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Thresholds for channel initiation at road drain outlets

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ABSTRACT

Slope–Area relationships have been widely used to identify channel initiation points in the landscape. More recently, the importance of road-related rill and gully erosion has been highlighted. Previous studies indicate that channel initiation at road drain outlets can be predicted from the contributing road area and hillslope gradient at the drain outlet. In this study the validity and usefulness of channel initiation thresholds for road runoff management has been evaluated using field data from three catchments in south-east Australia. None of these catchments show a clear separation between channelised and non-channelised sites based on contributing road area and hillslope gradient. Many drains without channel have similar contributing road area and slope gradients as drain with a channel at the outlet. This demonstrates a relatively large variability within our dataset and limits the identification of a slope–area threshold for these catchments. Logistic regression using road area and slope gradient shows that both variables contribute significantly to channel initiation in the Albert and Tyers River catchments, while for the Sandy Creek catchment only slope gradient is significant at the 0.05 level. Stepwise logistic regression on a wider range of variables shows the significance of cut-batter height in two of the catchments, indicating that flow interception at cut-and-fill roads may be important. Comparison of road-related channel initiation thresholds to previously published topographic thresholds, indicates that channels at road outlets tend to form at relatively small contributing areas and steep slopes. Current forest management guidelines do not consider the risk of channel initiation at road drain outlets in road design and drain spacing. The slope–area thresholds are still considered useful in minimising the risk of gully erosion, especially in forestry areas where it appears most likely that channel initiation occurs during a significant rainfall event immediately following hillslope disturbance or road construction.

1. Introduction

Gully erosion represents an important sediment source in a wide range of environments, with soil loss rates from gully erosion varying between 10 and 94% of total sediment yields (Poesen et al., 2003; Valentin et al., 2005). Gully erosion is commonly considered a threshold process, which was first applied by Patton and Schumm (1975) to describe the critical slope gradient (S) and drainage area (A) required to initiate incision (Poesen et al., 2003). Subsequent models (e.g. Dietrich et al., 1992, 1993; Montgomery and Dietrich, 1994) present different inverse relationships between the contributing drainage area and slope gradient and provide a physical basis for the use of S–A relationships of the general form outlined in Eq. (1):

$$S = a \cdot A^{-b} \tag{1}$$

with A the contributing area (most often expressed in ha) and S the sine of the slope gradient (e.g. Montgomery and Dietrich, 1988, 1994; Moore et al., 1988; Boardman, 1992; Prosser and Abernethy, 1996; Vandaele et al., 1996; Desmet and Govers, 1996; Desmet et al., 1999; Vandekerckhove et al., 1998, 2000). A detailed literature review of these studies has been published by Poesen et al. (2003).

Most of the above mentioned studies deal with channel initiation thresholds in landscapes with cultivated or pasture landuses. Gully erosion has also been widely observed in forestry environments as a result of forest clearing (Prosser and Soufi, 1998) and associated with runoff discharge from road networks (e.g. Montgomery, 1994; Wemple et al., 1996; Jungerius et al., 2002; Nyssen et al., 2002). The unsealed road network is considered the most important source of Hortonian overland flow and associated sediment fluxes in forested environments (e.g. Croke et al., 1999, 2005). Gullies in forestry environments, like other landuses, form effective pathways for the delivery of runoff and sediments to streams, increasing the hydrologic connectivity in the landscape (e.g. Montgomery 1994; Croke and Mockler, 2001; Poesen et al., 2002, 2003; Croke et al., 2006). Channel initiation thresholds at road drain outlets have, therefore, been used to define the optimal contributing area to a drain and thereby assist with soil conservation and off-site water quality management strategies (e.g. Montgomery, 1994). These threshold equations have taken the

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Table 1
Characteristics of the three study areas

	Albert River	Sandy Creek	Tyers River
Study area (km^2)	82	48	274
Type of forestry	Hard- and softwood plantations	Softwood plantations	Native forestry
Geology	Mudstone, sandstone	Granodiorite	Granodiorite, (meta) sediments, basalt
Major soil type(s)[a]	Brown dermosols	Red kandosols	Brown or red dermosols and ferrosols
Relief range (m)	40–750	600–1200	200–1600
Slope range (%)	30–60	10–30	30–50
Annual rainfall (mm)	1450	1215	1290
Stream density (km/km^2)	4.5	1.8	2.2
Road density (km/km^2)	4.2	5.9	1.8

[a] Terminology from the Australian Soil Classification (Isbell, 1996).

same form as the model initially proposed by Montgomery and Dietrich (1994) for channel initiation by turbulent overland flow:

$$A_r = c \cdot S^{-1} \quad (2)$$

whereby A_r is the surface area of the road contributing to the drain (m^2), S is the sine of the hillslope gradient and c is a constant. Different c-values reflect differences in climate and soil properties with reported values ranging from 70 for south-east Australia (Croke and Mockler, 2001) to 400 for the Pacific Northwest USA sites (Montgomery, 1994). In these two studies, the relevant threshold equations successfully predicted channelised sites with overall accuracies varying between 79 and 97%.

From a forest or road management perspective, there is obviously considerable practical benefit in the application of a simple model such as the S–A_r relationship to determine the required drain spacing in order to avoid channel initiation. Positive benefits include decreased off-site risks associated with channel connection to water courses and to road maintenance and road stability strategies. Current management practices for limiting road erosion and associated sediment delivery commonly only consider the slope of the road travelway and thereby ignore the important landscape connectivity aspects associated with channels forming at drain outlets. A model which incorporates the hillslope gradient at the road outlet has the potential to better reflect the probability of gully erosion enhancing landscape connectivity. However, for such a model to be widely applicable across a range of climates, soil types and landuses, the overall application of the S–A_r relationships needs to be evaluated in a wide range of environments. For example, the two existing models that have successfully demonstrated a useful S–A_r relationship in defining channel thresholds at road outlets were undertaken on relatively small lengths of road in small to medium sized catchments. Subsequent research found that the relationship is less straight forward, with the probability of channel initiation increasing with road contributing area only for slopes steeper than 40% (Wemple et al., 1996), and that indeed, other factors such as hillslope curvature and the distance from the drain to the natural stream network can be significant variables (La Marche and Lettenmaier, 2001).

Within the context of testing the application of the S–A_r relationship as a management tool in limiting gully erosion and hence hydrologic connectivity in forestry environments, the specific objectives of this study are twofold. Firstly, to investigate to what extent road contributing area and hillslope gradient can be used to predict the occurrence of channel initiation at road drain outlets in three different forested catchments in south-east Australia. Secondly, to evaluate to what extent these models can be improved by the inclusion of additional variables that are relatively easy to measure or can be derived from digital elevation models (DEMs).

2. Study sites

2.1. General characteristics

Forestry remains an important commercial landuse activity in south-eastern Australia with large estates of both native eucalypt and exotic pine plantations present along the coastal margin of New South Wales (NSW) and Victoria. Within this broad geographic region, three different catchments with contrasting forestry operations (selective native hardwood logging and commercial pine plantation) were selected for detailed study; the general characteristics of which are summarised below and in Table 1.

The Albert River catchment is located in the Strezlecki Ranges in Victoria (Fig. 1). It is mainly used for hard- and softwood plantations, with some pasture land. The upper 82 km^2 of the catchment, where approximately 65% of the plantation area is used for softwood and 35% for hardwood plantations, was selected. Elevations range from 40 m to 750 m. The study area is characterised by steep convex slopes, narrow ridges and incised steep drainage lines, with slope gradients commonly in excess of 40%. A soil cover of predominantly brown dermosols has developed on Cretaceous mudstones and fine grained sandstones. Mean annual rainfall is estimated to be around 1450 mm.

The Sandy Creek catchment (NSW, Fig. 1) has an area of 79 km^2 and the upper 48 km^2 of pine plantations was selected for study. Elevations range from 600 m to 1200 m. Slope gradients are relatively moderate, generally ranging between 10 and 20% with localised steep slopes. A deeply weathered granodiorite geology supports a 1 to 1.5 m deep red kandosol soil cover. Annual rainfall is c. 1215 mm with highest rainfall in the winter period.

The Tyers River catchment (Victoria, Fig. 1) has an area of 274 km^2 and is mainly used for native hardwood forestry. It has highly variable terrain, extending from 200 m to 1600 m relief, with slope gradients varying between 30 and 50%. Geology varies considerably across the catchment. Granodiorite is found in the alpine massif in the northern part of the catchment, a range of sedimentary and metasedimentary geologies form the dissected foothills in the southern half of the catchment, while basalt occurs in the eastern part of the catchment. Soil types and conditions vary in association with geology and altitude, with dermosols and ferrosols being the most common. There is a substantial rainfall gradient over the catchment, with highest rainfall amounts in the northern (highest) part of the catchment. Mean annual rainfall measured in the Middle-East of the

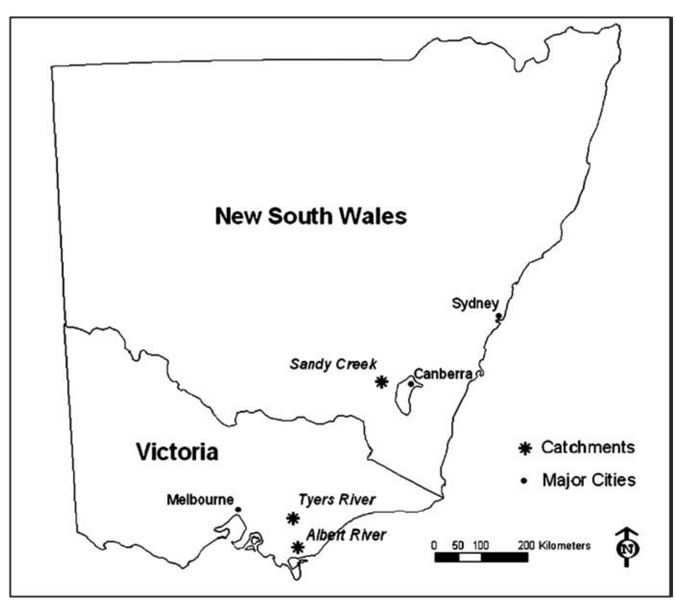

Fig. 1. Location of the study sites.