Instability of Alluvial Valley Floors: A Method for its Assessment

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ABSTRACT

USING previously collected data on the morphology of semiarid valleys, a technique is developed for discriminating between stable and unstable valley floors. Relations between drainage area, discharge, and flow depth are used to develop a shear-stress indicator that can be used to identify those reaches of a valley floor that are most likely to fail by gullying.

INTRODUCTION

The incision of gullies into valley alluvium is a severe soil conservation problem, resulting in deterioration of agricultural land, sediment pollution, filling of reservoirs, and water table lowering in the valley floor. Therefore, it is of importance to identify as accurately as possible those valleys which are prone to gullying, in order to establish priorities for soil conservation treatment within a geomorphic region. In other words, what is needed is an operational definition of the geomorphic threshold above which gully incision into the valley alluvium may occur (Schumm and Hadley, 1957; Schumm, 1973).

Patton and Schumm (1975) used two simple geomorphic attributes—drainage area and valley slope—to define a discriminant function distinguishing between gullied and ungullied valleys. The data were plotted on a semi-logarithmic paper, on which the discriminant function is a straight line. The line represents a relationship of the type:

$$a^A e^S = K,$$

where

- A = drainage area,
- S = valley slope,
- e = the base of natural logarithms, and
- a = a constant.

Here, K should be a certain threshold parameter, its values being constant along the discriminant line. However, such a parameter does not bear a clear relation to hydraulic variables such as shear stress or stream power. One result of this is that the distance of point from that line is but a qualitative measure of valley instability.

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Brice (1966) also used drainage area and valley slope in an attempt to define unstable valley floors, plotting these values on log-log paper. He used the regression line of all his data points as the discriminant function, and found that "the ratio of slope to drainage area that is associated with the initiation and rapid growth of a gully is not sharply defined".

The following is a suggested procedure for the definition of valley floor instability, modified after the methods used by Patton and Schumm (1975) and by Brice (1966).

METHOD

The data used for this study are those collected by Patton (1973), and used by Patton and Schumm (1975). They consist of measurements in 56 valleys, in 23 of which either continuous or discontinuous gullies were observed, and 33 were stable or ungullied. All the valleys are within the semiarid Piceance Creek basin in Northwestern Colorado. Within each valley Patton (1973) identified those reaches which were gullied, or, in the absence of gullies, the reach with steepest longitudinal slope. He surveyed the longitudinal slopes of these reaches and measured the drainage areas above these reaches from topographic maps at a scale at 1:50,000. These data, together with Nebraska data published by Brice (1966, Fig. 203) serve as a basis for this study.

The approach taken here is essentially deductive, starting with a search for a possible threshold parameter, related to gully incision, which has a physical meaning. A reasonable choice would be the average shear stress exerted by a flow on the valley floor (Partheniades and Paaswell, 1970; Graf, 1978). This average shear stress is a function of the hydraulic radius of the flow (R), the energy slope (S_e) and the weight per unit volume of the water (γ). All are related by the well-known equation:

$$\tau_o = \gamma R S_e \qquad [1]$$

For wide (shallow) flows, R can be replaced by the flow depth (d), and if the energy slope S_e is approximated by the average valley slope S, equation [1] becomes:

$$\tau_o = \gamma d S \qquad [2]$$

The problem now is to relate flow depth to the drainage area of the valley.

Using empirical relationships between flow depth (d) and water discharge Q, and a similar relationships between water discharge (of an event with a recurrence period of n years, Q_n) and drainage area A (Leopold et al., 1964, pp. 215, 251 and Table 7-5)

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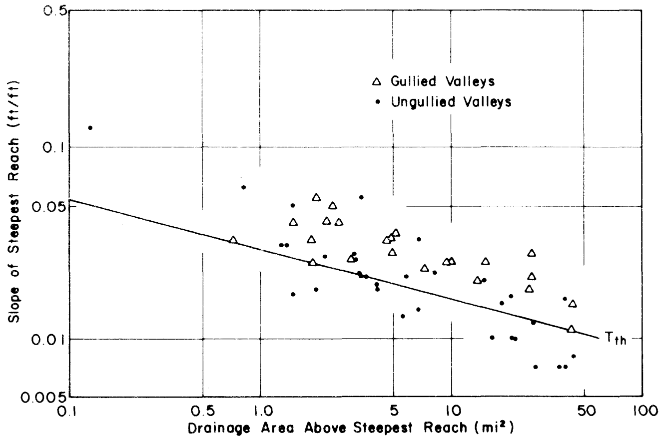

FIG. 1 Log-log area-slope relations for gullied and ungullied valley floors showing the threshold line of Shear Stress Indicator [T_{th}].

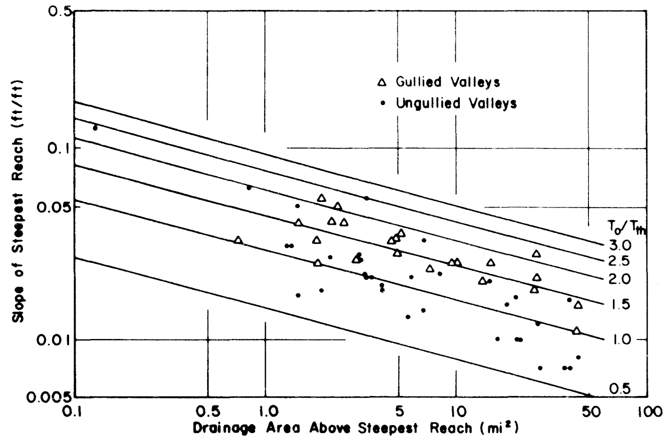

FIG. 2 Values of the relative Shear Stress Indicator [T_o/T_{th}] for the data of Fig. 1.

$$d = c_1 Q^f \quad (0.36 < f < 0.45) \qquad [3]$$

$$Q_n = C_2 A^r \quad (0.65 < r < 0.80) \qquad [4]$$

c_1 and c_2 are constants. Substituting equation [4] into equation [3];

$$d_n = c_1 c_2{}^f A^{rf} = c A^{rf} \quad \text{(where c is a constant)} \qquad [5]$$

From the known range of the exponents f and r, their product rf is expected to be within the range:

$$0.23 < rf < 0.36 \quad \text{or, say: } 0.2 < rf < 0.4$$

Substituting equation [5] into equation [2], we may define a relationship between average shear stress, drainage area and valley slope. Since this relation is based on simplistic assumptions, a different term is preferred for shear stress, which will be denoted here as the Shear Stress Indicator (T_o). $T_{o(n)}$ then is only an estimator of the actual shear stress $\tau_{o(n)}$, expected for a storm with a recurrence period of n years, and it is represented by:

$$T_{o(n)} = (c\gamma) A^{rf} S \qquad [6]$$

According to this equation, a line of equal values of the shear-stress-indicator plots as a straight line on a log-log paper. If valley slope S is plotted on the ordinate and drainage area on the abcissa, then the slope of such a line is equal to -rf, or rf is equal to the negative slope of that line.

PROCEDURE

Patton's data were replotted on a log-log-paper with slope on the ordinate (Fig. 1). Following the reasoning of Patton and Schumm (1975), a straight line was eye-fitted through the "lower-most" points of gullied valleys. This line is assumed to represent the threshold value T_{th} of the shear-stress-indicator, below which valley floors are stable. On Fig. 1, the slope of the line is -0.26, so that rf = 0.26, which is within the limits deduced above for the rf exponent.

After the rf exponent was established from the data, equation [6] was used to calculate the values of $A^{0.26}S$, which is equal to $1/d\gamma\ T_o$, for all the data points. The lowermost value of $1/c\gamma\ T_o$ for those valleys which are gullied, was considered to represent the threshold value $1/c\gamma\ T_{th}$.

Then, for each data-point, the value of T_o/T_{th} was calculated thereby eliminating $c\gamma$. This parameter is designated as the Relative Shear Stress Indicator. Lines of equal T_o/T_{th} values are plotted on Fig. 2, parallel to the basic line $T_o/T_{th} = 1.0$ which is the original line defined as T_{th}.

RESULTS

Fig. 2 shows that, although there are no gullied valleys in the area below $T_o/T_{th} = 1.0$ by definition, there are several ungullied valleys with T_o/T_{th} greater than 1.0. This situation is no different than the ones described by Patton and Schumm (1975) and Brice (1966). However, the present method allows for a quantitative assessment of the degree of instability which might be attached to such points. In order to achieve that, the following method was used.

Gullied and ungullied valleys were grouped according to the value of their Relative-Shear-Stress-Indicator, T_o/T_{th}. In each class the percentage of gullied valleys out of all the valleys in the class was calculated. The results are presented in Fig. 3. Obviously the small size inhibits the identification of a reliable trend line on Fig. 3. However, it is felt that with use of some judgment, a reasonable trend can be established. This pertains mainly to the decision to regard the two ungullied valleys with highest T_o/T_{th} as "outliers" (see additional discussion below).

Now, the percentage of gullied valleys within each class of equal Relative-Shear-Stress-Indicator may be considered as representing an estimate of the probability of a valley to be gullied, having a certain value of T_o/T_{th}. The reliability of the estimate is, of course, a function of the sample size but even with the small sample used here the estimate seems reasonable.

Under these assumptions, Fig. 3 can be interpreted as a diagram showing the increased probability for a valley to be gullied, which accompanies the increase of the Relative-Shear-Stress-Indicator.

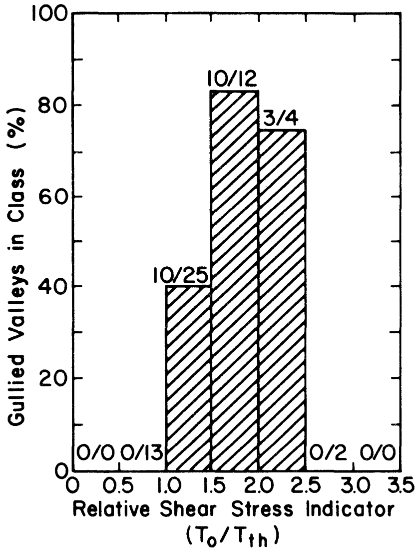

FIG. 3 Percent of gullied valleys as a function of the Relative Shear Stress Indicator To/T_{th}. Fractions denote number of gullied valleys and total number of valleys in each class.

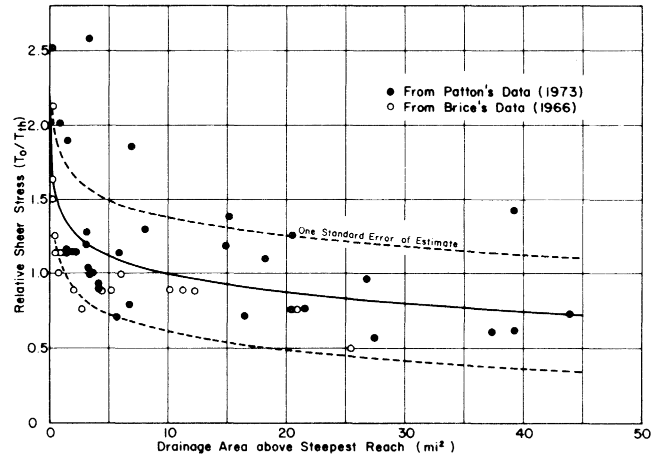

FIG. 4 Relationship between drainage area of valleys and their Relative-Shear-Stress Indicators, for ungullied valleys only. The curve is a least-square semi-log fit, the correlation coefficient is 0.50, and it is significant on a 0.01 level.

"SURVIVAL" OF VALLEY FLOORS

Examination of Fig. 2 reveals that the ungullied valleys with small drainage areas tend to withstand higher values of the Relative-Shear-Stress-Indicator. This becomes clear by plotting Fig. 4, in which only ungullied valleys were plotted and which also utilizes Brice's (1966) data. The T_o/T_{th} values are rather insensitive to change in drainage area for areas greater than about 7 square miles. However, valleys with smaller drainage areas "survived" markedly increased values of T_o/T_{th}. A related observation was made by Patton and Schumm (1975), who pointed out that their discriminant function is not applicable to valleys with drainage areas smaller than 4 square miles. They explained this by suggesting that in small basins the aspect of the valley becomes a dominant factor. Other reasons may be differences in vegetation cover, or shallowness of the alluvial mantle on small, first order streams.

DISCUSSION

Although the sample used in this study is quite small, the results are encouraging. The low reliability of the probability function is here attributed mainly to the small sample size; additional studies will hopefully be based on larger samples.

The method enables a planner to develop rational priorities of soil conservation measures, based on an es estimated probability of valley incision. However, the above numerical results pertain only to drainage basins with uniform geomorphic and hydrologic characteristics. Different values of the threshold Shear-Stress-Indicator are expected where geology, soils, climate and vegetation are different.

As an example, the data of Brice (1966, Fig. 203) were treated by the suggested method, and the results are shown, on Fig. 5. The sample is too small to enable any calculation of probability but the similarity of the slope of the Shear-Stress-Indicator lines (= exponent rf in equation [6] in Figs. 5 and 2 is noteworthy. Also, in both cases, valleys with small drainage areas tend to resist gullying while showing high values of the relative Shear-Stress-Indicator (see also Fig. 4).

This study is based on the concept of geomorphic thresholds, put forward by Schumm (1973, 1977). However, the results suggest a modified approach towards this concept. Fig. 2 indicates that a threshold Shear-Stress-Indicator may be defined, below which gully incision does not occur. However, increased values of the Relative-Shear-Stress-Indicator do not imply the deterministic result that gullying indeed takes place. Rather, it implies only an increase in the probability of a valley floor to be gullied. This seems reasonable in view of the basic stochastic mechanisms involved such as the temporal and spatial distribution of rainfall, the nonhomogeneity of soil and vegetation distribution, and measurement errors.

Such an explanation reconciles deterministic and probablistic approaches to geomorphic phenomena. The suggested procedure enables an approximate quantification of both attributes in estimating the relative stability of valley floors, in the form suggested by Fig. 6.

CONCLUSIONS

Above a certain threshold slope the probability of valley incision is largely increased. In order to assess this probability, the following procedure is suggested:

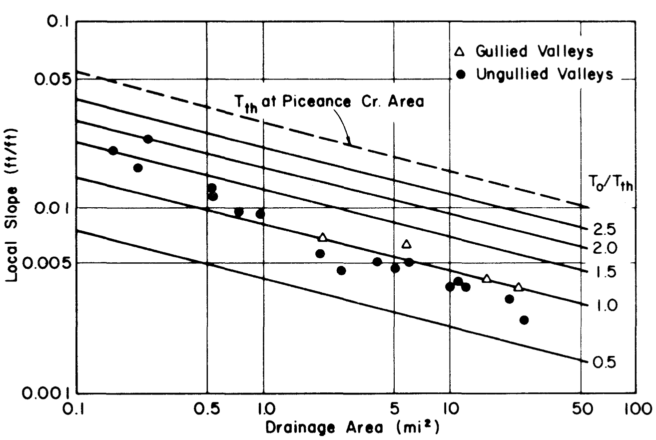

FIG. 5 Log-log slope-area diagram, showing relative-Shear-Stress Indicator, for valleys in Nebraska [data from Brice, 1966].

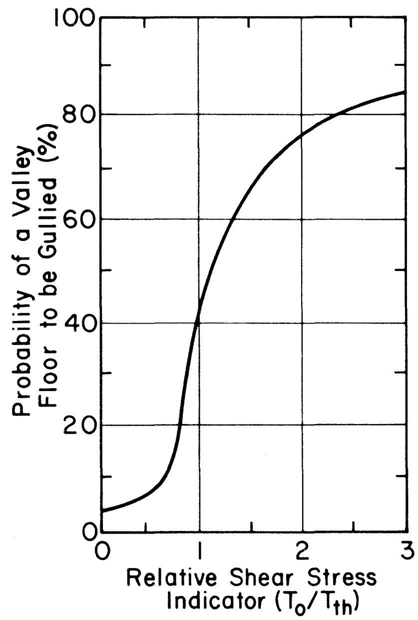

FIG. 6 A schematic relationship between probability of incision of a valley floor and the Relative-Shear-Stress Indicator [T_o/T_{th}]. The curve is based on Fig. 3.

1 Within a uniform drainage basin, measure the gradients of oversteepened reaches of valley floors (S) and the drainage areas above them (A). Also record whether they are gullied or not.

2 Plot the points on log-log paper with valley gradient on the ordinate, and draw a straight line through the lowermost points representing gullied reaches. A reasonable slope of this line is the negative of 0.3 ± 0.07, which is equal to the negative value of rf.

3 Using the above value of rf, calculate for each gullied valley data point the value of $A^{rf}S$; choose the lowest value of $A^{rf}S$ as the threshold value of gullying, T_{th}.

4 For all data points calculate $A^{rf}S/T_{th}$ which is the Relative-Shear-Stress-Indicator T_o/T_{th}. Subdivide the data into classes according to these values. Count the frequency of gullied valleys within each class and calculate its percentage of all the valleys in this class. This percentage is an estimate of the probability of incision of a valley having a certain T_o/T_{th} value.

In view of the complexity of the problem, the use of only two (though important) parameters for its solution must bring about some discrepancies. In future studies additional parameters can be incorporated in the basic scheme, in order to increase its resolution and practicality.

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