Road to Stream Connectivity: Implications for Forest Water Quality in a Sub-Tropical Climate

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Authors' contributions

This work was carried out in collaboration between all authors. Author AAW designed the study, managed the literature searches and wrote the first draft of the manuscript. Authors AAW and ILH jointly collected the field data. Author ILH managed the analyses of the study and reviewed the first draft of the manuscript. All authors read and approved the final manuscript.

Research Article

ABSTRACT

Unsealed roads and tracks are acknowledged as the major sources of sediment pollution in forested catchments. In particular, road to stream connectivity via gullied pathways as well as via diffuse overland flow can contribute to significant fine sediment inputs to forest streams. At present in the State forests of New South Wales (NSW), Australia, road drainage spacings are determined on the basis of road slope. In this study forest road surveys were conducted across seven coastal catchments near Coffs Harbour on the sub-tropical NSW mid north coast to determine connectivity between gravel roads and streams via channelised and diffuse pathways under a range of rainfall intensities. A total of 10.82 km of representative road sections was assessed, comprising 129 relief pipes and 22 mitre drains. Of the 151 drains surveyed, gullies were evident at the outlets of 26 relief pipes (20.2%) but at none of the mitre drains. Relationships previously derived between contributing road length and hillslope gradient, and between contributing area and hillslope gradient adequately predicted thresholds of gully formation at drain outlets. During lower intensity storms with average recurrence intervals of 10 years or less, less than 20% of drains are connected to streams via overland flowpaths. However, the

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degree of diffuse connectivity increases when contributing area takes account of table drains and cut batters, as well as with increasing rainfall intensity. We conclude that when constructing new roads or reassessing drainage on existing roads in forest environments, in addition to preventing erosion of the road surface, gully formation and connectivity with streams via diffuse overland flow should be avoided. This requires factoring in contributing area, hillslope gradient at drain outlets and distance to the nearest stream. Preventing or reducing road-to-stream connectivity is essential for reducing impacts on water quality across all land tenures.

Keywords: Road drainage; sediment connectivity; forest management; water quality; southeastern Australia.

1. INTRODUCTION

Sedimentation or increased concentrations of suspended sediment have been identified as a key environmental concern, with potentially deleterious effects on aquatic ecosystems [1]. There are many anthropogenic causes of sedimentation but in forest environments significant increases are generally associated with road construction and harvesting activities. A number of studies worldwide have highlighted the relative importance of roads and trail networks in delivering sediment to streams, including from the USA [2,3,4,5,6,7,8,9], Asia [10,11,12,13,14] and Australia [15,16,17,18,19,20,21,22,23]. Indeed in the USA, due to the significance of sediment generated from logging roads, there has been serious consideration given to designating them as point sources of sediment discharge into streams as a direct result of human activity [24].

In summary, the destination of road runoff and entrained sediment can be:

i. Direct infiltration into the soil below the road drainage outlet;
ii. Infiltration below a gully that does not extend to the stream channel;
iii. Entrance to a stream via a stream crossing;
iv. Entrance to a stream channel indirectly through the formation of a gully below a drainage outlet; or
v. Entrance to a stream below an ungullied slope via overland flow from a drainage outlet [25].

Outcomes (i) and (ii) are the most desirable as they ensure that there is no connected pathway between the road and stream networks. Outcomes (iv) and (v) are undesirable as they represent direct connectivity whereby the road network essentially becomes an extension of the drainage network. Outcome (iii) is difficult to avoid and case (iv) occurs where runoff discharged from a road drainage outlet is concentrated and of sufficient power to erode hillslope soil creating a gully. If such gullies extend to the stream network, it is believed that the road and stream are directly connected [19] resulting in undesirable water quality outcomes as road sediment can be easily conveyed to receiving waters.

In natural landscapes there are strong inverse relationships between contributing area and local channel slope at channel heads as there is generally a threshold value of surface or subsurface flow that is required to overcome surface resistance to erosion (Montgomery and Dietrich, 1988). These same processes were recognised with respect to gully formation at road drainage outlets by Montgomery [6] in the western United States. Following the methods of Montgomery [6], Croke and Mockler [19] studied gully formation processes in the

Cuttagee Creek catchment of southeastern New South Wales (NSW), Australia, at mitre drain and relief pipe outlets. From this they derived threshold relationships between contributing road length and hillslope gradient, and between contributing road area and hillslope gradient. The threshold they derived for gully initiation at drain outlets is similar to those described by Montgomery [6] for the western USA. Takken et al. [23] extended this work by surveying gullies at drain outlets in three different environments in larger catchments in Victoria and NSW, Australia. However, they also identified cut batter height as a significant variable in gully formation in some catchments, which indicated that flow interception at side-cut (cut-and-fill) roads may be important.

If the drain outlet is not gullied, there is opportunity to disperse road runoff onto the hillslope and allow water and sediment to infiltrate into the subsoil. However, the capacity of a given length of hillslope to disperse runoff is generally finite meaning that it is possible for drain outlets to be connected to streams via overland flow (v). Based on the rainfall simulation studies of Croke et al. [26], the concept of volume to breakthrough was introduced by Hairsine et al. [27]. The volume to breakthrough (*vbt*) is the volume of water that may enter an area before a discharge is observed at the downslope boundary of that area. For example, based on 20 simulations on red granite, light granite and metasediment soil types, Hairsine et al. [27] concluded that the mean value of vbt_5 was 336 litres. In other words, the mean amount of water that could be discharged onto a surface before runoff was observed 5 m downslope was 336 litres. The value of vbt_5 has been found to be reasonably consistent [25] and the concept has been utilised by Takken et al. [28] to assess the delivery of diffuse overland flow from road drains to streams.

The aim of this paper is to identify the predominant processes and variables contributing to gully formation at road drainage outlets in forested catchments in northern NSW, Australia, where these relationships have not previously been tested. More specifically, the paper aims to determine whether the slope-area relationships identified by Croke and Mockler [19] can be more universally applied to areas of differing geology and climatic conditions. A further aim is to assess diffuse connectivity between road drains and streams by applying the volume to breakthrough model of Hairsine et al. [27] under a range of rainfall scenarios.

2. MATERIALS AND METHODS

2.1 Study Area

The study area comprised a number of roads located in four State forests and one National park near Coffs Harbour (30.32ºS, 153.12ºE) on the NSW mid north coast (Table 1). The region, in general, has a subtropical climate that is moderated by the maritime influence of the Pacific air mass. Mean annual rainfall at the Australian Bureau of Meteorology Coffs Harbour station (No. 59040) for the period 1943 to 2012 was 1700 mm with a median of 1612 mm. The majority of rain falls, on average, between October and May. The forests surveyed comprised native hardwood species dominated by various species of *Eucalyptus*.

All roads surveyed were permanent, gravel feeder roads, with a combination of drainage structures including mitre drains and relief pipes (Fig.1). Only those sections containing three or more sequential drains were assessed. Given that Croke and Mockler [19] identified the most gullies at relief pipe outlets, the surveys focused mainly on side-cut roads with in-fall drainage to a table drain (Fig. 2).

Table 1. Characteristics of roads surveyed in the study area

State forest (SF)/ national park (NP)	Road name(s)	Dominant geology	Total road length measured (m)
Kangaroo River SF	Black Mountain	Triassic conglomerate	1743
Scotchman SF	Horseshoe	Permian slate	3750
Conglomerate SF	Gentle Annie	Triassic conglomerate &	1870
	Plum Pudding	Jurassic claystone	548
	Sherwood Creek		418
	Sherwood		761
Ulidarra NP	Shelter	Carboniferous greywacke & mudstone	1526
Newfoundland SF	Coast Range	Jurassic sandstone	206
Total			**10822**
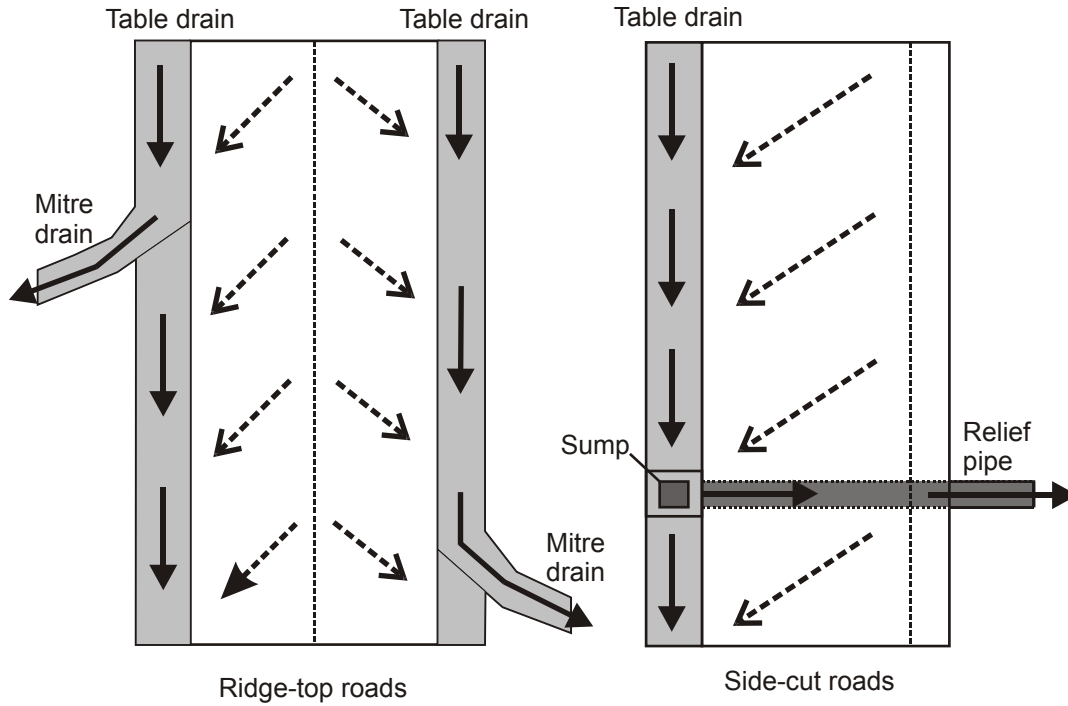
Fig. 1. Schematic diagram of the two main drainage types used on the roads surveyed: miter drains on ridge-top roads and Relief pipes on side-cut roads
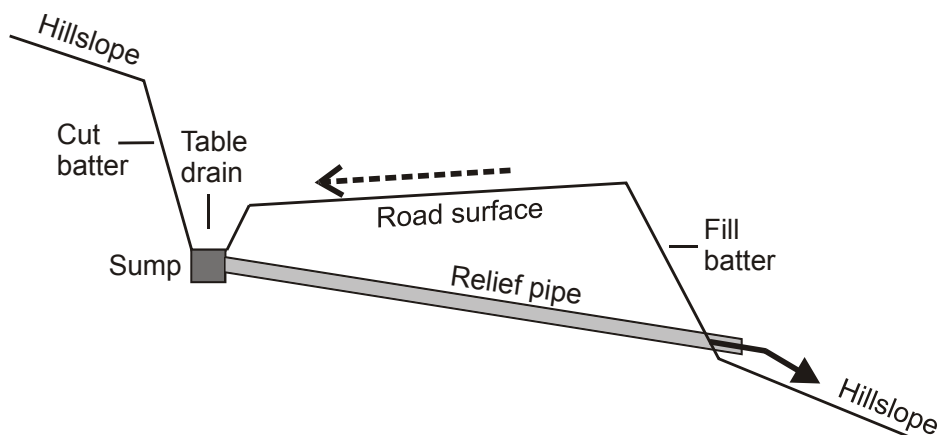
Fig. 2. Schematic cross section of a side-cut road

2.2 Methods

Road drains along each representative section of road were identified and their position mapped using a handheld GPS. For the section of road contributing to a particular drain, a number of features relating to the road surface, table drain, cut batter, drain, erosion at the drain outlet and stream connectivity were classified and measured in the field.

Road surface features assessed included:
- Length: measured using a hip-chain
- Width: measured using a measuring tape
- Slope: measured using a clinometer

Table drain features assessed included:
- Length: measured using a hip chain
- Width: measured using a measuring tape

Cut batter features, where present, assessed included:
- Length: measured using a hip chain
- Height: measured using a measuring tape

Drain features assessed included:
- Type: classified as either a 'sump' relief pipe, 'elbow' relief pipe or mitre drain
- Width: measured using a measuring tape
- Erosion control measures: where present were recorded and classed as either drop-down structures, rock dissipaters, concrete headwalls or flumes.

Hillslope features assessed below the drain outlet included:
- Erosion at drain outlet: presence or absence of scour, rills and/or gullies was recorded
- Hillslope gradient: measured with a clinometer along the flowpath from the drain outlet
- Road-to-stream connectivity: classified as either 'nil', 'partial channel' or 'full channel' connectivity following Croke and Mockler [19].

The slope distance from each drain outlet to the nearest stream was calculated using ArcGIS software.

2.3 Data Analysis

2.3.1 Channelisation thresholds

Croke and Mockler [19] performed an iterative discriminant analysis to determine an appropriate threshold relationship between various road length and area attributes and hillslope gradient to identify the probability of channelisation at drain outlets. In practical terms for forest management, the simplest threshold to apply in the field is a relationship between contributing road length and hillslope gradient. The relationship derived by Croke and Mockler [19] was:

$$L_t = \frac{25}{\sin \theta} \tag{1}$$

where L_t is contributing road length (m) and θ is hillslope gradient (degrees) at the drain outlet. Croke and Mockler [19] further derived a threshold relationship for road surface contributing area (A_t):

$$A_t = \frac{70}{\sin \theta} \tag{2}$$

In addition to A_t, total contributing area (A_{tot}) was calculated as:

$$A_{tot} = A_t + A_{CB} + A_{TD} \tag{3}$$

where A_{CB} is contributing area of the cut batter, and A_{TD} is contributing area of the table drain. Channelisation observed at drain outlets in this study was assessed against the predictive thresholds in equations (1) and (2).

2.3.2 Diffuse overland flow connectivity

According to the volume to breakthrough concept, the length of an overland flow plume can be predicted based on the amount of water discharged from a drain outlet (V_{out}):

$$L_{pred} = \frac{5.V_{out}}{vbt_5} \tag{4}$$

where L_{pred} is the predicted plume length (m), V_{out} is the volume of water discharged at the drain outlet (litres) and vbt_5 is the mean volume to breakthrough for 5 m of hillslope.

To determine if an overland flow plume will reach a stream located down-slope, it is critical to know the distance to the stream below the drain outlet and to be able to calculate the volume of water being discharged from the drain outlet. Volume of water leaving the drain is calculated as:

$$V_{out} = A. (R - I) .t \tag{5}$$

where A is contributing area (m^2), R is rainfall intensity (mm/hr), I is road surface infiltration rate (mm/hr) and t is the duration of a rainfall event (hr).

For overland flow plumes to be dispersed on the hillslope the following must hold true:

$$D > L_{pred} \tag{6}$$

where D is hillslope distance (m) to the nearest stream. By rearranging equations (4), (5) and (6) it is possible to calculate the maximum road contributing area (A_{max}) to avoid diffuse pollution of the nearest stream:

$$A_{max} = \frac{D.\,vbt_5}{5.\,(R-I)\,.t} \tag{7}$$

These equations were applied to the study area to predict diffuse connectivity between road drainage outlets and nearby streams. In so doing the mean vbt_5 value of 336 litres was used following Hairsine et al. [27], while a mean road surface infiltration rate of 11.74 mm/hr was used as found by Croke et al. [20]. Calculations were based on available rainfall intensity-frequency-duration curves [29] for Coffs Harbour for storms of 30 minutes duration after Takken et al. [28].

3. RESULTS AND DISCUSSION

3.1 Road, Drain and Landscape features

A total of 10.82 km of representative road sections was assessed (Table 1), comprising 129 relief pipes and 22 mitre drains. In general, the relief pipes were situated on steeper hillslopes, while the mitre drains were located on flatter terrain, such as ridgetops, or at the end of steep side-cut sections of roads (Fig. 3).
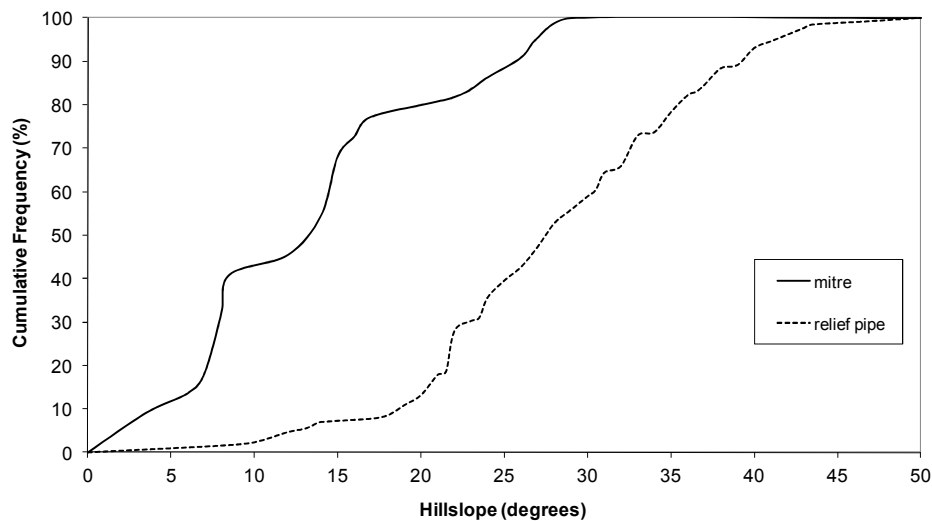

Fig. 3. Cumulative frequency of hillslope gradient at drain outlets by drain type

'Sump' relief pipes were the type of pipe installed when the majority of roads were originally constructed. These pipes consist of a box-shaped inlet that is at right-angles to the relief pipe which passes beneath the road (Fig. 4). They were often installed prior to the introduction of Environment Protection Licences [30] in the 1990s. Since that time, Forestry Corporation of NSW has been required to progressively upgrade road drainage as roads have become licensed during timber harvesting operations. As many older roads did not comply with the EPL conditions, additional relief pipes were installed to reduce drain spacings. Most of these newer drains in the study area are of the 'Elbow' type. These structures consist of a rounded inlet and a curved junction with the pipe that passes beneath the road (Fig. 5). These have been preferred in recent times as they more readily self-clean to prevent blockage with sediment and/or organic material washed in from the table drain.


Fig. 4. Sump relief pipe inlet on Black Mountain Road, Kangaroo River State forest conveying sediment-laden water from the table drain during a rain storm. The arrow shows the direction of flow in the pipe beneath the road surface

Fig. 5. 'Elbow' relief pipe inlet conveying sediment-laden water, Kangaroo River State forest

Existing road drainage spacings in the study area were determined by the slope of the road according to EPL prescriptions. Whilst all of the drains surveyed now comply with the EPL conditions [30] to protect the road surface from erosion, it is recognised that road slope is only one of several factors to be considered in relation to optimum drainage spacings for water quality protection [31]. Side-cut roads are often located on steep terrain and naturally the aim is to provide a road grade that is less steep than the adjacent hillslope. Fig. 6 demonstrates that on the roads surveyed hillslopes greatly exceeded road slopes for all relief pipes and for the majority of mitre drains.
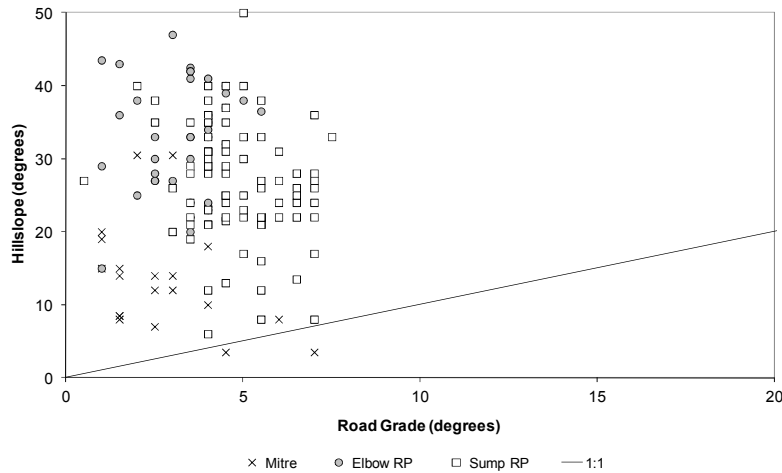
Fig. 6. Relationship between road grade contributing to a drain and hillslope grade at the drain outlet, by surveyed drain type
Mitre – mitre drain; RP – relief pipe

3.2 Connectivity via Channelised Pathways

Of the 151 drains, gullies were evident at 26 outlets or 17.2% of the drains surveyed. However, no gullies were evident at any of the mitre drains (Table 2). This is in contrast to the findings of Croke and Mockler [19] in the Cuttagee Creek catchment on the south coast of NSW, where 8% of mitre drains and 20% of "pushouts" displayed full channel connectivity. Similarly, of the relief pipes surveyed here only 20.2% displayed full or partial channel connectivity (Fig. 7) compared with 87% in the Cuttagee Creek catchment [19]. This result was unexpected given that higher total rainfall and rainfall intensities are experienced in the study area.

Table 2. Degree of connectivity via gullied pathways at surveyed drain outlets

Type of drain	*n*	*n* Full channel linkage (%)	*n* Partial channel linkage (%)	*n* Total channelised (%)
Sump relief pipe	91	17 (18.7)	7 (7.7)	24 (26.4)
Elbow relief pipe	38	0 (0)	2 (5.3)	2 (5.3)
Total relief pipes	*129*	*17 (13.2)*	*9 (7.0)*	*26 (20.2)*
Mitre drains	22	0	0	0
TOTAL	**151**	**17 (11.3)**	**9 (6.0)**	**26 (17.2)**

Fig. 7. Gully below a relief pipe conveying sediment laden water and exhibiting full stream connectivity

3.3 Thresholds for Gully Formation

Drain outlets with partial channel connectivity and those with full channel connectivity were combined and plotted as 'channelised', while those without connectivity were plotted as 'unchannelised' (Fig. 8). Across the study area no channelised pathways were evident where the hillslope gradient below drain outlets was less than 20º. In terms of predicting channelisation at drain outlets across the study area, the relationship in equation (1), based on contributing road length and hillslope gradient, was able to predict 88% of connected drains. However, the relationship was unable to satisfactorily predict non-channelised pathways at drain outlets, which is similar to the findings of Takken et al. [23]. In terms of preventing gullied pathways, this outcome is deemed acceptable as there could be many factors contributing to a lack of gully erosion at drain outlets. However, identifying a threshold for gully initiation is important for managing the worst case water quality scenario and is considered the best and most conservative approach [19].
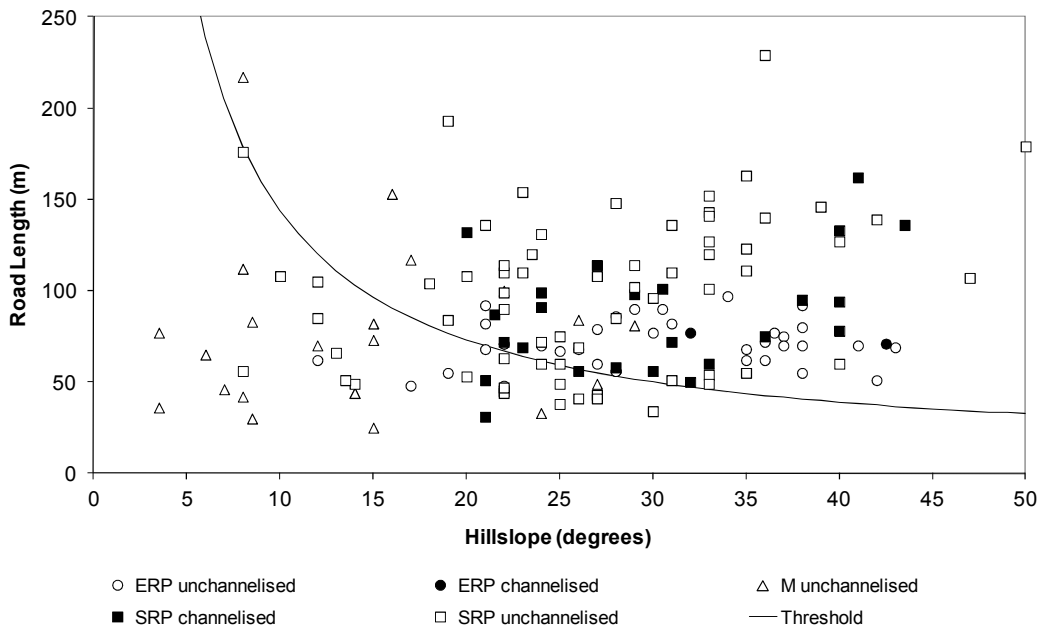
Fig. 8. Relationship between road contributing length (L_t) and hillslope gradient (θ) for channelised and unchannelised pathways. The threshold curve is that of Croke and Mockler [19] as presented in equation (1)
*ERP – Elbow relief pipe; M – Mitre drain; SRP – Sump relief pipe*

While contributing road length is easily identifiable in the field, the width of roads in the study area is variable. Therefore, thresholds of contributing area (A_t) and hillslope gradient were assessed. Using the threshold parameters in equation (2) enabled prediction of 96% of channelised pathways at drain outlets (Fig. 9), which is an improvement on equation (1). When total contributing area (A_{tot}), including cut batters and table drains, was substituted for contributing area (A_t) in equation (2), the threshold relationship of Croke and Mockler [19] correctly predicted 100% of the channelised pathways at drain outlets in the study area (Fig. 10). As with equation (1), regardless of whether A_t or A_{tot} was used, equation (2) predicted very few of the unchannelised drain outlets.
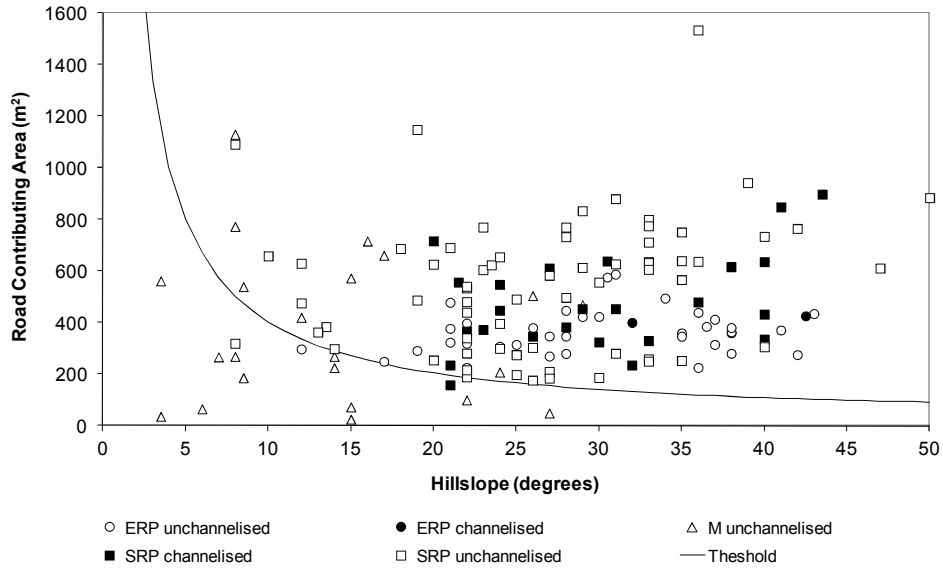
Fig. 9. Relationship between road contributing area (A_t) and hillslope gradient (θ) for channelised and unchannelised pathways. The threshold curve is that of Croke and Mockler [19] as presented in equation (2)

ERP – Elbow relief pipe; M – Mitre drain; SRP – Sump relief pipe
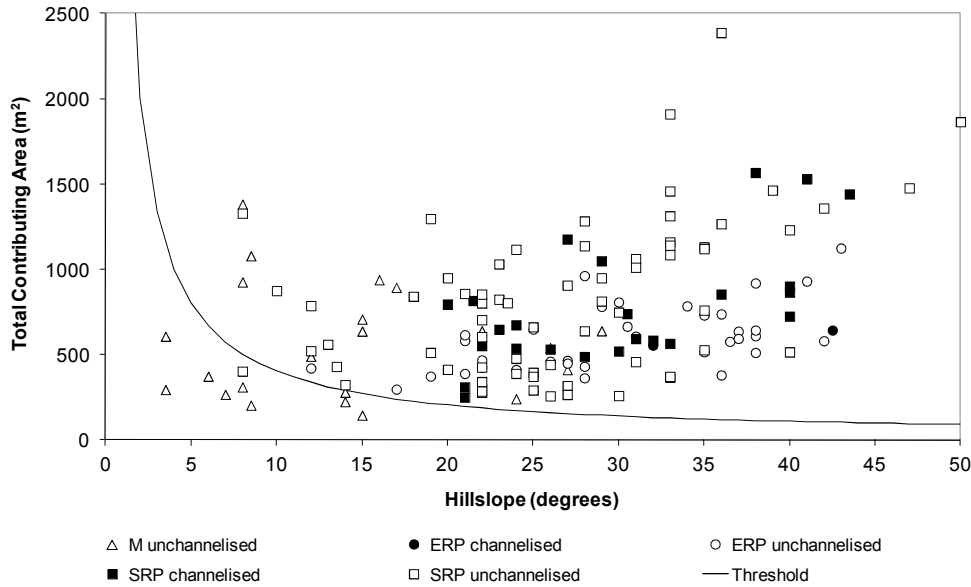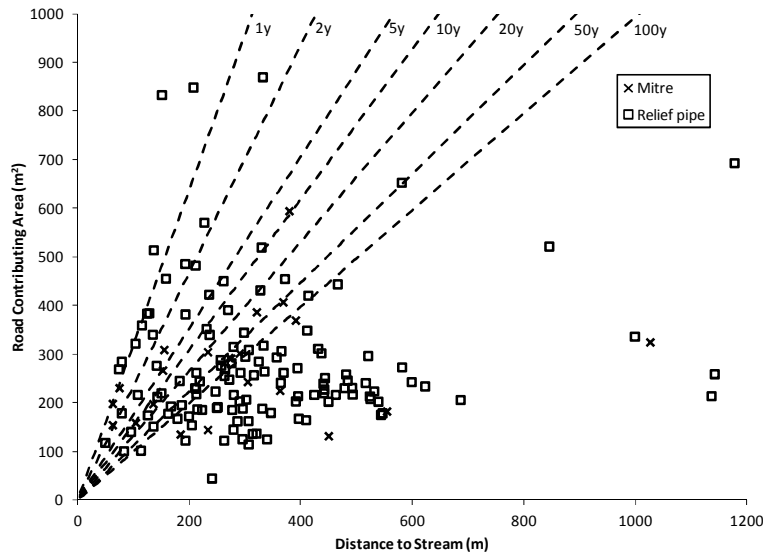

Fig. 10. Relationship between total contributing area (A_{tot}) and hillslope gradient (θ) for channelised and unchannelised pathways. The threshold curve is that of Croke and Mockler [19] as presented in equation (2)

While the relationships derived in equations (1) and (2) are able to adequately predict gully initiation at drain outlets in the study area, there remain a number of drain outlets exceeding the thresholds but where no channelisation is evident. This instigated further investigation of

other factors driving the resistance of outlets to gully formation, including the hillslope aspect, soil type and mitigation measures such as rock-dissipators and drop-down structures. In general, channelisation at drain outlets occurred regardless of aspect or soil type. Preliminary results from this study suggest that mitigation measures such as drop-down structures and rock dissipaters are effective at preventing gully formation under certain conditions. In the context of road drainage management, this is an important avenue to explore as in some circumstances it may be more cost-effective to install mitigation measures on existing drains as opposed to the often expensive installation of new drains. However, further data on the effects of such measures on thresholds of erosion are required before firm conclusions can be drawn regarding their effectiveness in a range of landscape settings.

3.4 Diffuse overland flow connectivity

In considering whether drains would be connected to streams via diffuse overland flow, any channelisation was disregarded. Across the study area the hillslope distance from drainage outlets to streams varied between 48 m and 1177 m (Fig. 11). If the road surface alone was considered in calculations of contributing area, the predicted degree of connectivity during a 30 minute duration storm of 1 year average recurrence interval (ARI) was low with 3.3% of all drains exhibiting connectivity. Under the EPL [30] the majority of prescriptions relate to 5 year ARI events and in this scenario up to 16.6% of drains are predicted to be connected to streams via diffuse overland flow. According to an extreme scenario, under a 100 year ARI storm of 30 minutes duration, it is predicted that 43.7% of drains would be connected to streams via overland flow. Further details of the degree of connectivity by ARI and by drain type are shown in Table 3. The relief pipes are generally located closer to streams and 'connect' at lower rainfall intensities.
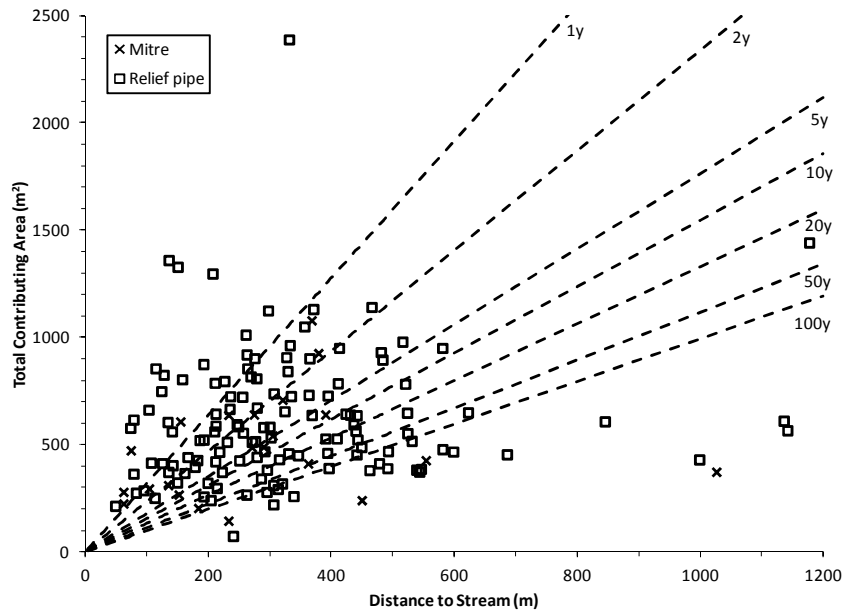

Fig. 11. Relationship between road surface contributing area (A_t) and distance to the nearest stream (D) by surveyed drain type. Also shown are the predicted thresholds (dashed lines) for diffuse connectivity during 30 minute duration rainfall events with average recurrence intervals between 1 and 100 years [29]

Table 3. Degree of connectivity via diffuse overland flow at surveyed drain outlets according to 30 minute duration storms with average recurrence intervals of between 1 and 100 years [29]. Calculations are based on road surface contributing area (A_t)

ARI (years)	Rainfall Intensity (mm/hr)	No. connected Mitre drains	No. connected Relief pipes	Total connected drains	% connected drains
1	53.9	0	5	5	3.3
2	69.2	3	15	18	11.9
5	87.9	4	21	25	16.6
10	98.7	6	23	29	19.2
20	113.0	8	31	39	25.8
50	132.0	10	42	52	34.4
100	147.0	14	52	66	43.7

If it is assumed that the table drains and cut batters also contribute flow to the drain outlets, i.e. using total contributing area in calculations, a greater proportion of drains are connected to the stream network, even during more frequent ARI events (Fig. 12). For example, during a 1 year ARI event 19.9% of drains are connected, which is more than are connected during a 10 year ARI event if road contributing area alone is considered (Table 4). Furthermore, during a 100 year ARI event some 83.4% of drains become connected, which is a plausible outcome given that during a 147 mm/hr storm a significant proportion of the catchment would likely be hydrologically connected in any case.

Fig. 12. Relationship between total contributing area (A_{tot}) and distance to the nearest stream (*D*) by surveyed drain type. Also shown are the predicted thresholds (dashed lines) for diffuse connectivity during 30 minute duration rainfall events with average recurrence intervals between 1 and 100 years [29]

Table 4. Degree of connectivity via diffuse overland flow at surveyed drain outlets according to 30 minute duration storms with average recurrence intervals of between 1 and 100 years. Calculations are based on total contributing area (A_{tot})

ARI (years)	Rainfall Intensity (mm/hr)	No. connected Mitre drains	No. connected Relief pipes	Total connected drains	% connected drains
1	53.9	4	26	30	19.9
2	69.2	7	52	59	39.1
5	87.9	13	74	87	57.6
10	98.7	16	81	97	64.2
20	113.0	16	91	107	70.9
50	132.0	17	101	118	78.1
100	147.0	18	108	126	83.4

These connectivity data predicted using the volume to breakthrough method highlight the further importance of considering distance to drainage features in addition to hillslope gradient and contributing area when planning appropriate road drainage. In practical terms it is unlikely that all connectivity can be avoided, especially during intense infrequent rain storms in sub-tropical climates such as experienced in the study area. However, taking an ARI such as 5 years and spacing road drainage to avoid as much connectivity as possible would be desirable from a water quality perspective. During more intense events it is likely that much of the catchment will be hydrologically connected and hence it is expected that any influxes of sediment will have a lesser effect on instream sediment loads due to natural erosion and sediment reworking processes. However, aside from determining appropriate drainage spacings, this diffuse connectivity framework can also be utilised to locate drains in places where connectivity is less likely to eventuate. For example, in some situations due to changes in local topography, it may be advantageous to increase drain spacing and contributing area in order to locate a drain such that it is further from a stream and/or located on a gentler hillslope.

4. CONCLUSION

Gully formation at drain outlets on unsealed forest roads in northern NSW creates direct road-to-stream connectivity with detrimental effects on water quality and aquatic ecosystems. This study has found that approximately 20% of relief pipe outlets on side-cut roads are directly connected to streams via channelised pathways. While existing road drainage prescriptions are designed to prevent erosion of the road surface, road length and/or contributing area and hillslope gradient are important determinants of the likelihood of gullies forming at drain outlets. Appropriate threshold relationships have been derived by Croke and Mockler [19] and these perform adequately in the study area, can be readily used in the field and take account of not only contributing road length and hillslope gradient, but contributing area of the road surface and hillslope gradient. This study has demonstrated that if total contributing area is calculated by accounting for the area of table drains and cut batters as well as the road surface, this increases the ability of Croke and Mockler's [19] threshold relationship to predict channelised pathways.

Furthermore, using the volume to breakthrough concept, this study has demonstrated how diffuse connectivity of drains is dependent upon the contributing area and hillslope distance between the road and streams. During lower intensity storms with average recurrence

intervals of 10 years or less, less than 20% of drains are connected to streams. However, the degree of diffuse connectivity increases when contributing area takes account of table drains and cut batters, as well as with increasing rainfall intensity. It is recommended that when constructing new roads in forest environments, in addition to preventing erosion of the road surface, consideration be given to preventing gully formation at drainage outlets as well as prevention of connectivity via diffuse overland flow. This requires factoring in contributing area, hillslope gradient at drain outlets and distance to the nearest stream. Preventing or reducing road to stream connectivity is considered essential for reducing impacts on water quality across a range of land tenures.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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