Hydrological and sedimentological connectivity of unsealed roads

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Abstract Unsealed roads are an important source of runoff and sediment and may affect the hydrology and water quality of streams. A recently-developed conceptual framework to model the hydrological connectivity between roads and streams in managed forest environments allows identification of the different types of delivery pathways and estimation of the runoff volumes delivered through them. While the model does not include sediment delivery explicitly, it is generally assumed that sedimentological connectivity can only be equal to, or smaller than hydrological connectivity. The objectives of this study are to quantify road runoff and sediment generation, and to investigate runoff and sediment travel distance below drain outlets. Preliminary field monitoring results show that roads in this catchment produce an order of magnitude more sediment compared to findings from other studies. Results from field experiments indicate that drains located within 40 m of the stream have very high probability of connecting to the stream during an event with a 10-year recurrence interval. The experimental results also indicate that the current modelling approach may over-predict connectivity, as observed flow losses down the hillslope were higher than would be predicted based on current model assumptions.

Key words overland flow; connectivity; modelling; bed load; suspended sediment; road drains; erosion

INTRODUCTION

Roads are linear features in the landscape that intersect, concentrate and redirect flow paths which can affect the hydrological response of the catchment (Wemple *et al.*, 2001). Moreover, sediment from unsurfaced roads can threaten water quality and in-stream ecology (Richardson, 1985). Sediment generation on road surfaces can vary by orders of magnitude—ranging from 70 mg/L (Reid & Dunne, 1984) to 130 000 mg/L (Croker *et al.*, 1993)—as a function of local variables such as road contributing area, road slope and traffic loads (Ramos-Scharron & MacDonald, 2005; Sheridan & Noske, 2007a), and regional factors such as geology and climate. Irrespective of the amount of sediment eroded from the road, it will only affect streams and biota if the eroded sediment is delivered to the stream. Two studies in southeast Australia showed that unsurfaced roads contributed between 4.5% (Sheridan & Noske, 2007b) and 39% (Motha *et al.*, 2003) of the total suspended sediment (TSS) load exported from forested catchments not susceptible to mass movements. It was argued that the range reflected the road position in the catchment (Sheridan & Noske, 2007b). The 4.5% contribution reported by Sheridan & Noske (2007b) equated to 50 ± 10 t of TSS per annum for a 134.5 km^2 catchment.

Takken *et al.* (2008) presented a modelling framework to assess road-to-stream hydrological connectivity. Herein, the estimates of runoff volumes delivered to streams through diffuse delivery pathways are calculated based on the Vbt5 model of Hairsine *et al.* (2002). This is a probabilistic model that uses the concept of the “volume to breakthrough”, which is the volume of runoff required to enter an area before discharge is observed at the downslope boundary of that area. Estimates of runoff volumes delivered to streams are made by conceptualising the hillslope as a series of 5-m long segments and sampling the probability density curve of the volume to breakthrough for 5 m (Vbt5) for each segment (Hairsine *et al.*, 2002). An assumption made within this model is that the volume to breakthrough includes all losses of overland flow, i.e. that once breakthrough at the downslope boundary of a segment occurs, there will be no further losses within that hillslope segment. The model has been applied to a number of forest catchments to assess the adequacy of road drainage and the degree of road-stream connectivity (Takken *et al.*, 2006, 2008), whereby it is argued that application of this methodology forms a conservative approach in terms of sediment delivery, as sedimentological connectivity can only be equal or smaller than hydrological connectivity.

The present study is conducted in the lower Cotter catchment, which is now part of the water supply catchment for Canberra, Australia. Major investments are being made to reduce catchment erosion, including major upgrades to road infrastructure. In this catchment we have started a study with the objectives first to quantify the runoff and sediment loads generated on local unsurfaced forest roads and compare these to similar studies within Australia, and secondly to investigate the travel distance of road runoff and sediment over the hillslope and to validate the underlying assumptions of the Vbt5 model. Preliminary results of this study are presented here.

STUDY AREA

The study area is in the Lower Cotter catchment, approximately 30 km west of Canberra in the Australian Capital Territory. The area was severely burnt in the 2003 Canberra bushfires and received lower than average rainfall from 2002 to 2007. Mean annual rainfall at Canberra airport is 619 mm, which is generally derived from summer storms and lower intensity winter rains. The lowest monthly mean minimum temperate is –0.1°C in July and the hottest monthly mean maximum is 27.9°C in January (B.O.M., 2008). Elevation varies from 580 m up to 940 m.

Prior to the 2003 fires, the Lower Cotter catchment was managed for softwood production, which required extensive unsurfaced road networks (~12 km/km^2, Takken *et al*., 2006). Since the fires, and due to drought and a growing population's water resource demands, the Lower Cotter catchment is being managed as a water supply area with native forest regeneration, road density reduction and road drainage being the key foci. The characteristics of the individual road segments studied are given in Table 1.

METHODS

The study comprises two components: (a) road runoff and erosion monitoring at drain outlets to determine volumes and loads exported from the road; and (b) a controlled experiment to measure dispersive overland flow and sediment plume characteristics below drain outlets.

Road runoff and erosion monitoring

Five road drain outlets were instrumented with monitoring equipment consisting of a bed-load trap to determine the volume of coarse sediment, a manifold overlying a tipping bucket (10–15 L) to measure discharge, and a split sampler and tank set adjacent to the tipping bucket to subsample

Table 1 Characteristics of monitoring sites.

Site /characteristic	R11	R12	R13	R14	R15
Road type	Cut & fill with table drain and culvert pipes	Cut & fill with table drain and culvert pipes	Cut & fill with table drain and culvert pipes	Box cut with rollover banks and mitres	4WD track with ruts intersecting bedrock
Wearing surface	Gravel/loam	Gravel subsoil	Gravel subsoil	Silty clay loam	Gravel/loam
Geology	Late Silurian rhyolithic volcanics	Late Ordovician metasediments	Late Ordovician metasediments	Late Ordovician metasediments	Late Ordovician metasediments
Average road slope (%)	7.5	7.0	7.7	26.7	32.4
Road contributing area (m^2)	468	86	270	498	412
Average weekly traffic (light vehicles)	130	12	12	7	5
Pre-fire land use	Native forest reserve	Pine plantation	Pine plantation	Pine plantation	Pine plantation

flow for TSS (Table 1). More details of the equipment used can be found in Sheridan & Noske, (2005). Rainfall was measured with eight raingauges located near the road plots. Measurements began in March 2007 and are still continuing. Here, we present data for the period from March to November 2007.

Pumping experiments

In February 2008, field experiments were performed at 43 sites along a 1.3-km length of road on which monitoring plot R11 is located. The sites included 10 existing drains and 33 sites that were selected objectively by application of the Vbt5 model. Hereto, the model was used to determine the best location for potential new drains by calculation of the maximum road length that should be allowed to contribute to a drain in order to prevent any runoff delivery to the stream during a 1-in-10-year rainfall event (Hairsine *et al*., 2002; Takken *et al*., 2008). These locations covered a range of hillslope steepness and surface roughness. At these sites, water was pumped down the hillslope to investigate dispersive overland flow and sediment transport distances. Two flow rates were applied; 3 L/s and 7 L/s. The flow rate of 3 L/s represents the predicted average flow rate through the existing drains during a 10-year event, and has also been applied in other dispersive overland flow studies in southeast Australia (e.g. Lane *et al*., 2006). The 7 L/s flow rate is more representative of short duration, peak flows observed at the monitoring sites. Experiments have been run for a maximum duration of 60 min for the 3L/s rate, and 30 min for the 7 L/s rate. However, if runoff connected to the stream within this time, the experiments were stopped soon after connection occurred. A quarry product called "blue metal dust" which matched the size range of eroded road sediment, but differed in colour to the road and hillslope soil material, was added to the 3 L/s flow at a rate of 6 kg/min based on monitoring data.

The hillslope below each (potential) drain outlet was divided into 5-m intervals between the outlet and stream for measuring flow arrival time. The coarse sediment plume lengths from the added blue metal dust were measured after each run. For comparison, the sediment plume lengths were normalised by the total volume of water.

RESULTS AND DISCUSSION

Road runoff and erosion monitoring

Fourteen rainfall events were recorded that produced road erosion between March and November 2007. Events 1, 2, 4 and 13 were short duration, highly erosive storms typical of summer rainfall (Fig. 1). Events 8 and 9 also produced high rainfall totals, but fell as low intensity rain typical of winter rainfall. The remaining smaller events were also low intensity events.

TSS concentrations were consistently higher at the two steep sites (R14, R15) compared to the gentler sloped sites (R11, R12 and R13) (Fig. 2(a)). Of these, R14, which was near the bottom of the hillslope with deeper soils, had higher TSS concentration than R15 further up the hillslope with shallow stony soils (μ_{R14} = 27.52 g/L, σ_{R14} = 24.29; μ_{R15} = 15.60 g/L, σ_{R15} = 23.81). The gentler sloped sites of R11, R12 and R13 had similar average surface slopes; however, R11 generally yielded higher TSS concentrations, which can most likely be attributed to the significantly higher traffic load (μ_{R11} =4.05 g/L, σ_{R11} = 4.45; μ_{R12} =2.39 g/L, σ_{R12} = 3.47; μ_{R13} =3.5 g/L, σ_{R13} = 4.26). Interestingly, values recorded for this study are an order of magnitude higher than those found by Sheridan & Noske (2005, 2007a), who used the same monitoring techniques for Victorian forest roads (μ_{ACT} = 10.5 g/L, σ_{ACT} = 17.8; μ_{VIC} = 1.2 g/L, σ_{VIC} = 1.4). While Sheridan & Noske (2005, 2007a) had a more constrained range of road slopes and included some two-lane gravel-surfaced roads, data for similar slopes and road types still indicate that roads in this study consistently yield higher TSS concentrations. This suggests that the geology and climate of this study region leads to more erodible road surfaces.

Bed load was also greatest for the two steepest sites, followed by the highly trafficked R11 site, then sites R13 and R12 (Fig. 2(b)). Event 13 values presented for R11, R13, and R14 and R15 are underestimates of bed load due the instrument's capacity being exceeded (R11, R13 and R14)

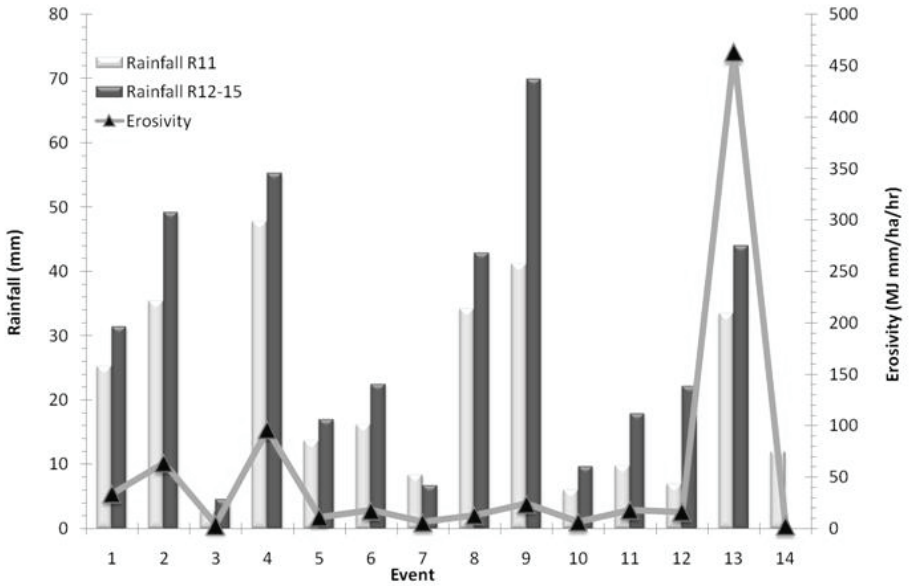

Fig. 1 Rainfall and erosivity for measured rain events between 20 March 2007 (event #1) and 26 November 2007 (event #14). Rainfall for sites 12, 13, 14 and 15 was similar and has been averaged; rainfall at site R11 has been consistently lower.

or failing (R15). The bed load yields show a clear effect of event erosivity with events 1, 2, 4 and 13 yielding high bed loads. Average bed load yield per event for the monitoring period was also an order of magnitude greater then reported for Victorian forest roads (μ_{ACT} = 26.8 kg/100m^2, σ_{ACT} = 53.6; μ_{VIC} = 0.7 kg/100 m^2, σ_{VIC} = 2.4) (Sheridan & Noske, 2005). For the Victorian roads, bed load comprised <10% of the eroded sediment, whereas, bed load in this study comprised up to 90% of the eroded sediment. As for TSS concentrations, the order of magnitude difference in bed load yields between the study regions may reflect the different geology and climate which lead to more erodible road surfaces in the ACT.

Pumping experiments

Flow paths and lengths for each experimental run are illustrated in Fig. 3. Collectively, 63% of sites connected with the stream, confirming the high degree of hydrological connectivity along this road. For drains located within 40 m of the stream, 88% connected, while no connection was observed for drains further than 50 m away from the stream. Flow path lengths for discharges of 3 L/s that ran for the full 60 min ranged from 10 to 44 m (n = 7). Path lengths for 7 L/s discharge that ran for the full 30 min ranged from 25 to 42 m (n = 9). These plume lengths are longer than previously reported distances of 15–20 m for southeast Australia (Croke *et al*., 1999; Hairsine *et al*., 2002; Lane *et al*., 2006).

The total volume of runoff added to the top of the hillslope at the time that the front of the plume arrived at 5 m distance below the outlet (i.e. the volume to breakthrough at 5 m; Vbt5) is on average 108 L (σ^2 = 5554) for the experiments with a flow rate of 3 L/s and 139 L (σ^2 = 5570) for a flow rate of 7 L/s. For existing drains, the mean Vbt5 (μ = 68.5 L) is significantly less compared to new drains (μ = 126 L) ($p < 0.001$). This is most likely a response to smoother pathways at existing drain outlets due to previous flows washing away leaf litter and depositing relatively smooth fans of bed load. These mean Vbt5 values are all lower than found in other studies; Hairsine *et al*. (2002) reported a mean Vbt5 of 336 L (σ^2 = 35 600) for the Eden Management Area of southeast New South Wales and Lane *et al.* (2006) found a mean Vbt5 of 543 L (σ^2 = 54 548) for the Upper Tyers catchment in Victoria. While more detailed analysis will be performed to look at the significance and causes of these differences, it seems to suggest that flow

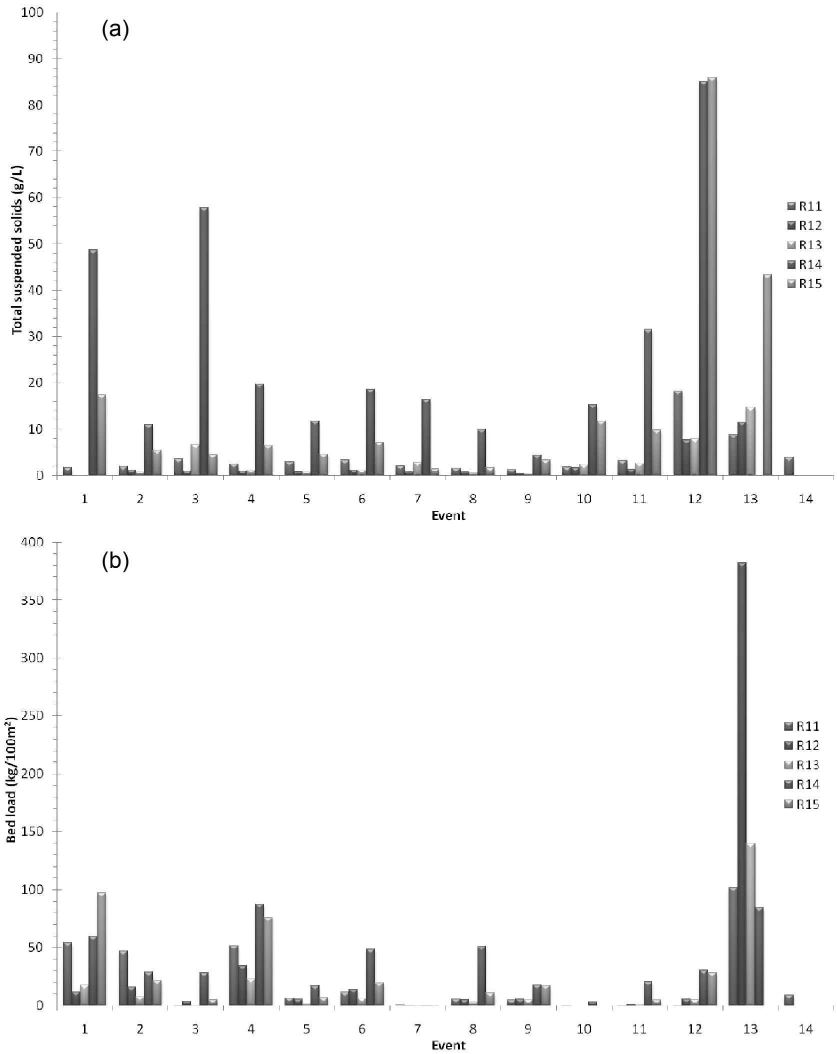

Fig. 2 (a) Total suspended sediment concentration and (b) bed load per 100 m^2 road contributing area for measured rain events between 20 March 2007 (event #1) and 26 November 2007 (event #14).

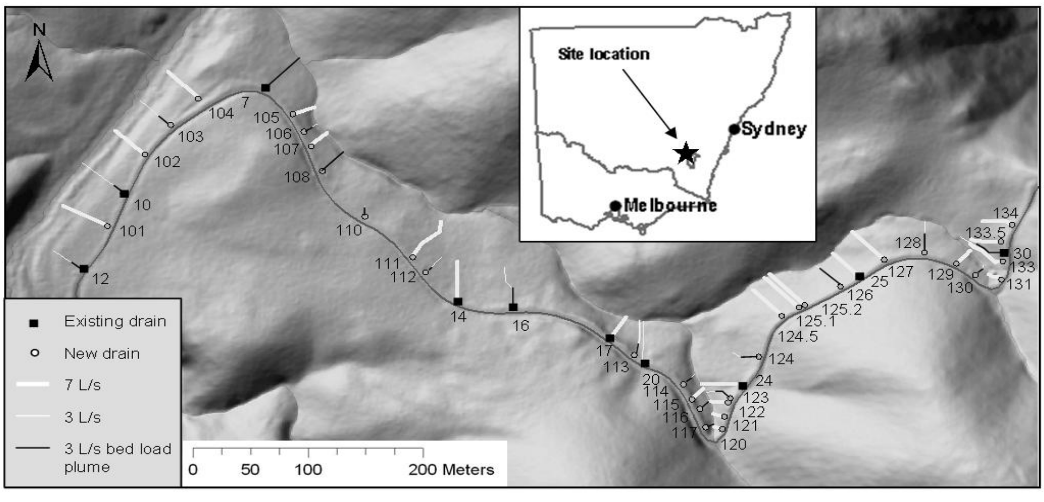

Fig. 3 DEM with Vanity's Crossing Road along which the pumping experiments were conducted. Site codes with approximate location of flow paths, lengths and bed load plume lengths are indicated.

loss through infiltration and depression storage is relatively small in this catchment. The effects of the 2003 fires could attribute to this, as soil cover by vegetation and litter seem still relatively sparse.

The volumes-to-breakthrough over longer distances downslope show both linear and non-linear trends with distance (Fig. 4). A linear trend confirms the Vbt5 model assumption that no significant flow losses occur within a 5-m long hillslope segment, after the front of the plume has reached the lower boundary of that segment, (so that on average Vbt10 would be twice Vbt5). The observed linear trends tend to be associated with shorter path lengths that connected with the stream. However, at most sites with longer connected path lengths, and at all sites that did not connect, the trends are not linear, but exponential. This result indicates that the above mentioned assumption of the Vbt5 model does not always hold true, in which case the model would over-predict the hydrological connectivity.

Previous investigations of Vbt5 and Vbt10 did not show a significant effect of slope gradient on the volume to breakthrough (Lane *et al*., 2006). While our data also show no correlation between slope and volume to breakthrough over a 5-m distance (Vbt5), the volumes of break-through over 15-m distance (Vbt15) were correlated with slope gradient for three of the four treatments, i.e. 3 L/s at new drains and 7 L/s at new and existing drains (Fig. 5). This indicates that over-prediction of hydrological connectivity is more likely to occur for relatively gentle slopes.

Field observations showed that in some cases subsurface flow through macropores reached the stream before the overland flow plumes. At site 10 (Fig. 3), subsurface flow via macropores, entered the stream 10 minutes before the surface flow. At site 30, only the subsurface flow reached the stream. Suspended sediment from the blue metal dust travelled as far as surface flow plumes, and was also observed at locations where the emergence of subsurface flow was noted. Bed load plumes reached the channel at four of the sites. For runs that lasted 60 min, bed load plume lengths ranged from 8 to 25 m in length, but for some shorter run times, bed load deposits were up to 49 m from the outlet when travelling along exiting flow paths. Bed load travel distances, standardised by total run volume, show that bed load plume length is a function of hillslope gradient (Fig. 6). Moreover, bed load plume lengths are longer for existing drains than for new drains, where the bed load filled in the abundant surface depressions formed by microtopography, leaf litter and woody debris before progressing down slope.

CONCLUSION

Globally, the issue of plantation and road network expansion is recognised as a significant contributor to land and water degradation. In many developing countries, road expansion alone may contribute to enhanced soil erosion and water pollution (e.g. Jungerius *et al*., 2002). Forest managers are faced with the practical challenges of addressing road location and design with respect to minimising water quality decline at a feasible cost. A modelling approach such as presented by Takken *et al*. (2008) provides catchment managers with an important tool that allows assessment of exiting road networks and can assist in road management and planning. Our monitoring and experimental results allow validation and parameterisation of the model, and from the preliminary results presented in this paper some interesting conclusions can already be drawn.

Firstly, the observed coarse and suspended sediment loads from roads in this catchment are significantly higher compared to previously reported values for other Australian catchments. The difference is most likely related to the high erodibility of the soils in this catchment and highlights a need to appropriately manage road runoff through road and drainage design. The volumes of break-through observed in this catchment are lower than reported for other regions and seem to reflect differences in soil surface roughness and/or infiltration characteristics. This may still be related to the 2003 bushfires and the subsequent drought, which may have resulted in relatively small/low surface roughness formed by litter and vegetation. Many of the experimental sites showed that there is no linear trend of volume to breakthrough values with distance downslope, and indicate that the assumption in the current Vbt5 model that the volume to breakthrough represents all flow

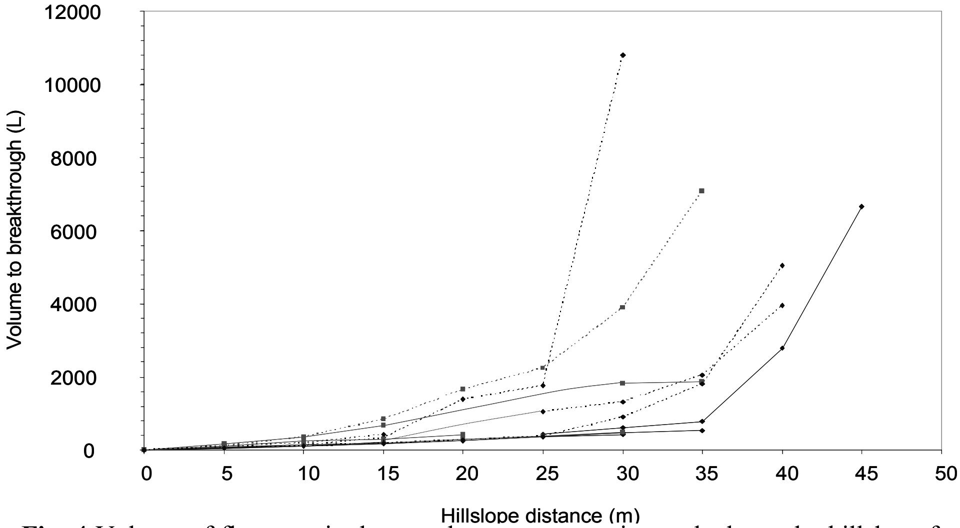

Fig. 4 Volume of flow required to reach measurement intervals down the hillslope for existing drains. Solid lines indicate flows that connect to streams and dotted lines indicate flows that did not connect.

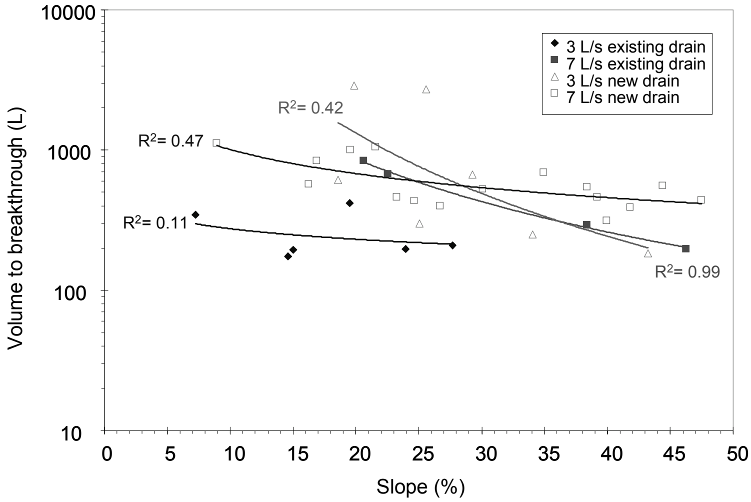

Fig. 5 Scatter plot of hillslope gradient against volume to breakthrough at the 15 m measurement station.

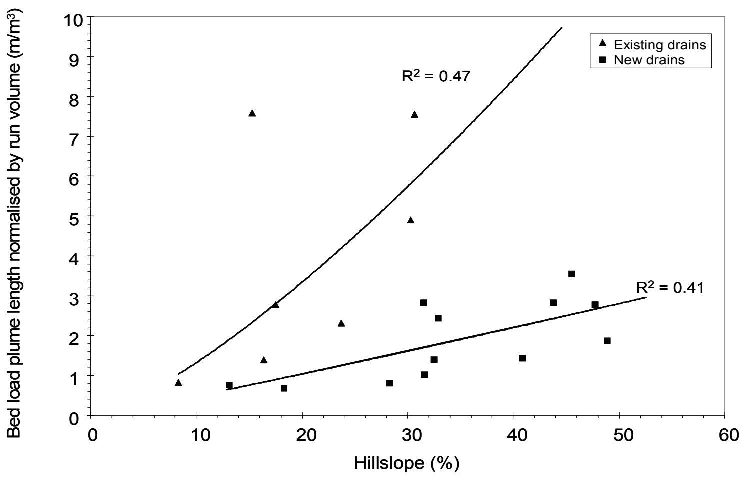

Fig. 6 Correlation between bed load plume length normalised by total run volume (i.e. run-time times discharge rate) and hillslope gradient.

losses, is not valid for these sites. As a result the model would over-predict connectivity for these sites. While the Vbt5 model has been (successfully) designed to make conservative predictions from a water quality management perspective, adjustment of the model to accommodate additional flow losses could improve predictions and may reduce the costs involved with implementation of the predicted best practises. Our experiments provide the first data that allow for assessment of sediment connectivity below a drain outlet and show a significant relationship between standardised bed load plume length and hillslope gradient. This study shows that for this region where a high proportion of the eroded road sediment is bed load, both TSS and bed load are connecting with the stream when roads are within 40 m of the stream. Further data analysis and experiments will be carried out to develop a sediment component for the road-to-stream connectivity model. This will improve the model's capability for more comprehensive cost-benefit analysis of road management options.

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