Processes and Trend of Gully Development in a Forest Environment in Australia

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Abstract: A catastrophic gully erosion has occurred during pine plantations in and around Bombala in southeast of NSW in recent years. This research aimed at finding the dominant hydrologic and erosional processes of gully development.

An extensive field survey, three and half years of monitoring and historic and anecdotal evidence were used to determine the trend of gully development and its hydrologic and erosional processes. Characteristics of a single gully such as view plan, long profile, soil of the head and banks were surveyed. Rainfall, the depth of the water table just uphill of the gully head, surface runoff and channel flow, and seepage were monitored.

The results of the research indicate that the trend of gully growth is exponential and that there is a rainfall threshold above which significant surface runoff, channel flow and water table rise.

It is also indicated that a mixture of processes such as seepage, soil creeping, block failure and scour were acting on gully development and that two hydrological processes, seepage and overland flow are important. Furthermore, seepage is the dominant process involved in headcut erosion but to maintain the headcut retreat, overland flow is necessary.

1 Introduction

Lack of enough information on the processes of gully development has limited the efficient design and evaluation of gully control projects(Higgins,1990). This has wasted a lot of money each year (Thornes,1989).

Due to the dominance of overland flow theories (Horton, 1945), most attention focused on examination of the role of overland flow on the processes of channel development(Ireland *et al*., 1939; Chorely, 1957;Chorely and Morgan, 1962). Some field observations and detailed studies have indicated that although overland flow was an imporant process in channel initiation, subsurface flow plays a dominant role in channel development (Dunne, 1980,1988; Roloff *et al*., 1981; Crouch *et al*. 1986; Higgins 1984, 1990; Hill and Lehre, 1990; Hagery, 1991a and b). Although subsurface flow is dominant hydrological process, overland flow is necessary for maintaining channel development (Piest *et al*., 1975a and b; Bradford and Piest, 1977; Imeson and Kwaad, 1980; Poesen and Govers, 1990; Montgomery, 1991; Dietrich and Dunne, 1993; Montgomery and Dietrich, 1995). For example, Piest *et al*., (1975a and b) in west of USA found that sediment concentration and discharge had a maximum level before the maximum of runoff. They showed that sediment had been provided by other processes and overland flow had a complementary role in gully development due to carrying sediment away.

Many processes have been found to exert an influence on gully development and they can be grouped into three general categories, tractive force processes (Ologe, 1972), seepage processes(Dietrich and Dunne, 1993; Higgins, 1984) and mass failure processes (Piest *et al*., 1975a; Bradford and Pies, 1978; Roloff e al. 1981). Surface and subsurface flows are dominant hydrological processes but other factors such as material and morphological characteristics also influence the activity of processes. Different mass failure processes have been found in channel erosion studies, that means mass failure in different shapes is identified as the main source of sediment in gully erosion (Piest *et al*., 1975a and b; Bradford and Piest 1978;Reid, 1989;Milton, 1969). Mass failure processes introduced by Milton (1969) could be grouped into three categories of slumping,block failure,tensile failure and spalling, and desication debris avalanches, based on the factors controlling, speed of movement and the shape of failure.

Sediment production by different erosion processes is a necessary but not sufficient condition to maintain gully erosion (Piest *et al*., 1975a and b; Higgins, 1990). For gully development, runoff is required to transport eroded sediment from the base of gully heads and sidewalls (Piest *et al*., 1975a and b;Roloff *et al*., 1981;Higgins, 1990;Bradford and Piest, 1978).

In order to give predictive models for gully development, it is useful to test how gullies develope through time. Gullies are formed when a geomorphic system is disrupted due to either decreasing resistance to ersion(such as omitting vegetation cover) or increasing erosive forces(such as increasing runoff). There is some evidence that the rate of gully growth could be explained by negative exponential function (Fig.1). Graf (1977) used the rate law to show the relationship between time and gully length in the following formula:

$$A_t = A_0 e^{-bt}$$
$$A_x = A_0 - A_0\, e^{-bt}$$

Where t = the time since disruption; A_0 = the potential equilibrium length of the gully; A_x = the length yet to be eroded at time t before equilibrium is reached; and b = decay constant.

The negative exponential function (Fig.1) shows that the rate of gully growth is higher in the early years of gully development and decrease rapidly after some years. After disruption by human in a system such as a forest, the geomorphic system experiences two periods to get a new steady state. The first period after disruption is *reaction time* (B in Fig.1). This is some time that elapses between the disruption (eg. clear cutting a forest) and the beginning of the change (eg. starting gully erosion). The second period is *relaxation time* (C in Fig.1). This is the period between the start of gully erosion and the establishment of a new steady state. Few studies proved that the trend of gully growth was negative exponential (Ireland *et al*., 1939;Graf, 1977;Imeson and Kwaad, 1980).

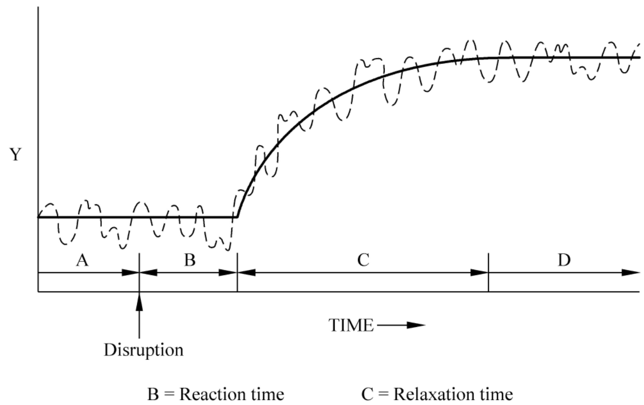

Fig.1 Graphic representation of the response of a geomorphic system subjected to disruption (after Graf, 1977)

In Australia, active processes have been documented based on gully geometry (eg. Crouch and Blong, 1989) and field measurement. In order to be able to get some insight and to suggest practical guidelines, it seems necessary to study hydrological and erosion processes quantitatively in a gully to learn more about development processes as Higgins mentioned (1990, P.143-144). The aims of this paper are to examine the processes of gully development and the trend of gully erosion in a forest area in Australia.

2 Study area

This research was done in the Kapunda forest in south-east New South Wales, south of Bombala with a longitude between 149°20′E and 149°30′E and a latitude between 37°4′S and 37°8′S. It is the lower part of the Wog Wog River catchment with hilly landform and elevations between 340m around the Wog Wog river to 410m on he crest of hills. The study area is underlain by middle Devonian granite.

The average rainfall in the nearest rain station,Towamba PO (Rosebank), was 860mm (the length of record was 24 years) with highest rainfall in November and lowest in August. The study area is mainly timber land. Various types of forest such as dry open forest and moist forest are found in the area (Soufi, 1977). Different varieties of Eucalyptus and Accacia could be found in different locations of the study area. Pine plantations started in the late 1960 in and around Bombala. Pines were planted on the granite from 1980 until 1995. Severe gully erosion happened in the pine plantation of 1988 age class in the Kapunda forest. Two main groups of soils have been identified in the study site by field observations The first group are duplex soils with yellow- grey clay B horizons which occupy a limited area specially in depressions and flat areas in main drainage ways. The second and dominant group is yellow reddish granite soil which is coarse and highly dispersible. Gullies are developed mainly in the yellow- reddish soils (Soufi, 1997).

3 Methods and materials

A single gully was selected in order to find out in detail how gullies are developed in the Kapunda pine plantation and to investigate hydrological and erosional processes in detail. The Kapunda pine plantation gullies are valley side gullies. They are discontinous with U-shaped cross sections. The form of the gully heads is an overhanging cave type. As there is one type gully and monitoring of hydrological processes such as seepage, channel flow and overland flow needs to apply accurate and expensive devices, only one typical gully was selected for detailed monitoring. For ease of monitoring, the selected gully has a simple form, one that has a single channel head, no tributaries, and a fan at the gully foot. It has 95 m length, 1.5 m average depth and 2 m average width.

Rainfall was monitored at the site using one storage rain gauge and one automatic Unidata tipping bucket gauge. The automatic rain gauge measured rainfall continously with a 20 minute logging interval and a tip size of 0.2 mm. A sequence of 9 piezometers in three locations was used to monitor the depth of the water table in auger holes excavated just uphill of the gully head. The distance between the sites and also the distance between the first site and the gully head was approximately 3 meters. Each site had three piezometers positioned at different depths. The maximum depth was equal to the maximum height of the headcut. The piezometers consisted of a 51 mm diameter slotted PVC pipe leaving 20 cm lip above the ground surface to stop the drainage of surface runoff into the piezometers. They were installed in 76 mm diameter hand auger holes. The depth of the water table was monitored continously using one meter depth probes that were connected to the data loggers. The depth of water table was also checked manually in each field measurement.

Surface runoff and channel flow were monitored using two differen devices. Runoff plots were used to collec surface runoff from the gully banks and two U.S.D.A. H-type flumes were used to monitor the flow at the head and the bottom end of the gully. The bank runoff plots were each 2m wide, connected troughs with open plot sides and upper boundry. Runoff was funnelled into storage drums. The discharge at the head and the end of the gully was monitored between July 1994 and October 1995 using two U.S.D.A. H-type flumes and Unidata water level recorders. The uphill flume was installed in a defined channel, 55m upstream from the gully head and the second flume was installed at the bottom end of the gully. Water level was monitored at 20 min. logging intervals using Unidata water level recorders. Discharge was calculated using standard rating tables for the flumes. Seepage was monitored between January 1994 and October 1995 by five seepage meters at the gully head and six seepage meters at the gully banks. The seepage meter is comprised of a one closed- end PVC cup and a hose pipe leading to a sealed drum or tipping bucket. Fifty five soil samples from different soil units at the gully head and gully banks were chosen to analyse particle size and aggregate stability. Soil units were classified using soil texure, bank morphology, the slope of the banks and the existence of plant roots. Headcut retreat was surveyed using two methods. Advance of the rim of the headcut was surveyed in plan form periodically using level. Headcut retreat was also monitored by surveying six vertical profiles around the gully head. These stations consisted of 2m long stakes which were installed at the foot of the gully head. The vertical stakes were marked at 10cm intervals from their top. The horizontal distance between each stake and the gully head was measured by a level ruler at each 10cm interval. The total volume of erosion at the headcut was calculated by the sum of partial volumes of fixed stations. The partial volume of head erosion at each fixed station was calculated by multiplying the toal head retreat a each fixed station during the monitoring period by the partial area of that station:

$$V_p = \sum (\mathrm{Api} \times \mathrm{Di})$$

Where Vp = parial volume of head erosion at each fixed station, m3; Api = partial area around fixed station number I, m^2; and Di = average retreat of gully head during the monitoring period at the fixed station number I, m.

Aerial photographs, field survey and monitoring were used to determine the trend of gully growth between 1988 and 1995 5n the apunda pine plantations. The linear extension of gullies between 1988 and 12.12.1990 was measured using the photogrammetric map derived from colour aerial photographs aken in 12.12.1990. Then the linear extension of gullies between 12.12.1990 and 1993 was calculated using the length of gullies measured on the photogrametric map (12.12.1990) and measured in the field(1993). After 1993, uphill movement of gully heads was monitored using reference points in 1994 and 1995.

4 Results

The monitored gully has a notched head and a smaller digitated head using Ireland *et al*.,(1939, Figure1.3) classification. The notch is the point of entry of concentrated runoff. The profile of the headcut is undercut beneath vegetation that is something to cave and vegetated type in Ireland *et al*.,(1939, Figure 1.4) classification.

The results of hydrological monitoring indicate that there is a rainfall threshold higher than which significant surface runoff, channel flow and water table rise occur. Surface runoff monitoring from the gully banks indicates that more than 30 mm daily rainfall with a 20 minutes intensity of >6 mm/20 minutes was necessary to get significant surface runoff from the gully banks.

The results of channel flow monitoring suggest that a higher rainfall threshold than surface runoff from the gully bank is necessary to have significant channel flow. The evidence suggest that daily rainfall of more than 38 mm with a 20 minutes intensity of >8 mm/20 minutes produced substantial channel flow. In addition, there is a high correlation between surface runoff from the gully banks and channel flow.

The evidence of this study suggest that massive catchment runoff as rapid throughflow with minor saturated overland flow and plot runoff occurred when rainfall intensity was of >60 mm/h. In continous rainfall of more than 140 mm, more saturation overland flow with seepage and minor plot runoff contributed to the hydrograph.

Water table monitoring indicates that a similar rainfall threshold to surface runoff from gully banks was necessary to have significant water height in piezometers. More than 30 mm daily rainfall with a 20 minutes intensity of >6mm/20 minutes was enough to change the depth of water table by 1 meter(Figure 2). The evidence of water table and seepage monitoring indicate that flow movement was toward the headcut and the highest seepage discharge occurred in the middle layer of the head profile.

The results of seepage monitoring indicate that the headcut experienced great seepage after daily rainfalls of >30 mm with a 20 minutes intensity of >8 mm/20 min, but minor seepage occurred at low rainfall as well. The evidence shows that rainfall threshold for bank seepage is less than that for head seepage. These results suggest that substantial bank seepage occurr in the top bank layers, providing evidence for rapid shallow sub-surface flow.

The study of erosion processes on the monitored gully indicate that a mixture of processes such as seepage, soil creeping, rainsplash, wash, spalling, block failure and scour are acting on gully erosion in the Kapunda pine plantations. The morphology and spatial pattern of erosion along the gully show that two hydrological processes, seepage and overland flow are important in gully erosion. The evidence of erosion monitoring demonstrate that in the haedcut erosion, seepage is the dominant process(Figure 3) but to maintain the headcut retreat, overland flow is necessary. The statistical relationship between headcut erosion and monitored hydrological processes at the gully head, indicate that seepage is the dominant hydrological process in headcut erosion with R2 = 0.93. It shows that 93% of variation in the headcut erosion is explained by variation in seepage. These results support the results of morphological measurement at the headcut (Figure 3) that seepage is the dominant hydrological process a the gully head. These results support relationship between gully morphology and process introduced by Imeson and Kwaad (1980) and Ireland *et al.*, (1939).

The results of this study suggest that there is an exponential trend in gully development in the Kapunda pine plantation (Figure 4). It is indicated that more than half the total length of the gullies developed during 1988-1990 after initiation in 1988. The gullies approached a new equilibrium length 8 years after initiation.

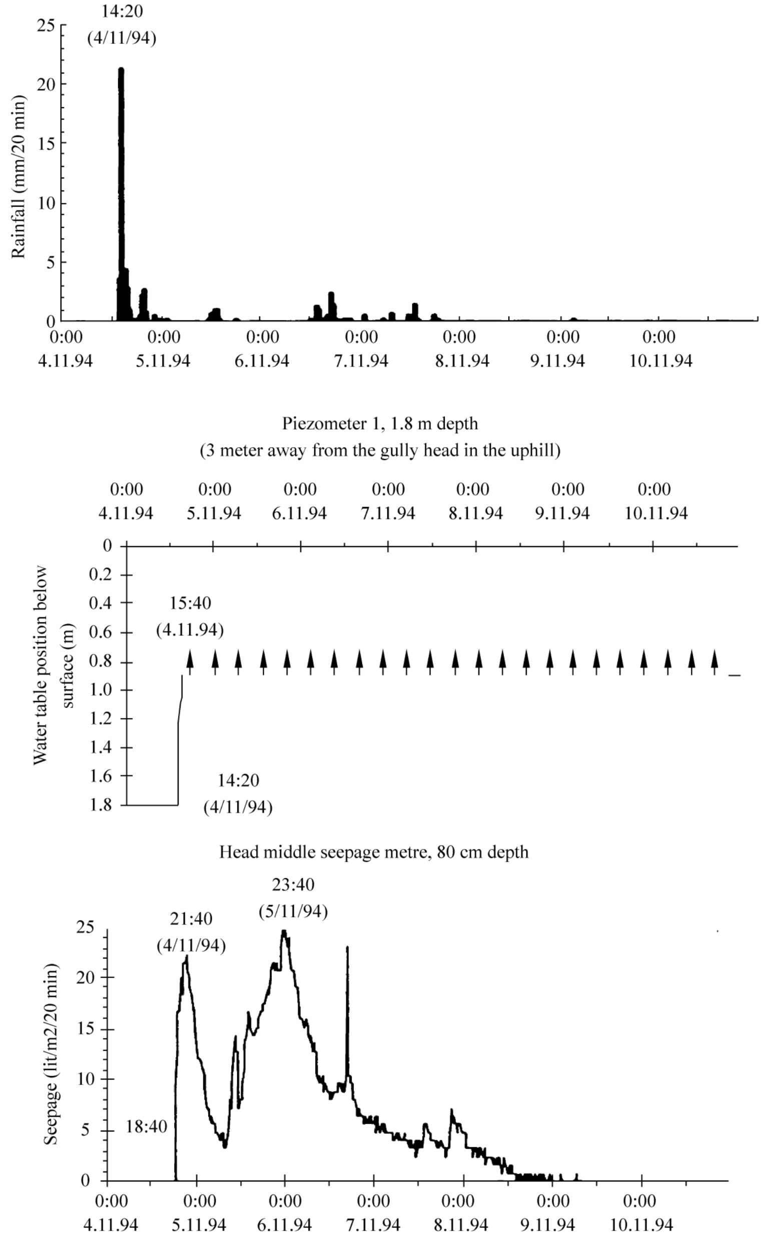

Fig.2 Comparison of seepage at the base of the gully head and piezometer 1 and rainfall on 4.11.1994

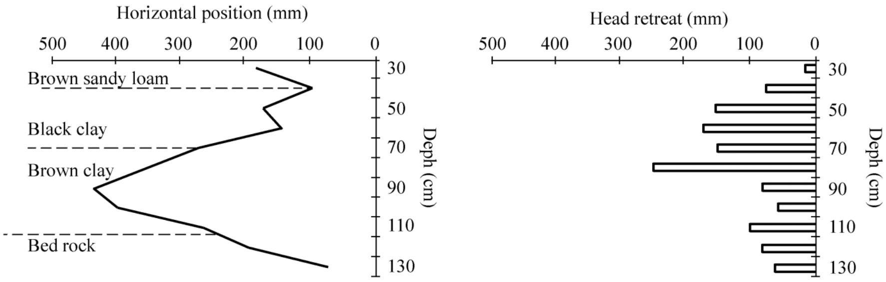

Fig.3 Total headcut erosion along the vertical profile of gully head

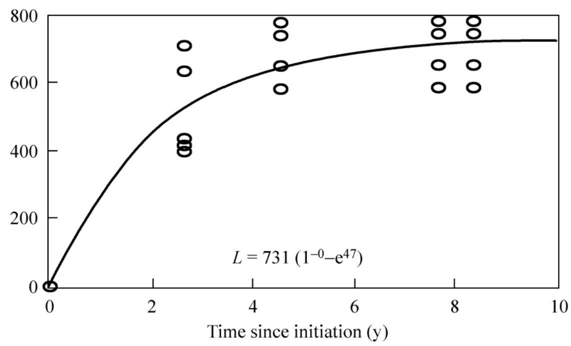

Fig.4 Trend of gully growth in the Kapunda pine plantation in southeast Australia

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