A practical method for the management of road runoff

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Abstract In this paper we outline a conceptual and methodological approach to evaluating the impacts off unsealed forest roads on in-stream water quality based upon the principal of hydrological connectivity. The methodology is based on the Vbt5 model of Hairsine *et al.* (2002) and makes use of simple empirical relationships that only require input data that are generally available or relatively easily to obtain, such as the road contributing area to drains and the distance from drain outlets to the streams. Using a plantation forestry catchment in the Australian Capital Territory, we demonstrate that the degree of connectivity along a road network is affected by the spatial distribution of the runoff delivery pathways. Furthermore, we illustrate how the methodology can be used to extract practical guidelines for appropriate drain spacing and to develop risk assessment maps to assist in prioritizing roads for removal or relocation.

Key words connectivity; diffuse overland flow; risk assessment; runoff delivery

INTRODUCTION

Runoff and sediments generated on unsealed forest roads have been recognized as a significant contributor to off-site water quality impacts (e.g. Bilby *et al.*, 1989; Grayson *et al.*, 1993; Ziegler & Giambellucia, 1997). Practical guidelines on how best to manage these road networks are limited and policy guidelines, if present, are often based on some arbitrary assessment of road density or stream crossing index. A number of studies have focused on identifying the dominant pathways in which road runoff reaches a stream; a high risk of connectivity is represented by stream crossings, gullies at the outlets of road drains, and excess runoff delivered as diffuse overland flow (Croke *et al.*, 2005; Takken *et al.*, 2005). In order to predict the distribution of these types of connectivity pathways, various studies have addressed gully initiation thresholds at road drain outlets based on road contributing area (m^2) and hillslope gradient at the drain outlet (sin θ) (Montgomery, 1994; Croke & Mockler, 2001). While additional factors, such as hillslope curvature or the location of an obstacle at the drain outlet, are also important factors (La Marche & Lettenmaier, 2001), the importance of these factors is more variable and can be impossible to quantify. For this reason, road contributing area and hillslope gradient are still considered the two most dominant factors in explaining gully formation at drain outlets. Few studies have addressed the degree of connectivity through diffuse pathways. Hairsine *et al.* (2002) developed a model (referred to as the Vbt5 model) to predict the probability of road-derived runoff reaching the stream by diffuse overland flow. It uses the concept of "volume to breakthrough", which is the volume of runoff that may enter an area before discharge is observed at the downslope boundary of that area.

In this paper, we outline a methodological approach to evaluating the impacts of unsealed forest roads on in-stream water quality based upon the Vbt5 model that only requires input data that are generally available or relatively easily to obtain. Using field data from a plantation catchment in the Australian Capital Territory, Australia, we demonstrate how the methodology can be used to extract practical guidelines for appropriate drain spacing, to develop risk assessment maps or to assist in decisions regarding road relocation.

STUDY AREA

The study area is part of the Cotter River catchment located in the Australian Capital Territory (ACT). A small area (10.7 km^2) within the Cotter River catchment was selected for this study. Elevations in the study area range from 590 to 1130 m, with slope gradients up to 39°. Soils in the study area are variable ranging from clays and clay loams to sandy clays and sandy clay loams, but are all relatively stable. The extent of the road networks is considerable, with an average road density of ~12 km km^{-2}.

METHODS

Data collection

A total of 32 km of road network was surveyed, representing approximately 40% of the total road inventory. The locations of 167 road drainage structures were mapped using a GPS, including different types of road drains and 58 stream crossings. Detailed field surveys were carried out at all drains and at 28 of the stream crossings, where road contributing area, identified by the actual road length and width contributing to the drain inlet, together with slope gradients of the road surface draining towards the drain and of the hillslope at the drain outlet were measured. The available hillslope length (i.e. the distance from the drain to the stream) was defined by the length of the flow-line drawn manually from the drain location to stream perpendicular to contour lines (10-m interval) in a GIS.

Connectivity analysis

The degree of connectivity of the drains is quantified using the Vbt5 model of Hairsine *et al.* (2002). Firstly, the volume of runoff that discharges into the drain, V_{in} (m^3), is calculated as:

$$V_{in} = CA \cdot (R - I)\, t/1000 \qquad (1)$$

where *CA* is the contributing road area (m^2), *R* is the rainfall rate (mm h^{-1}), *I* is the infiltration rate (mm h^{-1}) and *t* is the duration of the event (h). Subsequently, the runoff volume reaching the stream, V_{out} (m^3), is estimated by:

$$V_{out} = V_{in} - D \cdot Vbt_5/5 \quad (2)$$

where D is the available hillslope length and Vbt_5 is the volume of breakthrough for a 5-m long hillslope segment (Hairsine *et al.*, 2002).

We modelled predicted runoff volumes for three 30-min rainfall events, with intensities of 28.8, 45.2 and 78.0 mm h^{-1}, corresponding to a 2-, 10- and 100-year recurrence interval, respectively. A mean steady-state infiltration rate of 11.74 ± 9.35 mm h^{-1} as reported for road surfaces by Croke *et al.* (2006) was applied. The *mean* value of the volume to breakthrough for a 5-m long hillslope segment (0.336 ± 0.189 m^3) was used.

RESULTS

No major gullies were observed at road drain outlets in the catchment. In Fig. 1 contributing road area is plotted *vs* the slope gradient at the road drain outlet. The three lines in the graph represent the gully thresholds found for catchments in Australia (Croke & Mockler, 2001) and the USA (Montgomery, 1994). The graph indicates that only five drains exceed the high gully threshold found in the Huesdonk Ridge catchment (Montgomery, 1994). As such, runoff connectivity via gullied pathways is not considered a major form of connectivity in this catchment.

Results of the calculated runoff volumes being delivered to the streams indicate that the total volumes delivered by the 28 surveyed stream crossings, which represents only 48% of the total number of stream crossings, are similar to the total runoff volumes predicted to reach the streams by diffuse overland flow. During a 10-year event, only 45 of the 109 surveyed drains are predicted to deliver runoff to the streams,

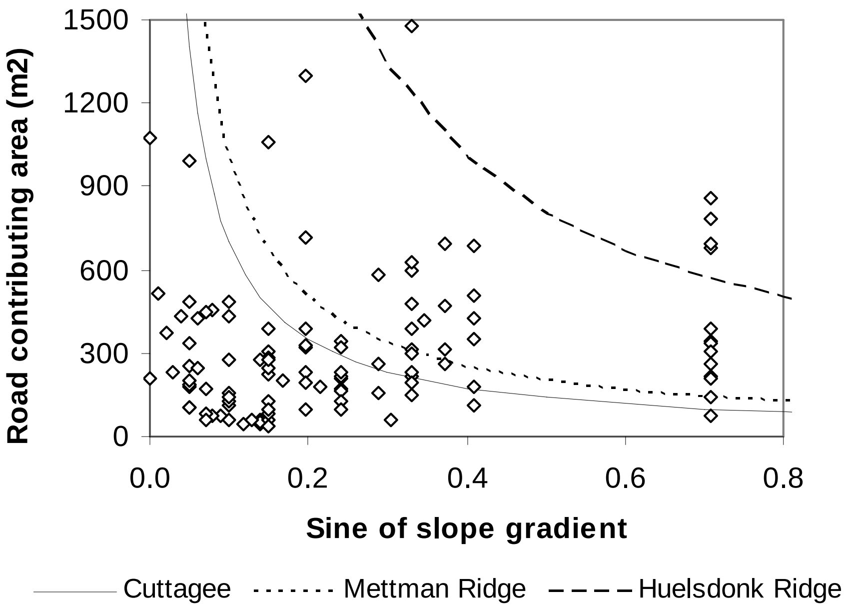

Fig. 1 Contributing road area *vs* discharge hillslope gradients for surveyed drains in the catchment. The lines represent thresholds for gully initiation found for the Cuttagee catchment in NSW (Croke & Mockler, 2001) and for Mettman Ridge and Huelsdonk Ridge in the USA (Montgomery, 1994).

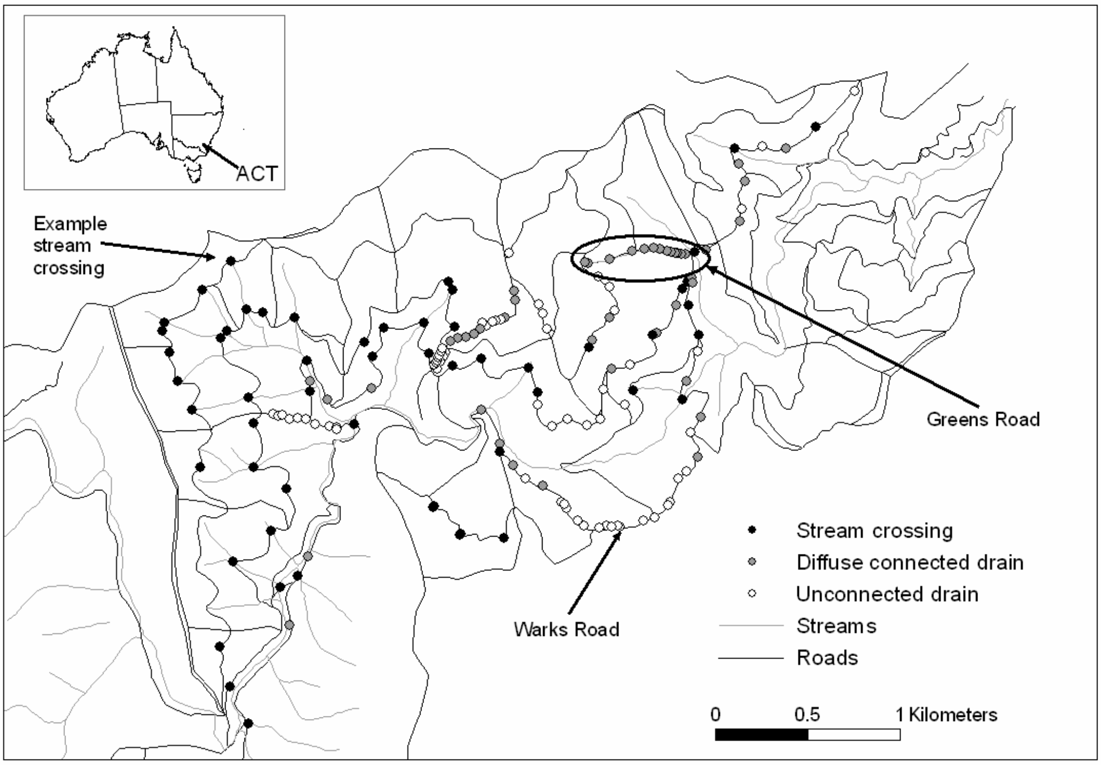

Fig. 2 The spatial distribution of drains at stream crossings, drains predicted to be connected through diffuse overland flow or to be unconnected during a 10-year event.

and even during a 100-year event only 58% of the surveyed drains are predicted to deliver any runoff. The spatial distribution of stream crossings and drains connected by diffuse overland flow shows that some parts of the road network are highly connected, such as along Greens Road, while there are relatively few connected drains along Warks Road (Fig. 2).

MANAGEMENT SCENARIOS

Road design and drain spacing determine the volume of runoff that discharges through a drain and can be manipulated by the placement of extra drains along the road. It is often unclear, however, how many additional drains are required to prevent connectivity. We can specify the *maximum* area that should be allowed to discharge to a particular drain to avoid runoff delivery through diffuse overland flow:

$$CA_{max} = D \cdot Vbt_5 \,/\, 5 \cdot 1000/((R - I) \cdot t) \qquad (3)$$

The number of drains required along the road segments presently discharging to the drains can be estimated on the assumption that the distance to the stream remains constant along the whole road segment:

$$\text{Number of drains} = CA/CA_{max} \qquad (4)$$

Using equation (4), we calculated the additional number of drains required to avoid runoff delivery to the streams during a 1 in 10-year event. There were 64 drains in the catchment that were not connected during a 10-year event and do not require any additional drains (Table 1). Of the remaining 45 drains, 21 could be rehabilitated with just one additional drain and another two drains would require two additional drains (Table 2). The placement of these 23 additional drains would reduce the runoff volume delivered by diffuse overland flow during a 10-year event by about 18%. Of note are the 16 drains that require >20 additional drains to limit diffuse connectivity (Table 2). These drains are located primarily along Greens Road, where the distance to stream is extremely short. This section of road contains 13 (12%) of the surveyed drains (excluding stream crossings), but contributes 106 m^3 of runoff through these drains, which is 39% of the total volume of runoff delivered by the total 109 surveyed drains. This illustrates that the drain spacing required along roads parallel and close to streams can be unrealistically short and that diffuse connectivity along valley-bottom roads is almost impossible to avoid. On the other hand, along roads that do not run parallel to a stream, the distance from the road to the stream will increase in an upward direction from the drain, which means that by assuming constant distance to the stream we over-predict the number of (additional) drains required. A more accurate estimate of the additional number of drains required can be made, if the distance to the stream and the maximum road contributing area is recalculated for each additional drain placed upwards from the existing drain. This methodology can also be applied to limit runoff delivery at stream crossings. We illustrate this here for the stream crossing highlighted in Fig. 3. Currently, 140 m of road length is draining to this crossing from the east and 225 m of road length from the west. With an average road width of 2.5 m, the contributing road area draining to this crossing is currently 912 m^2. For a 10-year

Table 1 Total volumes of runoff delivered to the streams (m^3) at surveyed stream crossings (n = 28) and drains with a connected diffuse delivery pathway during 2-, 10- and 100-year events.

Recurrence interval	Total volume stream crossings	Number of connected drains*	Total volume diffuse overland flow (m^3)
2-year event	181	25 (22.9%)	118
10-year event	334	45 (41.3%)	276
100-year event	606	63 (57.8%)	661

*Out of 109 surveyed drains (excl. stream crossings).

Table 2 Number of surveyed drains with diffuse flow pathways (first column) that require a particular number of additional drains (second column) to avoid runoff delivery during a 1 in 10-year event (e.g. 21 drains require one additional drain).

Number of drains	Number of additional drains
64	0
21	1
2	2
2	4
1	7
2	10
1	12
16	>20

event, 18 m^3 of runoff is discharged directly at this point. By installing five additional drains at the locations outlined in Fig. 3, the total contributing length draining to the stream would be reduced to 20 m, reducing the runoff volume discharged directly at the stream crossing to less than 1 m^3 or 5.5% of the original volume. This demonstrates that significant reductions in overland flow delivery can be achieved by

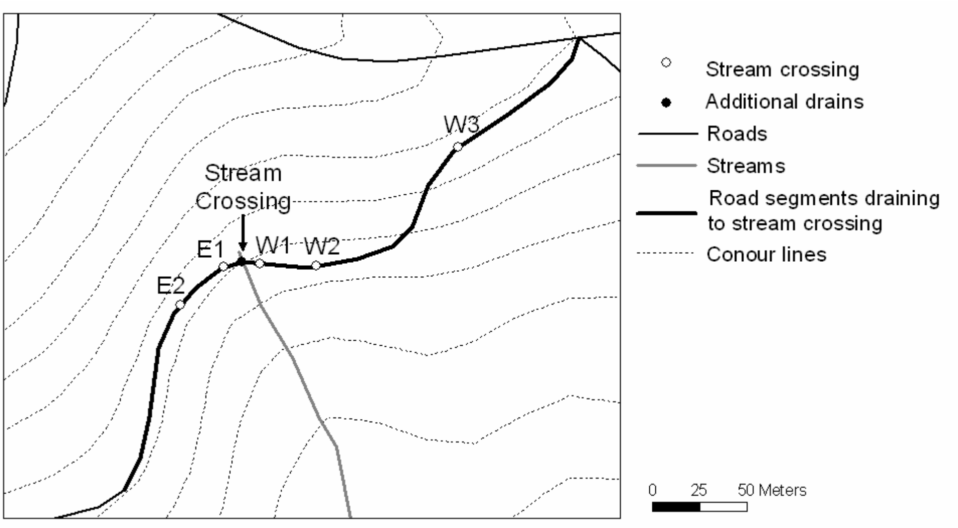

Fig. 3 Proposed location of five additional drains at the example stream crossing.

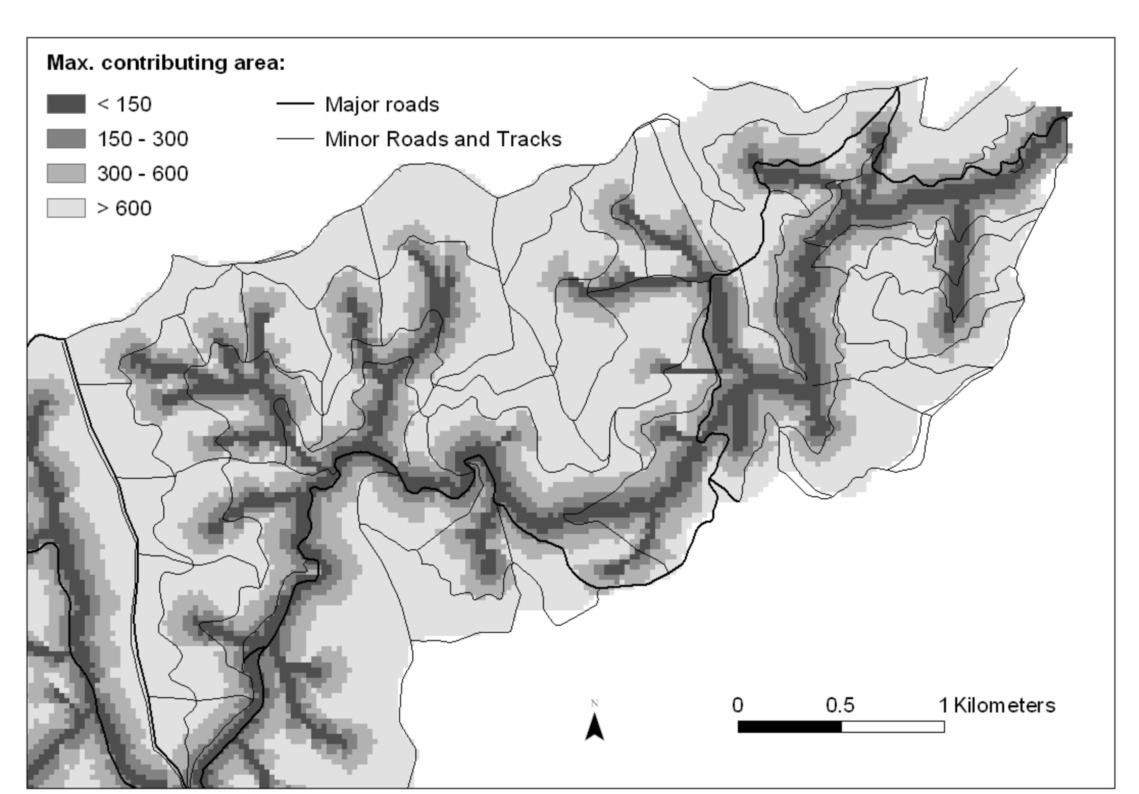

Fig. 4 Risk assessment map, showing maximum contributing road areas that should be allowed to avoid delivery of diffuse overland flow.

increasing the number of drains both upslope and downslope of existing stream crossings.

An alternative, though often costly, option for road management involves road relocation or removal. In many plantation areas, where road density has been recognized to be extreme, this represents the only viable option. As illustrated above, Greens Road is a highly connected road segment that would require an unrealistic number of additional drains to limit connectivity by diffuse overland flow. ACT Forests have committed to a management plan to reduce road density by 33% of its current value. To assist in this process, equation (3) is used to create a map showing the appropriate contributing road areas throughout the catchment by using a catchment map of flow distances to the streams as input to the equation (Fig. 4). The map shows that areas of greatest risk are essentially located closest to the stream, while areas best suitable for road construction are ridge tops, where relatively large drain spacings can be used.

DISCUSSION

The presented methodology is relatively simple and requires input data that are generally available or relatively easily obtained. In the case of connectivity via gullied pathways, contributing road area and hillslope gradient have previously been identified as the dominant variables. Likewise, we identified contributing road area and distance to the stream as the two most important factors affecting diffuse overland flow delivery. Using these two variables, the degree of connectivity of a road network can be expressed as a volume of runoff that may reach the stream. The calculated runoff volumes should be treated as estimates only, or can be considered an index for diffuse overland flow delivery. We recognize that the methodology has limitations, as for example we disregard variations in the volume to breakthrough that exist depending on characteristics of the hillslope below the drain outlet. In spite of recognized uncertainties, the framework allows relative differences in hydrological connectivity between different parts of the road network to be highlighted. This provides important and often unavailable information to forest managers, who could use the model to prioritize road rehabilitation or removal strategies based on predicted road segments with a high risk of runoff (and sediment) delivery to streams.

CONCLUSIONS

Hitherto, forest managers and environmental protection authorities have had little scientific guidance on how best to manage road runoff sources for pollution control. The proposed model is a first step in the use of hydrological connectivity as a framework to prioritize road segments that are a high risk and to provide some practical options for rehabilitation. The increasing use of Geographic Information Systems in forest management is also amenable to this methodology where major input variables can be calculated directly from appropriate digital elevation models and road inventory networks.

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