the fact that flow velocity hardly increased with increasing slope, while hydraulic radius decreased somewhat because the flow became more concentrated at increasing slope, leading to rill erosion. Several factors can help explain why there is little increase in velocity with slope angle. All of these factors only apply to surfaces that can be eroded by the flow. The first is that Giménez and Govers (2001) have shown that, for eroding rills, there is an increase in roughness with increasing slope angle. The second is that the observed increase in erosion rates for steeper slopes results in the development of more vertical headcuts, which effectively decrease the slope angle. The measurement results confirm that this may be a partial explanation. The third explanation is that velocity can be hypothesised not to increase with slope because more energy will be used for erosion and transportation of sediment. Our findings do not seem to support this hypothesis, but do not indicate that it should be rejected either. An increase in Manning's *n* with slope angle was only observed for cropland. Other land uses, like woodland, have virtually no erosion and the velocity then increases with the slope angle.

The results imply that in soil erosion models using Manning's equation, the value of *n* should be a function of slope for surfaces that can be eroded by the flow. The results also raise doubts about the validity of the application of a correction factor to convert measured velocities to average velocities.

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