Gully formation and the role of valley-floor vegetation, southeastern Australia

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ABSTRACT

Attempts to understand the causes of gully erosion have been hampered by a poor understanding of quantitative changes to the force of flows and the resistance to scour. We used flume experiments on an unincised valley floor to determine flow resistance and the critical shear stress for scour under natural and degraded vegetation covers. Applying the results to sites of gully formation in southeastern Australia demonstrates the crucial role that reduced vegetation cover plays in increasing the susceptibility of valleys to channel incision. Widespread and rapid gully formation in the 19th century required degradation of valley-floor vegetation and was not solely the result of land use or climatically induced increases in discharge.

INTRODUCTION

The causes of gully erosion have been the subject of a long but inconclusive debate. Climatic change, land use, and intrinsic instability have all been invoked as potential causes (e.g., Albritton and Bryan, 1939; Tuan, 1966; Patton and Schumm, 1981), but their relative importance remains poorly resolved because most work has concentrated on erosion histories and circumstantial evidence (Cooke and Reeves, 1976; Graf, 1983). Channels have long been considered to form when the force of flow overcomes the resistance of a surface to scour (Horton, 1945; Schumm, 1973), but causes of gully formation have rarely been considered in terms of these processes. Melton (1965), Cooke and Reeves (1976), and Graf (1979) speculated on potential changes to force and resistance, but were limited by a lack of data on actual changes in discharge, flow resistance, and critical shear stress for scour. Reid (1989) used published data from experiments on artificial grassy waterways to explore channel initiation, but the hydraulics and scour of natural valley floors remain relatively unexplored.

We examined the processes of gully formation by using flume experiments conducted on an unchanneled valley floor to measure flow resistance and the critical shear stress for scour (τ_{cr}) under a range of natural and degraded vegetation covers. The results are applied to known sites of gully formation, allowing us to explore the susceptibility of gully erosion to (1) historical increases in discharge induced by land use or climatic change and (2) changes to valley-floor vegetation that reduce flow resistance and τ_{cr}. We consider the processes of initial scour into unchanneled valley floors, but not subsequent headcut retreat or the extension of preexisting channels. The gullies considered are valley-bottom gullies: steep-sided, flat-floored channels incised into cohesive Holocene alluvium.

HISTORY OF GULLY EROSION

The history of gully erosion and the morphology of valley floors before gully formation provide information on the processes of gully formation and need to be considered before describing the flume experiments. Early Australian explorers and surveyors reported numerous swampy, treeless alluvial flats, often containing ponds but with no connecting channels (Eyles, 1977). Most valleys that contained these swampy meadows, similar to cienagas (Melton, 1965) and dambos (Boast, 1990), now contain gullies incised as much as 10 m to the underlying bedrock. Further information on valley form prior to incision is provided by remnant swampy meadows. These have a dense cover of sedge and *Poa* tussock and a flat cross section over which flows spread across the width of the valley. Larger meadows, those with catchment areas of >10 km^2, often contain drainageways of concentrated flow as much as 0.5 m deep and 1–10 m wide but with no discernible banks. Within drainageways, sedge is more prevalent than tussock, and 30–40-cm-high aquatic plants predominate at sites of standing water. *Poa* and sedge are the natural vegetation cover, and the species composition has been relatively unaffected by grazing (Costin, 1954).

Gullies incised swampy meadows across hundreds of square kilometres of the southern tablelands of New South Wales within a few decades of agricultural expansion in the 1830s, and they had grown close to their present extent by the early 1900s (Eyles, 1977; Prosser, 1991). The many sites of gully erosion, covering areas larger than individual storms, require that erosion was initiated by several floods. Widespread erosion over a few decades also suggests that these floods were of 100 yr recurrence interval (Q_{100}) or less, as multiple larger events are improbable over a short period. Valley-fill stratigraphy reveals that gullies also incised episodically during the Holocene, separated by 1000–4000 yr of relatively continuous aggradation under swampy meadows with no continuous channels (Prosser et al., 1994).

FLUME EXPERIMENTS

A 20 × 1 m form-ply flume, fed from a 50 m^3 swimming pool, was constructed on a remnant swampy meadow in the Murrumbateman Creek catchment near Canberra, Australia. Experiments were undertaken on two 10 × 1 m plots within each of two drainageways on the meadow. Plots A, C, and D (Table 1) had vegetation typical of swampy meadows with drainage areas of <10 km^2 and the more vegetated drainageways of larger swampy meadows. Plot B had aquatic

TABLE 1. CHARACTERISTICS OF PLOTS USED FOR FLUME EXPERIMENTS

Plot	Description	Undisturbed vegetation			Disturbance	
		Prone cover* (%)	Biomass † (kg/m^2)	Length (cm)	Description	Prone cover* %
A	Tussock grass	100	0.6	80	Clipped to 10 cm height	50
B	Aquatic plants	100	0.4	40	Vegetation clipped and ripped	5
C	Sedge	100	0.8	100	As above, but sedge stocks remained	10
D	Tussock grass and sedge	100	0.8	70	Clipped to 10 cm height	60

* Percentage ground cover during discharge.
† Above ground oven dried mass.

GEOLOGY, v. 22, p. 1127–1130, December 1994

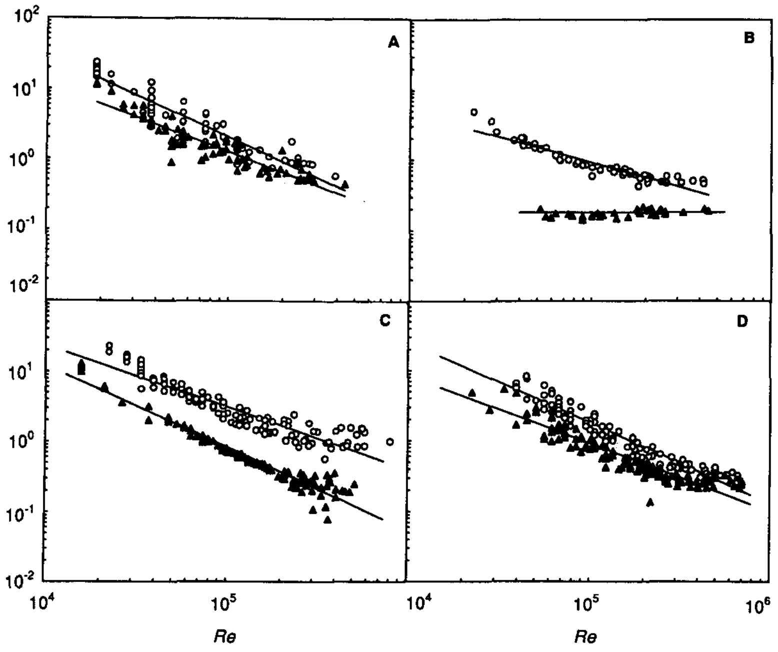

Figure 1. Flow resistance (*f*) vs. Reynolds number (*Re*) for undisturbed (circles) and disturbed (triangles) swampy meadow surfaces. A: Plot A, tussock—$f = 1\,350\,000Re^{-1.2}$ ($r^2 = 0.85$); clipped tussock—$f = 86\,000Re^{-1.0}$ ($r^2 = 0.86$). B: Plot B, aquatic plants—$f = 3050Re^{-0.71}$ ($r^2 = 0.88$); clipped and ripped aquatics—$f = 0.18$. C: Plot C, sedge—$f = 83\,000Re^{-0.89}$ ($r^2 = 0.82$); clipped and ripped sedge—$f = 580\,000Re^{-1.7}$ ($r^2 = 0.91$). D: Plot D, tussock and sedge—$f = 988\,000Re^{-1.1}$ ($r^2 = 0.95$); clipped vegetation—$f = 58\,000Re^{-0.96}$ ($r^2 = 0.91$).

vegetation typical of the wettest drainageways of larger swampy meadows. Vegetation on plots A and D was clipped to 10 cm height to simulate the effect of light degradation by grazing or fire (Table 1). Plots B and C were clipped to root level, and the surface was ripped with a mattock to simulate heavy degradation including plowing or trampling by livestock. The underlying alluvium was an organic, fine-sand–bearing clay with water-stable aggregates. It is permanently close to saturation and has low hydraulic conductivity, and so wetting and seepage processes are negligible. Plant stems were flattened and completely inundated during each run.

Discharge was measured by continuous recording of pool water level and was controlled by a gate at the head of the flume. Constant discharge was achieved for 1–2 min, after which discharge declined gradually owing to the drop in pool water level. Flow depth was measured by capacitance recorders at two stations along the flume, and mean flow velocity at each station was calculated from discharge and depth recordings. The friction slope for nonuniform flow was calculated from water-surface slope and spatial and temporal changes in discharge and flow depth.

Individual runs lasted for only 3–5 min, but each plot was subjected to up to 1 h of accumulated flow. Scour of the bed was assessed by observations of bed condition and turbidity as well as measurement of erosion pins. Visible scour of roots and of all aggregate sizes over accumulated runs was considered the minimum criterion for channel formation, assuming that maintenance of discharge would continue to enlarge the scour. Hydraulic conditions for channel formation have never been observed in the field, but laboratory experiments on bare surfaces suggest that rills form when boundary shear stress is twice that required for surface-wash erosion (Slattery and Bryan, 1992).

FLOW RESISTANCE AND CRITICAL SHEAR STRESS

Relations of flow resistance (*f*) against Reynolds number (*Re*) are required to calculate boundary shear stress (τ_0) from characteristic discharges (*Q*) over swampy meadows. Combining $\tau_0 = \rho gds, f = 8gds/v^2$, $Q = wdv, f = aRe^b$, and $Re = vd/\nu$ yields

$$\tau_0 = \alpha Q^{(2+b)/3}, \qquad (1)$$

where $\alpha = (g^2 s^2 \rho^3 a / 8\nu^b w^{2+b})^{1/3}$, *w* is width of valley floor, *d* is mean flow depth, *v* is mean velocity, *a* and *b* are empirical constants derived from the experiments, ρ is density of fluid, *g* is acceleration due to gravity, *s* is friction slope, and ν is kinematic viscosity. Equation 1 is relatively insensitive to the recorded range of *a* and *b* values; consequently, the data for individual *f*/*Re* relations were combined if they caused τ_0 to vary by <50 dyn/cm^2 for characteristic discharges.

Plots A, C, and D have similar *f*/*Re* relations for undisturbed vegetation (Fig. 1), which were combined to describe flow resistance over mosaics of tussock grass and sedge:

$$f = 460\,000Re^{-1.06} \qquad (r^2 = 0.839). \qquad (2)$$

Aquatic plants at plot B had five times lower *f* than plots A, C, and D at low *Re*, reflecting the smaller-sized plants ($f = 3050Re^{-0.71}$; Fig. 1B), and after clipping and ripping, *f* was lowered by as much as an order of magnitude to a constant value, statistically independent of *Re* ($f = 0.18$). Clipping and ripping of sedge at plot C lowered *f* by a similar amount, but root stocks still provided considerable form resistance ($f = 580\,000Re^{-1.7}$; Fig. 1C). Clipped tussock grass and sedge from plots A and D had similar *f*/*Re* relations, and the combined data were used for lightly degraded surfaces:

$$f = 145\,000Re^{-1.02} \qquad (r^2 = 0.869). \qquad (3)$$

No scour was observed under undisturbed conditions (Table 2). Therefore, τ_{cr} for aquatic plants is at least 1050 dyn/cm^2 (plot B). High shear stresses were not attained at plot A because of the lower slope, but τ_0 values of 3330 and 2450 dyn/cm^2 were recorded at plots C and D, respectively. These high values for τ_{cr} are confirmed by an independent estimate from a remnant swampy meadow of tussock and sedge at the head of Wangrah Creek, south of Canberra. That meadow has remained unincised for over 1000 yr (Prosser et al., 1994) and is therefore resistant to scour by at least Q_{100}, which exerts a τ_0 shear stress of 2350 dyn/cm^2. Shear stress was calculated by using equations 1 and 2, and Q_{100} was estimated by the rational method (see below). Consequently, a τ_{cr} of 2400 dyn/cm^2 was adopted as a minimum for tussock and sedge, consistent with values for smoother grassy surfaces (Reid, 1989).

Plot B was scoured visibly after disturbance, including tearing of roots at $\tau_0 = 700$ dyn/cm^2, and scour continued during subsequent runs (Table 2). The disturbed plot 3 was also scoured above $\tau_0 = 700$ dyn/cm^2. Below $\tau_0 = 700$ dyn/cm^2, sediment transport in both plots was restricted to loose aggregates, suggesting that scour would not continue to enlarge. Therefore, $\tau_{cr} = 700$ dyn/cm^2 was used as a conservative estimate for the reduction of τ_{cr} as a consequence of heavy disturbance. The data from plot D were used for lightly disturbed sedge and tussock because of the low gradient at plot A. Scour began at $\tau_0 = 1800$ dyn/cm^2 but was restricted to bare patches between root stocks. We have observed swampy meadows with 30-cm-deep ruts between root stocks but with no undercutting of roots; therefore $\tau_{cr} = 1800$ dyn/cm^2 is a minimum criterion

TABLE 2. RESULTS OF FLUME EXPERIMENTS CONDUCTED ON A SWAMPY MEADOW

Run	Plot*	Friction slope	Water depth (cm)	Boundary shear stress (dyn/cm^2)	Scour
1-5	Au	0.014-0.020	28-35	380-660	None
6	Ad	0.009	27	250	None
7	Ad	0.013	34	420	Minor over 10 cm^2
8	Ad	0.010	28	280	None
9	Ad	0.014	35	480	Minor over 10 cm^2
10	Ad	0.012	35	420	Minor over 10 cm^2
19-22	Bu	0.036-0.049	18-23	640-1050	None
23	Bd	0.024	17	392	Loose peds only
24	Bd	0.023	18	385	Loose peds only
26	Bd	0.037	20	720	Peds and roots
27	Bd	0.037	20	700	Peds and roots
28	Bd	0.038	22	750	Total: 1 cm deep
35-39	Cu	0.051-0.11	32-33	1560-3330	None
45	Cd	0.025	24	460	None
46	Cd	0.026	25	530	Small peds
47	Cd	0.043	28	820	2 mm scour; armour of -
48	Cd	0.028	28	680	large peds, roots
49	Cd	0.023	25	500	None
50	Cd	0.026	29	610	Turbid water
51-55	Du	0.079-0.12	19-25	1800-2450	None
56	Dd	0.126	18	2230	Only between tussocks
57	Dd	0 .10	17	1509	None
58	Dd	0.081	22	1800	Only between tussocks
59	Dd	0.078	19	1340	None
60	Dd	0 .11	19	2110	5 mm on bare patches

Note: All values are means over 60 s of maximum discharge.
* u = undisturbed treatment, d = disturbed treatment.

for channel formation. Reid (1989) reported a mean τ_{cr} of 210 dyn/cm^2 for bare clay.

PROCESSES OF GULLY FORMATION

The impacts of vegetation degradation and increased discharge on gully formation were investigated by applying the experimental results to characteristic discharges at gully sites. Thirteen sites of gully formation on the southern tablelands of New South Wales were identified by locating distinct splays of sand and gravel deposited downstream of the sites of initial incision (Leopold et al., 1964; Melville and Erskine, 1986). Valley-floor width and gradient were surveyed at each site, and Q_{100} was calculated by using the rational method (Pilgrim, 1987). This is a stochastic method of flood estimation based on catchment size, topography, regional rainfall intensity, and stream-gauging data.

Discharges have varied over historical time in response to climatic fluctuations and forest clearing. Since 1950, Q_{100} in coastal streams of New South Wales, has doubled as a result of increased summer rainfall (Erskine and Bell, 1982), and a similar climatic perturbation occurred between 1885 and 1895 (Pickup, 1976). Twenty of the 28 gauging stations used to calculate Q_{100} values have records from 1950, and the largest floods in the remaining stations occurred after 1950 (Mittlestadt et al., 1992). The increase in discharge after 1950 is thus included in Q_{100}, and halving the values provides an estimate of Q_{100} before 1950. Comparison of the hydrology of cleared and forested catchments suggests that Q_{100} at most doubles as a result of clearing and grazing (Burch et al., 1987). Eighteen of the gauged catchments used to calculate Q_{100} are relatively unaffected by clearing or grazing, so doubling Q_{100} values provides a maximum estimate for historical time. Therefore, $2Q_{100}$, Q_{100}, and $0.5Q_{100}$ encompass the range of likely gully-forming discharges.

For each site of gully formation, τ_0 was calculated for $2Q_{100}$, Q_{100}, and $0.5Q_{100}$ by using equation 1 and was compared to

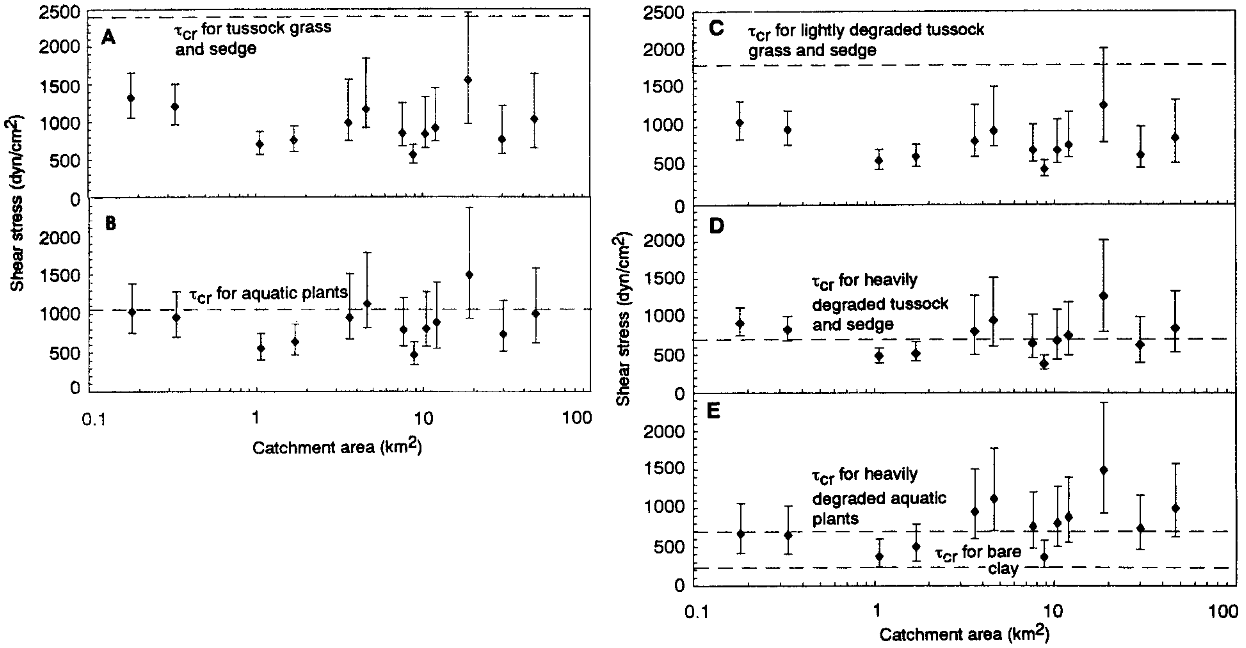

Figure 2. Comparison of τ_0 with τ_{cr} (dashed lines) for sites of gully formation on southern tablelands of New South Wales under natural and degraded vegetation cover. Boundary shear stresses were calculated for Q_{100} (diamonds), $2Q_{100}$ (upper bounds), and $0.5Q_{100}$ (lower bounds). A: Equation 2 *f/Re* relation was used. B: Plot B (Fig. 1B) *f/Re* relation was used. C: Equation 3 *f/Re* relation was used. D: Plot C (Fig. 1C) *f/Re* relation was used. E: Plot B (Fig. 1B) *f/Re* relation was used; τ_{cr} for bare clay is from Reid (1989).

matching values of τ_{cr} (Fig. 2). The *f*/*Re* relations were extrapolated to $Re = 1 \times 10^6$, above which *f* was assumed to be constant as a result of low relative-height-of-roughness elements. This calculation produces maximum estimates of τ_0 for the higher values of $2Q_{100}$ and the uneven bar sizes in Figure 2.

For undisturbed tussock and sedge, $\tau_0 > \tau_{cr}$ at one site for $2Q_{100}$ (Fig. 2A); and for aquatic vegetation, $\tau_0 > \tau_{cr}$ at two sites only for Q_{100} (Fig. 2B) out of thirteen sites. Ten valleys were susceptible to scour at $2Q_{100}$ under aquatic vegetation, including all five valleys with catchment areas of >10 km^2. Only one valley was susceptible to incision under lightly disturbed tussock and sedge (Fig. 2C). With heavy degradation of sedge or aquatic plants, however, two sites were susceptible to scour at $0.5Q_{100}$, increasing to ten to eleven sites at $2Q_{100}$ (Fig. 2, D and E). For bare clay, $\tau_0 > \tau_{cr}$ at all sites for all discharges (Fig. 2E).

It is impossible to determine the changes that caused incision in each valley, but the results demonstrate a strong control of valley-floor vegetation on susceptibility to gully formation. Swampy meadows covered by tussock and sedge are very resistant to incision. Historical increases in Q_{100} alone, or increases in Q_{100} coupled with light grazing, are not capable of initiating incision into these surfaces, if it is assumed that the gullies formed by Q_{100} or smaller flows. Tussock and sedge are only susceptible to incision if there is heavy degradation of vegetation coupled with increased discharge, or if the surface is laid bare. On larger swampy meadows, vegetation cover is naturally reduced by persistent base flow in drainageways. The reduced vegetation cover increases the sensitivity of a surface to incision by increased discharge, and all valleys with catchment areas of >10 km^2 are susceptible to incision under the maximum Q_{100} or after heavy disturbance.

Rapid gully formation across all scales of catchment during the 19th century required significant degradation of valley-floor vegetation in addition to increases in discharge from historical climatic changes and forest clearing. There are many recorded instances of swampy-meadow degradation by plowing and early road and drain construction in addition to the impact of livestock (Eyles, 1977; Bird, 1985; Melville and Erskine, 1986; Prosser, 1991). The flume experiments suggest that such disturbances are capable of reducing τ_{cr} by three to eleven times compared with at most a fourfold increase in discharge in historical times.

The analysis has not considered sediment supply to valley floors and the transporting capacity of flows. Rates of sediment supply in these catchments are very low (1–10 $m^3 \cdot km^{-2} \cdot yr^{-1}$; Neil and Galloway, 1990; Prosser et al., 1994), but incision is prevented by vegetation providing a high resistance to scour independent of sediment load. Such conditions clearly do not apply for incision of preexisting channels where greater sensitivity to discharge and sediment supply is well documented (Erskine and Bell, 1982; Hereford, 1984; Balling and Wells, 1990). It appears important then to distinguish enlargement of preexisting channels from channel formation, despite the difficulties that this may present.

ACKNOWLEDGMENTS

Supported by an Australian Research Council major grant and the Department of Biogeography and Geomorphology, Australian National University. Paul Bishop, John Chappell, Ian Rutherford, Stephen Wells, and Thomas Gardner provided valuable comments.

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Manuscript received May 26, 1994
Revised manuscript received August 22, 1994
Manuscript accepted August 29, 1994