Predicting the Limits to Gully Erosion

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ABSTRACT: *Gully erosion in much of agricultural Australia poses problems of accelerated soil loss, erosion of structures and reduced water quality. The most intensive gully erosion occurred decades ago following clearing and the introduction of stock to the landscape. There is evidence that many of these gullies are now approaching stability and pose a low risk for future erosion. Given limited land management resources, it is important to develop techniques to distinguish those gully networks that are stable from those with considerable potential for future erosion.*

A technique that combines digital terrain modelling and a simple representation of erosion processes is explored to predict the stable extent of gully networks. The TOPOG package of digital terrain and hydrological models was used as the framework for the procedure.

The model is initially applied to a 5.5 km^2 *cleared catchment on the Southern Tablelands, NSW, where the positions of gully heads within a stable gully network are accurately predicted. A combination of specific catchment area and local gradient proved to be the best topographic predictor of the gully network. The distribution of high boundary shear stress successfully predicts the mapped extent of the gully network and provides a process interpretation for the observed topographic limits. Realistic values of boundary shear stress were simulated using storms of one hour duration and runoff generated by Hortonian overland flow. The model is then applied to a second catchment where gullies are believed to be actively eroding. The model indicates the potential for further gully erosion in several valleys of the catchment, whilst other gully networks appear to be close to their stable limit.*

1. INTRODUCTION

The introduction of European-style agriculture to south-eastern Australia last century precipitated a major phase of gully erosion. Analysis of sequential aerial photography shows that many of these gully networks are now relatively stable as they have not expanded in the last forty to fifty years (Eyles, 1977; Starr, 1989; Prosser, 1991). However, some of these systems are still extending while recently intensified landuse in other locations is resulting in further gully initiation (Prosser & Winchester, in press). In both these cases it would be useful to distinguish those sites that are most susceptible to future gully erosion, and to predict the eventual limits of the gully networks.

Assessment of the limits to gully networks can be made using techniques that range from visual assessment of sequential aerial photographs to field inspection and topographic analysis to computerised landscape modelling. In most cases it would be inadvisable to rely on one method of analysis alone. A number of erosion processes may be acting in concert within a catchment to produce a gully network and not all may be detected if reliance is placed on one analysis tool. However, the high cost of gully control structures means that assessment of the limits of the gully network is vitally important. The premise adopted here is that gullies already at their limits do not pose a threat of further erosion and do not need further control.

Dietrich *et al.* (1992, 1993) investigated linkages between erosion processes and channel network extent with a simple threshold based theory of erosion and a steady state runoff model. They were able to assess the topographic controls on channel networks and interpret them in terms of a critical shear stress for channel incision due to saturation overland flow.

In this study, we demonstrate strong topographic control on gully erosion in a catchment with a stable gully network and define topographic thresholds for the limits to gully erosion. Modifications to the Dietrich *et al.* (1992, 1993) model enabled us to predict the boundary shear stress (τ_b) applied by Hortonian overland flow. We found that mapping sites of high τ_b successfully defined the stable gully network. In applying the τ_b that defined the stable gully network, to an active gully system, we used the model to assess the spatial pattern of erosion risk within a second catchment.

2. STUDY SITES

We selected the upper 5.5 km^2 of the Gungoandra Creek catchment as our initial site for model testing and calibration. Gungoandra Creek is 80 km south of Canberra on the Southern Tablelands of New

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South Wales. The site is a typical steep catchment of south-eastern Australia with an extensive gully network that has not expanded since 1944. Soils, climate and other details of the catchment are described more thoroughly elsewhere (see Abernethy, 1994; Prosser & Abernethy, subm.).

We used a second catchment, Grove Creek, to test if the parameters as calibrated at Gungoandra Creek could be used to predict gully erosion elsewhere. The Grove Creek catchment has a drainage area of 2.4 km^2 and is situated some 40 km to the north-east of Canberra near Lake George. Gullies in the catchment are known to be actively eroding. In many other respects the catchment is similar to Gungoandra Creek. It was settled and cleared in the latter half of last century and soils are similar to those of the lower hillslopes and flats of Gungoandra Creek with thin soils mantling the upper slopes. The stratigraphy of alluvial deposits in Grove Creek is further described by Coventry & Walker (1977).

3. DIGITAL TERRAIN MODELLING

Following the approach taken by Dietrich *et al.* (1992; 1993), we have relied on the TOPOG digital terrain and hydrologic modelling package (Burch *et al.*, 1986; O'Loughlin, 1986; Moore *et al.*, 1988a; Vertessy *et al.*, 1990) to link steady state erosion models with catchment hydrology and terrain. TOPOG divides a catchment into a network of irregularly shaped elements defined by upper and lower contour sections and flowlines drawn normal to the contours (O'Loughlin, 1986; Moore *et al.*, 1988b). It is assumed that both shallow sub-surface and overland flow follow flowlines with little lateral diffusion (O'Loughlin, 1986).

TOPOG requires high resolution topographic data so we commissioned a purpose drawn topographic map of the Gungoandra Creek catchment. The map was drawn from 1:25 000 colour aerial photographs using analogue photogrammetry and prepared to a scale of 1:7 500 with a 5 m contour interval. The channel network was well represented on the map, because of low vegetation cover, but we subsequently checked it in the field.

The base map was digitised and used to construct a digital terrain model (DTM) of the catchment. The Gungoandra Creek DTM consists of 9 130 discrete elements with an average element width of 40 m. A DTM of the Grove Creek catchment (Maunder & Wilson, pers. comm.) was produced from digital photogrammetry of the same series of aerial photographs as that used for Gungoandra Creek. This DTM consists of 8487 elements with an average width of 18 m.

4. TOPOGRAPHIC LIMITS

The TOPOG package calculates a number of terrain attributes for each element: upslope catchment area (a), element width (b), specific catchment area (a/b) and gradient ($\tan\theta$). Using the method described by Montgomery & Dietrich (1988) and Dietrich *et al.* (1992, 1993), graphs of a/b and a plotted against $\tan\theta$ for Gungoandra Creek showed clear separation of gullied and non-gullied TOPOG elements. For any given gradient, gullied parts of the landscape have a larger upslope catchment area than non-gullied parts of the landscape. Moreover, elements containing channel-heads plot at the boundary of the gullied and non-gullied fields. This is to be expected, as channel heads represent the transition between slope and channel processes.

The threshold line that was found to best separate gullied from non-gullied elements in a plot of upslope catchment area versus local slope is

$$a = 1420 \tan\theta^{-1.6} \qquad (1)$$

which correctly discriminates 87% of elements as gullied or non-gullied. A similar relationship can be demonstrated for a/b plotted against $\tan\theta$:

$$\frac{a}{b} = 30 \tan\theta^{-1.6}\,. \qquad (2)$$

This topographic threshold correctly accounts for 85% of elements. Equation (2) contains all the variables required to move the investigation from a purely empirical to a potential process interpretation of the channel network.

5. HORTONIAN OVERLAND FLOW

We believe that Hortonian overland flow is the dominant runoff process responsible for gully erosion in the study catchments. Hence, the algorithms presented by Dietrich *et al.* (1993; p. 263) for predicting channel incision by saturation overland flow were modified by Prosser & Abernethy (subm.) to predict channel incision by Hortonian overland flow. In the model, incision by overland flow is considered to be driven by τ_b. For non-accelerating flows

$$\tau_b = \rho g d M\,, \qquad (3)$$

where ρ is fluid density, g, is acceleration due to gravity, d is mean depth of overland flow, and M is local slope ($\sin\theta$). To determine the τ_b applied by a given discharge requires knowledge of flow resistance, here characterised by the Darcy-Weisbach friction factor (f):

$$f = \frac{8gdM}{u^2}\,, \qquad (4)$$

where u is mean velocity. For flow over grassed surfaces f can be expressed as a power function of Reynolds number ($f = kRe^c$). Noting that $Q = udb$ and $Re = ud/\nu$, where ν is the kinematic viscosity of fluid, equations (3) and (4) may be re-expressed, after Prosser & Abernethy (subm.), as:

$$\tau_b = \left(\frac{g^2 k \rho^3}{8 \nu^c}\right)^{\frac{1}{3}} M^{\frac{2}{3}} \left(q \frac{a}{b}\right)^{\frac{2+c}{3}} . \qquad (5)$$

Boundary shear stress is now a function of topographic parameters automatically read from the DTM (*a/b* and *M*), and user defined flow characteristics and rainfall excess (*k*, *c* and *q*).

For the purposes of this study we have assumed that infiltration rates and vegetative roughness are all spatially uniform. Although this may seem somewhat unrealistic we suggest that topography places some constraint on these parameters and is a stronger influence on patterns of erosion than variations in infiltration or vegetation. In any case, simulations conducted with spatial variability were not found to increase the accuracy of predictions to any significant extent. The disproportionate amount of detailed field work required to describe field variation of non-terrain parameters appears to be unwarranted in light of the only minor improvements gained. By similar reasoning, we also kept precipitation spatially uniform.

We tested the model first at Gungoandra Creek. There, the channel network has been stable for fifty years, so we chose the one in fifty years, one hour duration rainfall intensity of 42 mm/hr (Pilgrim, 1987) to represent a typical channel forming event. The steady state infiltration rate was estimated to be 20 mm/hr based on soil texture (Craze & Hamilton, 1991) and rainfall simulator experiments conducted on similar soils (Fisher, 1993). This gave q a value of 22 mm/hr.

We used the relationship of $f = 1500Re^{-0.7}$ to characterise flow resistance. This is a typical relationship for concentrated overland flow on a degraded grass surface (Prosser *et al.*, in press). Predictions of τ_b are not significantly affected by changes in the relationship of less than an order of magnitude. Therefore, using relationships from other studies will not unduly impact upon the results.

The results of simulating Hortonian overland flow, using the inputs described above and Equation (5), are shown in Figure 1. Values of predicted τ_b at the gully heads range from 100 to 590 dyne/cm^2. Referring to Figure 1, we have partitioned the catchment into three zones of susceptibility to gully erosion. The predicted τ_b of 80% of gully head elements falls within 210 and 290 dyne/cm^2 and as Figure 1 shows, elements with τ_b in this range map out the extent of the channel network very well. Elements with a predicted τ_b of more than 290 dyne/cm^2 are very likely to be incised and are found downstream of the gully heads. Elements with a predicted τ_b of less than 210 dyne/cm^2 are unlikely to be incised and are located in the unchannelled parts of the catchment.

The model underestimates the τ_b that would incise gullies in reality because τ_b is calculated as a mean across the full element width. We observed in the field that flow is usually restricted to the hollow axis, hence flow width is often much narrower than element width. Constraining flow to realistic widths in the axis of hollows, produces τ_b values up to three times model predictions for flow across entire elements. These higher values can be favourably compared to estimates of the τ_b, for incision, derived from field experiments (Prosser & Slade, 1994; Prosser *et al.*, in press).

Recognising that there are some mismatches between the mapped and predicted gully networks, the Hortonian overland flow simulation creates a reasonable representation of the channel system. Some of the scatter around the mapped network is likely to be due to variations in vegetation for which we have not accounted. Unchannelled valleys and steep slopes at Gungoandra Creek that are predicted to contain channels generally have a southerly or easterly aspect. These locations could be expected to have greater soil moisture with better vegetation cover, and presumably greater resistance to incision.

The good results of the topographic analyses, above, and those shown in Figure 1, indicate the usefulness of this approach to reliably map the headward limits of gully erosion. After calibrating the model to define the stable gully network at Gungoandra Creek, we then applied the same values of q k and c to Grove Creek, where gullies are still eroding. A simulation of Hortonian overland flow produced the τ_b distribution shown in Figure 2a.

Of the five main gully heads shown in Figure 2, the two northern-most are situated very close to their predicted limits. Field inspection revealed that these heads are now gradual, merging with the upstream hillslope hollow, and display no obvious signs of recent erosion. The model predicts high susceptibility to gully erosion in ungullied parts of the southern and eastern valleys. Gully heads are migrating upslope in the two southern valleys, and farm dams have been used to prevent gully erosion in the north-eastern valley.

The model does not predict the full extent of the eastern-most gully. Two factors contribute to this. Firstly, TOPOG produces very wide elements in the

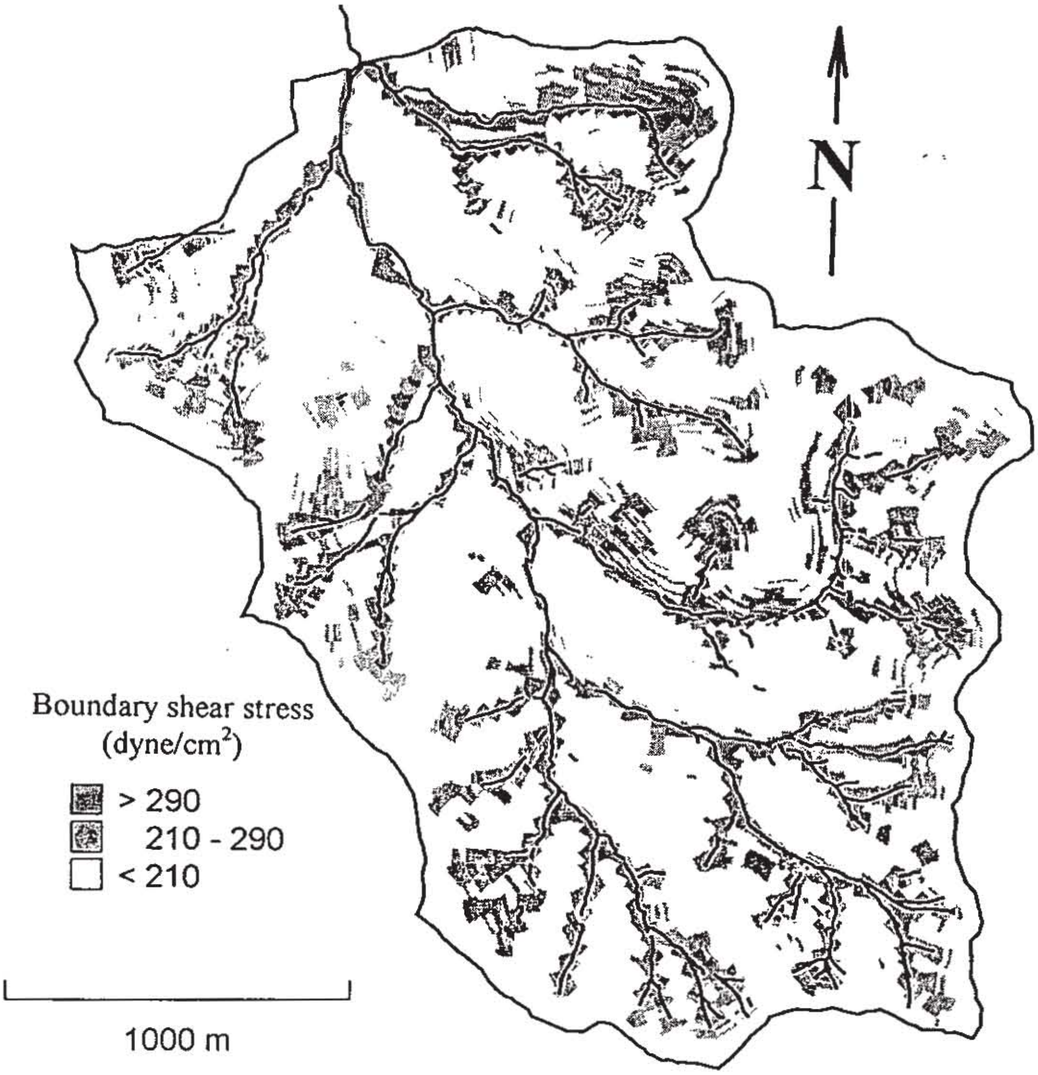

Figure 1. Comparison of the channel network at Gungoandra Creek with predicted values of τ_b applied by Horton overland flow.

axis of this valley which reduces the value of predicted τ_b. Secondly, strong seepage processes have aided in extension of the gully much closer to the divide than would otherwise be expected. In the first instance, a marked improvement of model predictions in this part of the catchment could be achieved by constraining the width of TOPOG elements to that of flow width. However, the cost of computational complexity due the addition of thousands of elements prohibits such a fine scale segmentation of the DTM. The example provided by the second point demonstrates that full reliance should not be given to any single technique to predict the limits to gully erosion. Results of all simulations should be tempered with knowledge of local circumstances wherever it is available.

6. DISCUSSION & CONCLUSIONS

Analysis of the DTM for Gungoandra Creek shows that topography is a strong control on the limits to the gully network. Good definition of the position of channel heads was achieved using a range of topographic thresholds. While the threshold of $a/\tan\theta^{1.6}$ could also be derived from field measurements at the channel heads, the DTM allows rapid analysis of the whole catchment. The DTM may also provide a more accurate method as it is difficult to define the upslope catchment area in weakly convergent terrain.

Despite its advantages, though, use of the DTM is limited by the quality of data inputs required. The fine resolution needed to accurately predict gully erosion is usually beyond that offered by commercially available digital elevation data. Indeed many of the gullied hollows at Gungoandra Creek do not appear on the 1:25 000 map sheet; the smooth contours of this scale show only the hollows

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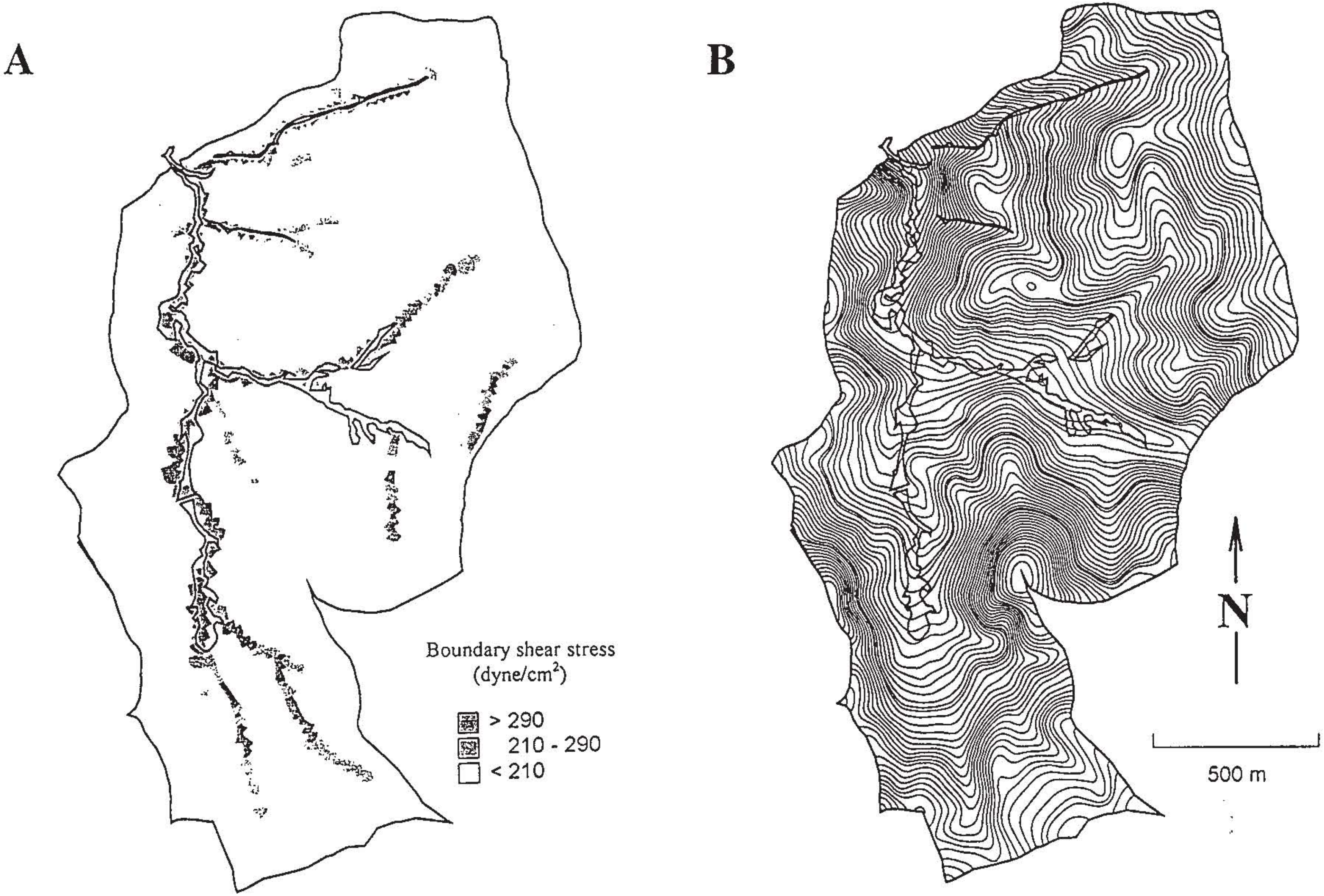

Figure 2. a) Comparison of the channel network at grove Creek with predicted values of τ_b applied by Hortonian Overland Flow. b) Topography of the Grove Creek Catchment.

that support the main trunk gullies. Also, the complexity of terrain and size of the Gungoandra Creek catchment are at about the limit of TOPOG's usefulness for the approach outlined here.

The application of topographic and process thresholds in a TOPOG framework allows a quantifiable and mappable technique for assessing gully erosion in different catchments. One should never lose sight, however, that the technique outlined here is but one approach of many available to the land manager. Field checking will verify model predictions but once validated this approach will enable managers to quickly ascertain gully erosion extent.

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