CSIRO PUBLISHING

Australian Journal of Soil Research

Volume 37, 1999

A journal for the publication of original research
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the Australian Academy of Science

Aust. J. Soil Res., 1999, **37**, 947–64

Sediment generation from forest roads: bed and eroded sediment size distributions, and runoff management strategies

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Abstract

A rainfall simulator and overland flow study was conducted to determine *in situ* and eroded sediment size distributions for a range of forest road surfaces at 2 important commercial plantation centres in subtropical south-east Queensland, Australia; and parameters necessary for running the CREAMS model to assess erosion and sediment transport from road/table drain systems.

Results revealed very low concentrations of fine particles in the surface of gravel roads, and somewhat higher proportions in ungravelled (dirt) road surfaces. However, there was considerable enrichment of fine particles in sediment eroded under simulated rain, with concentrations of particles $<0{\cdot}02$ mm in diameter being up to 8 g/L.

Table drains were generally resistant to scour by overland flows, with the only exception being a drain bordering a newly gravelled road. This drain was bare of vegetation and contained significant quantities of loose gravel from which the fine component was easily eroded. It demonstrated the need to construct both roads and table drains at the end of the wet season when consolidation and re-vegetation can occur under lighter rains during the dry season.

CREAMS model runs for a ‘standard’ road and drain configuration predicted considerable enrichment of fine particles in sediment from all road surfaces. The major factor controlling predicted concentrations of fine particles was the rate of erosion from the road surface, with gravelled surfaces showing considerably less erosion than ungravelled surfaces.

Because road surfaces will be significant sources of fine sediment during erosive rains, a second part of this study was designed to model whether hillslopes could be used to infiltrate runoff, thereby controlling sediment movement. For the modelled hillslopes—typical of those used to support commercial forest plantations in south-east Queensland—design runoffs from forest road turn-out drains could be infiltrated. It is suggested that forest managers use hillslope infiltration as the primary tool for managing flows and sediments from road turn-out drains, and that vegetative filter strips be used only as a secondary support tool.

Introduction

For much of a forest plantation rotation, forest roads represent the major area of bare soil and, therefore, have potential to be major long-term sources of sediment (Haydon *et al.* 1991; Coker and Fahey 1993; Costantini *et al.* 1997*a*). Control of sediment and runoff from roads is thus a major priority for sustainable management of forest plantation areas (Costantini *et al.* 1997*a*).

Management strategies used by the Department of Primary Industries in Queensland for controlling sediment pollution from forest roads include avoiding concentration of road runoff water wherever possible, and where unavoidable, designing a network of table drains to actively manage runoff. To restrict flows in table drains to non-erosive and non-flooding quantities, runoff water is emptied at

10.1071/SR98088 0004-9573/99/050947$10.00

prescribed intervals via turnout drains designed to decelerate runoff and discharge it onto hillslopes of vegetation or surface litter where sediment will be deposited rather than transported off-site.

In forests, there are 2 basic approaches to managing sediment entrained in road runoff exiting turnout drains: (*i*) use physical barriers such as settling ponds and vegetative filter strips (VFS) to slow runoff and facilitate deposition; and (*ii*) allow runoff to infiltrate into hillslopes. A complementary study (Loch *et al.* 1999) has shown that sediment trapping by VFS is strongly dependent on sediment size and settling velocity. Sediment fractions $>0\cdot125$ mm in diameter will settle out rapidly in VFS, but their effectiveness in removing sediment fractions in the range of $0\cdot05$–$0\cdot125$ mm is dependent on residence time, settling velocity, and flow depth. Sediment $<0\cdot05$ mm in diameter is relatively slow to settle, and is difficult to remove from runoff using the widths of filter strips commonly used in forest management to buffer water courses. This sediment size fraction will ideally be managed by spreading outflow from turnout drains as widely as possible across hillslopes, to reduce flow depths and enhance infiltration, which would further reduce flow rates and depths.

However, as there is currently no information on the sizes of sediment likely to be eroded from forest roads in south-east Queensland, it is difficult to judge the potential for movement of fine sediment to create problems for management of water quality. Such information is essential to enable a thorough assessment of alternatives for control of sediment in runoff.

This study had 2 components. The first was a study of erosion rates and size distributions of sediment eroded from forest roads in major south-east Queensland plantation areas, and of potential erosion of table drains. The second part of the study investigated the potential for hillslopes in south-east Queensland forest plantations to infiltrate concentrated runoff from forested road turnout drains. Computer simulations were used to consider the potential for infiltration of flows discharged onto hillslopes from side drains, and to evaluate current approaches to the control of sediment movements from roads.

Methods

Overview

The study of erosion from roads and table drains used rainfall simulation to generate runoff and erosion from road surfaces, and overland flow studies to assess table drain stability and sediment generation. The experimental data were used in deriving parameters for the CREAMS erosion model (Knisel 1980), so that erosion and sediment size could be predicted for a range of storms, and so that different road surfaces could be compared for standardised conditions. To provide the hydrologic inputs necessary so that the erosion component of the CREAMS model could be run for design storms, the KINCON model (Connolly and Barton 1990) was used to model road and table drain runoff. The combination of models was adopted because KINCON is ideally suited to prediction of runoff hydrographs for road/channel systems, and the erosion component of CREAMS is ideal for considerations of sediment transport, as it allows the user to input sediment size and density for a relatively large number of sediment classes.

Infiltration of concentrated flows into forested hillslopes was modelled using ANSWERS (Beasley *et al.* 1980). Being a distributed parameter model, ANSWERS considers spatial variation in infiltration and overland flow, making it ideally suited to consideration of downslope movement and infiltration of flows discharging from a table drain. Although there are many possible road/storm/antecedent soil conditions that might have been simulated, a limited number of combinations were simulated here to illustrate the potential for hillslope infiltration of runoff from road table drains in forest plantations.

Rainfall simulation studies on forest roads

The rainfall simulator used during the study was adapted from the design of Bubenzer and Meyer (1965). Simulated rainfall on plots 1·5 m wide by 4 m long was produced by flat fan Veejet 80100 nozzles mounted on an oscillating manifold. The rain had a kinetic energy approximating 29·5 $\mathrm{J/m^2}$.mm (Duncan 1972), a level similar to that of natural rain at intensities >40 mm/h (Rosewell 1986). Coefficients of variation for intensity across the simulation plots are <10%.

Rainfall simulator treatments

Locations and brief descriptions of the road surfaces studied are given in Table 1. Both Toolara (26°00′S, 152°83′E) and Imbil (26°46′S, 152°67′E) are located in subtropical south-east Queensland, Australia, in some 110 000 ha of *Pinus* spp. plantations and 45 000 ha of *Araucaria* spp. plantations, respectively. Detailed climatic, edaphic, and topographic descriptions are provided by Coaldrake (1961), Costantini *et al.* (1997*a*, 1997*b*), and Loch *et al.* (1999). In brief, Toolara is located in coastal lowlands where predominantly coarse-textured soils on flat–gently undulating slopes support *Pinus* plantations. Imbil is situated in steeper, broken country where predominantly fine-textured soils support *Araucaria* plantations. Both areas are exposed to high-intensity, runoff-generating storm events in most years.

Table 1. Locations and properties of rainfall simulator plots established on road surfaces

Plot	Location	Gradient (%)	Description
1	Toolara	5·80%	Sandy material on road base, approximately 50% cover by litter and grass
2	Toolara	5·10%	Sandy surface over hard road base, approximately 50% cover by litter and grass
3	Toolara	4·80%	Gravel road—areas of fine, loose gravel
4	Toolara	9·80%	Gravel road—some hard surface and some loose, coarse gravel
5*a*	Imbil	5·70%	Ungravelled, grass-free road, fine-textured surface material
5*b*	Imbil	5·70%	As above, wheeltracked wet, 10-min storm only
6	Imbil	12·45%	Gravel road, fine-textured gravel
7	Imbil	7·90%	Gravel road, fine-textured gravel

Study locations were selected to be representative of a range of road slopes and gravel types at both sites. Roads at Imbil were located in plantation areas that were being actively managed in the inter-rotation period—the period between clearfelling of one crop and control of the site by the next crop rotation, when road use and exposure is greatest.

Plot establishment and procedures

Rainfall simulator plots were established on surfaces so that their long axes were orientated in the downslope direction, which for non-level roads meant that plots did not follow the road centre line. Plot edging was placed on the road surface, fixed with pegs, and sealed with bentonite.

Three raingauges were set up on each plot to record rainfall intensity. Rain was applied to each plot at an intensity of approximately 100 mm/h for 20 min.

For each simulated storm, samples of sediment in runoff were taken on 6 occasions, starting 1 min after appreciable runoff was registered, with sampling times then being evenly spaced through to the conclusion of the run. At the second, fourth, and sixth samplings, duplicate sediment samples were taken for sediment size measurements. At the conclusion of the run, 2 surface soil samples were taken using a spatula following the technique of Loch (1994), and analysed to determine size distributions of bed sediment (sediment available for entrainment).

One plot (Plot 5) was wheeltracked following completion of the simulated rain application, to test whether vehicle traffic on wet roads could increase erosion rates. Immediately following simulated rainfall, plot edging was removed, and a utility vehicle reversed onto and off the plot. Once this was done, the plot edging was replaced, and 10 min later a further 10-min period of rainfall was applied, with the initial simulated rainfall application being denoted as

Plot 5*a*, and that after wheeltracking being denoted as Plot 5*b*. For Plot 5*b*, sediment in runoff was sampled 4 times, with duplicate samples at the second and fourth sampling times.

Overland flow studies

Lengths (10 m) of 2 table drains were selected at each location to investigate sediment generation from actively flowing table drains. Water was introduced to drains in a non-erosive manner by discharging initially onto a sheet of plastic, so that flow velocity from the supply hose was able to dissipate before water flowed onto the soil surface. A downslope outlet for the overland flow was installed, incorporating a pit to enable sampling of sediment in runoff, and a metal frame to provide flow constriction, and an overfall to facilitate sampling.

Flow rates of 2, 4, 6, and 8 L/s were applied, each for approximately 4 min. Flow depth and width were measured for each flow rate, and single samples of sediment in runoff were taken at 1, 2, and 4 min after establishment of each flow rate.

Laboratory analyses

For single runoff samples, total sediment was measured gravimetrically. For duplicate runoff samples, particles <0·05, <0·02, and <0·002 mm in diameter were measured by pipette sampling. Prior to pipette sampling, each sample was poured through a 0·125-mm sieve, to determine the proportion of sediment >0·125 mm.

Samples of the rain-wetted surface were washed through sieves 0·5, 0·25, and 0·125 mm, and the fractions on those sieves oven dried and weighed. Subsequently, pipette sampling was carried out on the material passing through the 0·125-mm sieve to determine the size classes (<0·05, <0·02, and <0·002 mm in diameter) as for runoff samples.

Overland flow studies generated samples for total sediment measurements only.

Derivation of CREAMS model parameters

For road surfaces, the erosion parameters for the CREAMS model (Knisel 1980) were derived by identifying combinations of parameters that predicted both the observed amounts of erosion, and the proportion of eroded sediment <0·05 mm in diameter from each plot or road surface type. Emphasis was given to the size class <0·05 mm because Loch *et al.* (1999) showed little deposition of that size fraction in short VFS. A hydrology pass file was created for each rainfall simulator plot. In calculating total and peak runoff, an infiltration rate of 5 mm/h throughout the storm was assumed. This rate was deliberately selected to be slightly greater than expected infiltration on the hard, compacted road surfaces, which on the basis of long-term infiltration data from forest roads in the USA would be in the range of 2–3 mm/h (Luce and Cundy 1994). Although the slight over-estimation of infiltration was low (<1·7 mm), it was intended to compensate for the initial loss associated with wetting of the loose layer of dry material on the road surface.

The version of the CREAMS model used allowed user input of sediment size and specific gravity classes. This feature was considered essential, as it enabled a relatively wide range of size classes to be considered, in this case, all with specific gravities of 2·6 g/cm^3, as material on the road surface was either coarse (gravel) or disaggregated by vehicle traffic.

Simulations of runoff and erosion from roads and table drains

Runoff and erosion were simulated using a combination of the KINCON model (Connolly and Barton 1990) to predict runoff, and the CREAMS model to predict erosion. This enabled comparison of the various surfaces for a standard set of conditions, and for design storms.

The KINCON model is an event-based runoff hydrograph/hydraulic model designed specifically to simulate runoff within and from contour bank/waterway systems. The model represents a plane (in this case, a road) discharging into a channel. Infiltration on the plane is simulated using a 2-layer Green Ampt infiltration model to determine rainfall excess through time during a rainfall event. The kinematic wave equations (Stephenson and Meadows 1986) are then solved to give a runoff hydrograph discharging into the channel. The kinematic wave equations are then applied to the channel, accumulating lateral inflow from the batter, to calculate a hydrograph at the channel outlet. The model inherently accounts for effects of travel time and of temporary surface storage.

Input data for the KINCON model were:

- 1 in 2 and 1 in 10 year rainfalls for the Toolara area for a 20-min period; average intensities in those time periods were 80 and 111 mm/h;
- rainfall intensity distributed across 4 time periods; a design hyetograph from Pilgrim (1987) was used to estimate time variation in rainfall intensity, with the resulting hyetographs shown in Fig. 1;
- 2-m width of road draining to the table drain, with side slope of 4%;
- road/drain length of 60 m (distance between turnout drains for a 6–7% slope);
- table drain gradient of 7%;
- hydraulic conductivity of the road set to 1·0 mm/h, consistent with measurements of Reid and Dunne (1984) and Luce and Cundy (1994).

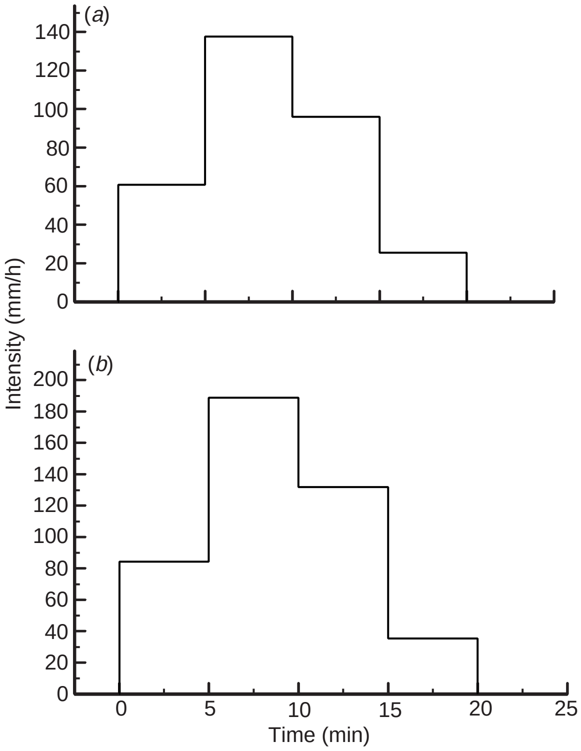

Fig. 1. Hyetographs for (*a*) 1 in 2 year storm, and (*b*) 1 in 10 year storm, both at Toolara.

Erosion modelling also needed rainfall erosivity information for the storms considered. To calculate erosivity, storm energy was estimated using the equation proposed by Rosewell (1986):

$$E = 0{\cdot}29[1 - 0{\cdot}596\mathrm{e}^{(-0\cdot04I)}]$$

where E is energy and I is intensity, both in SI units. Energy was calculated for each segment of the design storms, and then summed for the whole storm. Average intensity for the 20-min storm was substituted for I_{30} in estimating storm erosivity, and the erosivity values were converted to metric units for use in CREAMS.

Output from KINCON modelling was used to create a hydrology pass file for the erosion component of the CREAMS model, which was used to predict sediment detachment and transport from the same road/drain system for 1 in 2 and 1 in 10 year storm events. It was assumed that road runoff moved to the drain at a net gradient of 8%, with an effective flow length of 4 m.

Three road surfaces were modelled, each for both 1 in 2 and 1 in 10 year storm events: a coarse gravelled surface at Toolara represented by data for Plot 4; an ungravelled surface at Imbil (Plot 5); and a gravelled surface at Imbil (Plot 6). Parameters for the table drain were set so that no scour occurred in the drain. Bed sediment sizes were input from Table 4, with an assumption that all size classes had a specific gravity of 2·6 g/cm^3, as the material on the road surface was almost entirely disaggregated (by compaction and shear associated with vehicle traffic). All roads were assumed to be bare of vegetation.

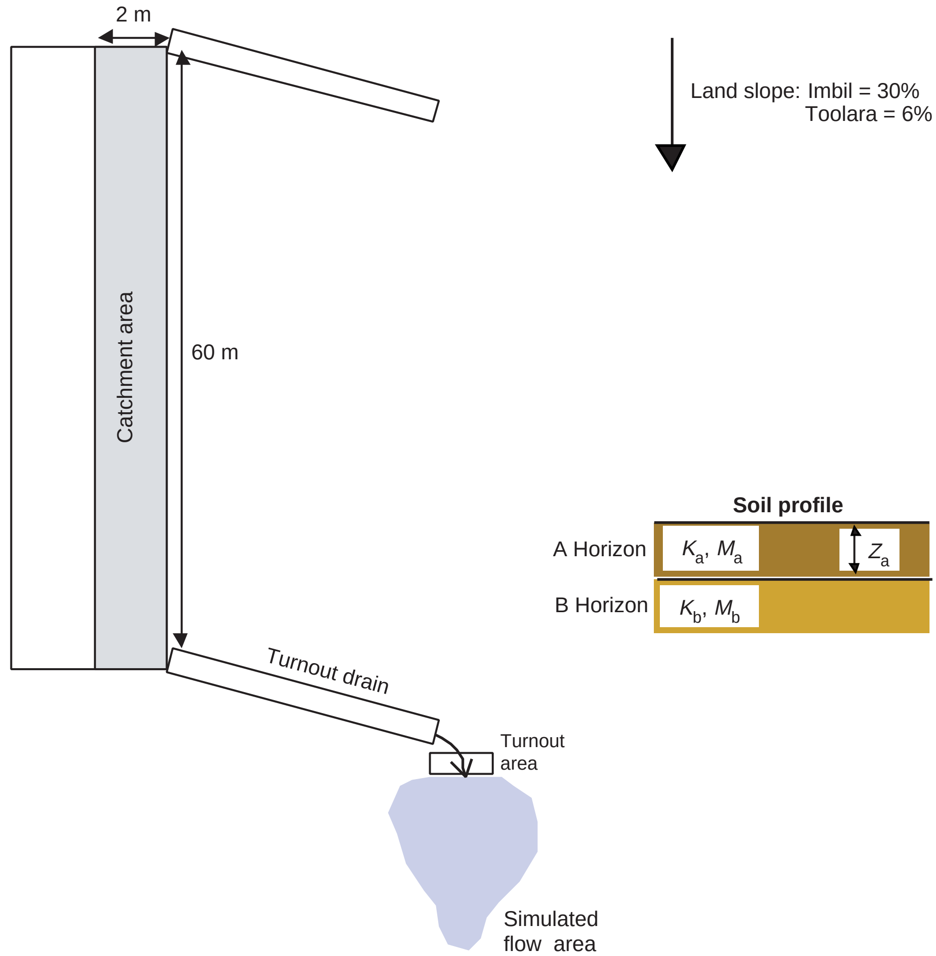

Fig. 2. Schematic layout of the road/turnout drain. *K* and *M* refer to hydraulic conductivity and volumetric moisture deficit respectively, with A and B horizon denoted by subscripts a and b, and *Z* denotes horizon depth.

Simulations of infiltration downslope of the discharge points from turnout drains

The simulations were designed to reproduce a subset of conditions likely in plantations at Imbil and Toolara in south-east Queensland. The road layout shown in Fig. 2 was simulated. Turnout drains were assumed to be spaced 60 m apart. With a contributing road width of 2 m, the modelled road catchment contributing to each turnout drain was 120 m^2. Slopes of receiving hillslopes at Imbil and Toolara were assumed to be 30% and 6%, respectively.

Runoff from a 20-min rainfall event with an average recurrence interval of 10 years was simulated (Fig. 1).

Runoff exiting each turnout drain was assumed to discharge onto an area 6 m across slope by 2 m downslope at the outlet of the turnout drain (the turnout area). From this turnout area, runoff was assumed to move downslope and was either allowed to spread to a maximum of 22 m during simulation, or not allowed to spread. Runoff was allowed to continue downslope until completely absorbed by the soil. (Flows spreading to a width of 22 m are somewhat uncommon, with some flows tending to spread initially and then concentrate again as they move downslope. The degree of flow spreading will depend greatly on hillslope vegetation.)

Rainfall in and downslope of the turnout area was ignored to simplify the analysis. This was necessary to avoid confounding effects of runon from an upstream catchment or turnout drains.

A modified version of ANSWERS (Beasley *et al*. 1980; Connolly *et al*. 1995) was used to simulate downslope flow of runoff from the 12-m^2 turnout area. ANSWERS is a hydrologic model which routes water across the soil surface, accounting for infiltration and surface roughness. Runoff is routed downslope as overland flow until it infiltrates. The version of ANSWERS used here has a Green and Ampt representation of infiltration.

Infiltration capacity of the soil was derived from rainfall simulator data taken in previous field studies at Toolara and Imbil (A. Costantini, Department of Primary Industries, unpubl. data). A summary of parameter values used is given in Table 2. Green and Ampt parameter values were derived for 2 surface soil conditions at Imbil: a normal inter-rotation hillslope condition (Costantini *et al*. 1997*b*) and a reduced infiltration condition corresponding to a compacted soil; and a normal inter-rotation hillslope surface soil condition at Toolara (Costantini *et al*. 1997*a*). Hydraulic conductivity of the A and B horizons was assumed to be identical, so the parameter Z_a was not used. Two antecedent soil moisture contents (medium wet and very wet), together with 2 levels of surface roughness (relatively smooth and very rough Manning's n) were simulated. A 2-m cell width, 20-s time increment, and 60-s infiltration increment were used during ANSWERS modelling.

Table 2. Green Ampt infiltration parameters and surface roughness values used in ANSWERS modelling

K denotes hydraulic conductivity, S denotes suction at the wetting front, and M denotes volumetric water deficit, with subscripts a and b denoting A and B horizons, respectively

Parameter	Toolara	Imbil
K_a (mm/h)	100	70 (normal) 30 (reduced)
K_b (mm/h)	100	70 (normal) 30 (reduced)
S_a (mm)	150	150
S_b (mm)	250	250
M_a (v/v)	0·15 (medium) 0·01 (very wet)	0·15 (medium) 0·01 (very wet)
M_b (v/v)	0·15 (medium) 0·01 (very wet)	0·15 (medium) 0·01 (very wet)
Manning's n	0·085 (smooth) 0·40 (rough)	0·085 (smooth) 0·40 (rough)

Results

Rainfall simulator studies on road surfaces

Erosion totals and average sediment concentrations for the plots studied are shown in Table 3. In general, concentrations of sediment in runoff decreased throughout the rainfall simulation interval by 25–50%.

The vegetative cover (litter and grass) on roads at Toolara (Plots 1 and 2) greatly reduced sediment concentrations and total soil loss from those plots. The highest sediment concentrations were recorded from the ungravelled road at Imbil (Plot 5*a*). Plot 5*b*, which was wheeltracked when wet, showed an increase in average sediment concentrations in runoff of approximately 29% relative to Plot 5*a*. However, this appears to be at least partly accounted for by the 19% higher rainfall intensity applied to Plot 5*b*. Considerably more deposition occurred in the collection gutter for Plot 5*b* than for Plot 5*a*, suggesting that one effect of the wheeltracking was to mobilise some coarser sediment size classes.

Size distributions of bed sediment (from the road surface) were relatively coarse, with quite low proportions of sediment <0·02 mm in diameter (Table 4). However, size distributions of sediment in runoff (Table 5) showed very high proportions of sediment <0·02 mm, from which it can be inferred that concentrations of sediment <0·02 mm were as high as 7–8 g/L for some plots. The enrichment of fine particles indicates that sediment transport from the road surfaces was extremely selective, which is to be expected for sites of relatively low gradient that are dominated by interrill transport.

Table 3. Overview of rainfall simulator data for forest roads

Plot	Intensity (mm/h)	Mean sediment concentration (g/L)	Erosion (t/ha)[A] for event applied
1	87·5	3·03	0·77
2	89·9	2·10	0·49
3	82·7	9·43	2·14
4	81·1	10·95	2·19
5*a*	91·5	12·43	3·17
5*b*	109·2	16·01	2·65[B]
6	83·5	7·20	1·64
7	83·5	8·35	1·91

[A] Erosion calculated per unit area of road surface.
[B] Erosion from a 10-min storm, whereas all other plots were subjected to a 20-min storm.

Table 4. Size distributions (% in each size class) of bed sediment on forest road surfaces

Plot	>0·5 mm	0·5–0·25 mm	0·25–0·125 mm	0·125–0·05 mm	0·05–0·02 mm	0·02–0·002 mm	<0·002 mm
1	24·39	35·94	24·88	9·75	2·91	1·71	0·41
2	25·63	32·18	24·74	13·77	2·29	1·06	0·33
3	46·52	23·34	15·98	7·48	4·60	1·92	0·17
4	64·30	15·48	10·14	5·79	2·24	1·82	0·22
5	45·48	12·02	9·33	12·37	3·87	10·96	5·98
6	69·05	8·66	6·41	5·56	3·96	5·00	1·36
7	59·96	12·36	8·53	5·88	4·12	6·72	2·42

CREAMS parameters for road surfaces

Parameters derived from rainfall simulator data are shown in Table 6. Manning's n for bare soil (n_{bov}) was kept constant at 0·01, and interrill erodibility (K_{i}) and Manning's n for covered surfaces (n_{cov}) varied so that both erosion amount and the proportion of sediment fractions <0·05 mm in diameter were predicted correctly. A 'C' (Cover) factor of 0·4 was used for Plots 1 and 2 to account for surface cover by litter and grass.

Parameter values (Table 6) were strongly linked to road surface condition. Higher Manning's n values were estimated for vegetated areas (Plots 1 and 2), and for most of the gravelled roads. For shallow flows, rock fragments on the surface of gravel roads would constitute considerable roughness compared with the smooth surface of an ungravelled road such as Plot 5. This is consistent with the CREAMS handbook which shows Manning's n values for stone mulch that are considerably higher than the default value of 0·01 for bare soil. The gravel road (Plot 3) for which a low value of n was estimated had areas of fine gravel and smooth hard road base, whereas the other gravel road at Toolara (Plot 4) had visibly coarser gravel on the surface, and a higher Manning's n value. Size distributions of sediment (Table 4) also indicate that the surface of Plot 3 was finer than that of Plot 4.

Table 5. Size distributions of sediment in runoff (% in each size class), 4-m-long rainfall simulator plots on forest roads

Plot	0·25–0·125 mm	0·125–0·05 mm	0·05–0·02 mm	<0·02 mm
1	7·40	2·00	2·00	88·60
2	12·61	2·00	4·00	81·39
3	24·59	2·00	22·00	51·41
4	26·18	2·00	2·00	69·82
5*a*	1·10	8·98	8·38	81·5[A]
5*b*	1·55	2·00	7·00	89·4[B]
6	2·61	2·00	11·03	84·36
7	11·05	2·00	7·00	79·95

[A] Sediment size estimates slightly in error as approximately 10% of total erosion was deposited in the collection gutter.

[B] Sediment size estimate considerably in error as approximately 38% of total sediment was deposited in the collection gutter.

Table 6. CREAMS parameters derived from rainfall simulator data for forest roads

Plot	K_i (interrill erodibility)	Manning's n (n_cov)
1	0·98	0·022
2	0·90	0·023
3	0·65	0·0125
4	0·75	0·022
5	0·30	0·0132
6	0·50	0·017
7	0·30	0·020

The roads at Toolara (Plots 1–4) had extremely high K_i values, indicating very high rates of detachment. This is consistent with the observed layer of loose, easily detached material present on Plots 1–4, overlying a hard, compacted surface. The 3 plots studied at Imbil had lower erodibility parameters, with variations between those plots probably reflecting differences in the amounts of loose, detached material on the road surface.

Erosion by overland flows

Overland flows in the 2 table drains tested at Toolara did not cause any scour, and resulted in no sediment movement at all. One drain had an average gradient of 2·8% with heavy cover of swamp grass and pine litter. The other had an average slope of 4·3% and 30–50% grass cover. Both these drains were well consolidated.

Overland flows in table drains at Imbil produced more variable results. One drain, with 25–30% vegetation cover on a 2·7% slope produced relatively low sediment concentrations (Fig. 3) mostly associated with movement of some fine material that had been deposited in the drain after being eroded from the road.

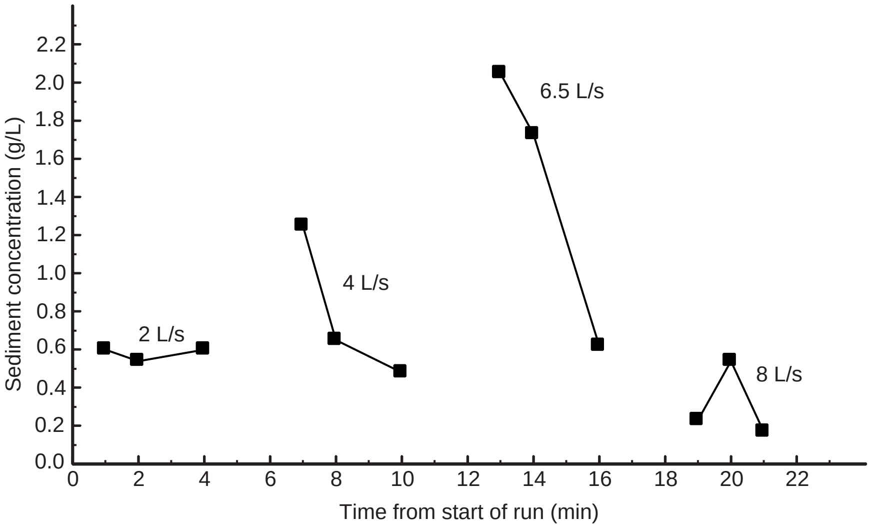

Fig. 3. Effects of overland flow rate and time on sediment concentrations in flow, for a table drain at Imbil with 25–30% vegetation cover.

The other drain at Imbil had a 10% slope, bordered a road that had been newly gravelled, and contained loose gravel overlying a rocky base. It had minimal vegetation cover. This latter drain eroded heavily (Fig. 4), although there was a steep decrease in sediment loads through time as fine materials were rapidly eroded from the gravel, leaving a coarser gravel pavement.

CREAMS model simulations

Results of the CREAMS simulations are shown in Tables 7 and 8. Predicted rates of erosion and concentrations of fine sediment were much higher from the ungravelled road than from the gravelled surfaces, illustrating the higher erosion potential of ungravelled surfaces. All surfaces were predicted to produce high proportions of fine sediment, with concentrations of fine sediment being largely controlled by rates of erosion. Sediment concentrations were predicted to increase with storm size, although the proportion of sediment $<0 \cdot 05$ mm in diameter present in runoff remained relatively constant.

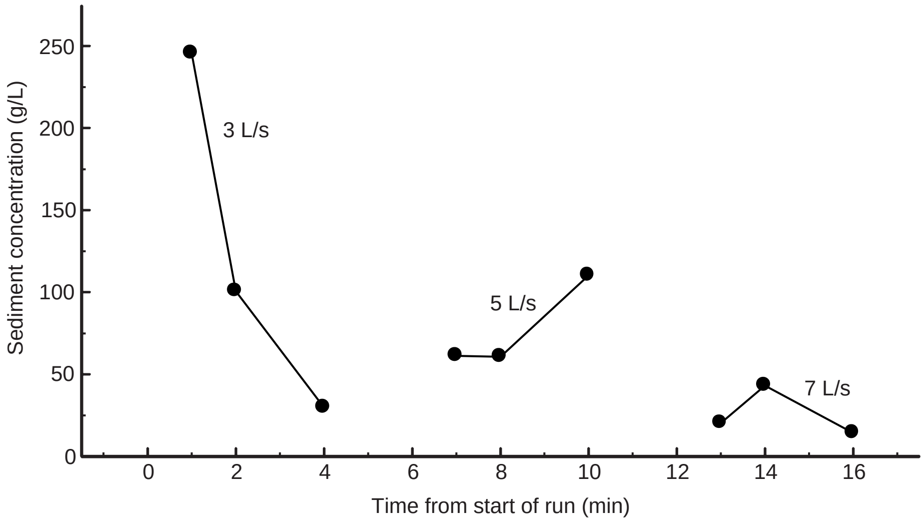

Fig. 4. Effects of overland flow rate and time on sediment concentrations in flow, for a table drain at Imbil containing loose soil overlying a rocky base.

Table 7. CREAMS model predictions for a 1 in 2 year storm on a range of forest road surface materials

Road surface	Total erosion (t/ha)[A]	Total sediment concentration (g/L)	Concentration of sediment $<0\cdot05$ mm in diameter (g/L)
Gravelled, Toolara	1·67	7·70	4·90
Ungravelled, Imbil	4·66	21·46	9·75
Gravelled, Imbil	0·92	4·22	4·07

[A] Units are t/ha of road surface.

Table 8. CREAMS model predictions for a 1 in 10 year storm on a range of forest road surface materials

Road surface	Total erosion (t/ha)	Total sediment concentration (g/L)	Concentration of sediment $<0\cdot05$ mm in diameter (g/L)
Gravelled, Toolara	3·25	10·1	6·47
Ungravelled, Imbil	8·6	25·8	12·87
Gravelled, Imbil	1·76	5·48	5·16

All road surfaces studied and modelled have the potential to produce significant concentrations of sediment $<0\cdot05$ mm (Tables 5, 7, 8).

Simulated infiltration downslope of the discharge points from turnout drains

Simulated runoff patterns downslope of the turnout area for various combinations of antecedent wetness, surface roughness, and degree of flow spreading are shown in Figs 5–8. Fingering in some of the predicted runoff patterns is a result of microtopography and degree of flow spreading simulated with the model.

At Toolara, the more flow was encouraged to spread, the shorter the distance it moved downslope. Flows moved 15–30 m downslope when allowed to spread (Fig. 5), and 40–55 m downslope when confined (Fig. 6).

The distance runoff moved downslope at Toolara was moderately sensitive to surface roughness, with rougher surfaces slightly reducing travel distances (Fig. 7). Runoff pattern was not sensitive to antecedent soil water, primarily because soil infiltration capacity is large even when the soil is very wet.

Runoff travel distances for Imbil were longer than those observed for Toolara due to the steeper slopes. Flows moved 20–40 m downslope when allowed to spread (Fig. 7), and 40–75 m downslope when confined (Fig. 8). Roughness was also more effective in reducing travel distance at Imbil because of the steeper slopes. This is particularly noticeable with the non-spreading flow, where a rough surface reduced downslope travel distance by almost half. As for Toolara, the runoff pattern was not sensitive to antecedent soil water due to the high inherent infiltration capacity of the soil.

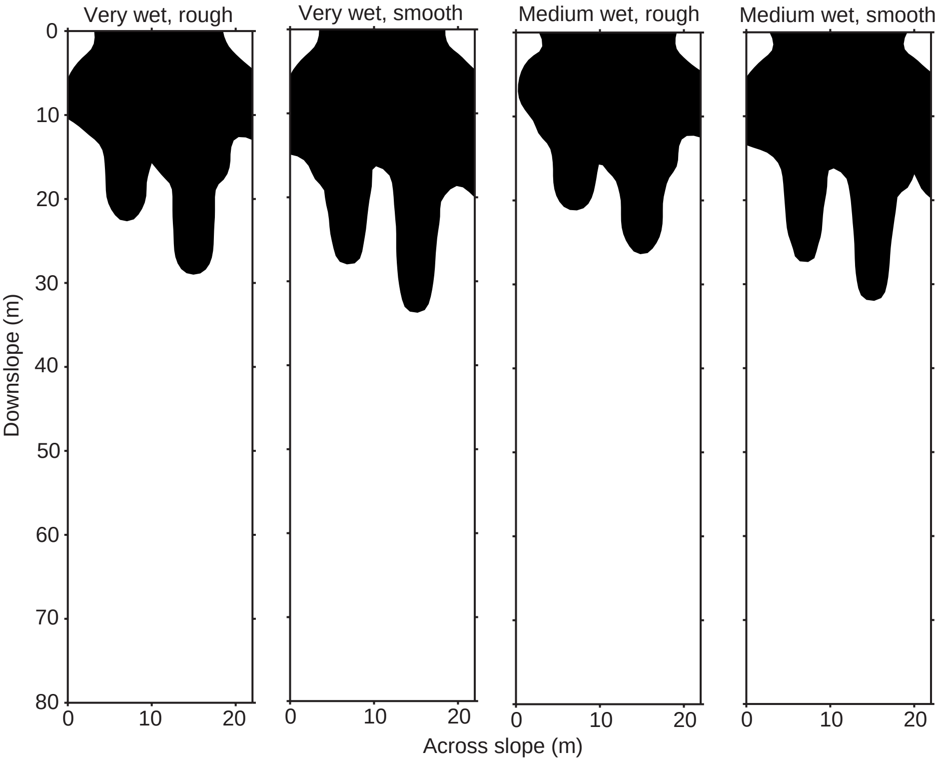

Fig. 5. Simulated runoff downslope of the turnout area at Toolara, with flow spreading.

Discussion

Sediment generation from roads and road drains

Consistent with studies by Bilby *et al.* (1989) and Coker *et al.* (1983), our data show that sediment produced from road surfaces has a high component of fine (suspended) particles. The constant disruption of surface particles by road traffic could be expected to provide a continuing source of fine particles. However, as shown by bed particle size distributions and by derivation of CREAMS parameters in this study, the high proportion of fine particles in eroded sediment is less a matter of supply than of the road surfaces operating as a high detachment/high deposition environment where selective transport is extremely high. This would be particularly the case where interrill erosion is the dominant process (as in this study) and surface roughness is high due to presence of gravel. It would be less so if rills develop in downslope ruts.

The relatively small measured effect of wheeltracking on sediment concentrations in this study can be attributed to both the low number of vehicle passes applied and the lack of any continued disturbance during rainfall. Coker *et al.* (1993) found effects of wheeltracking to be relatively short lived, but measured increases in erosion where plots had received 20 truck passes prior to application of simulated rain.

In contrast to road surfaces, erosion of properly designed table drains in south-east Queensland plantation areas is generally unlikely. Indeed, drains with a significant component of grass/vegetation cover have a high capacity to resist scour. The only drain that eroded in this study was both steep and in a freshly formed condition, suggesting that care is needed where road construction and maintenance operations result in significant quantities of loose soil and gravel being pushed into table drains. Ideally, these operations should be carried out at the end of the wet season, permitting time for loose material in the drains to consolidate and vegetate under light rain prior to the next wet season.

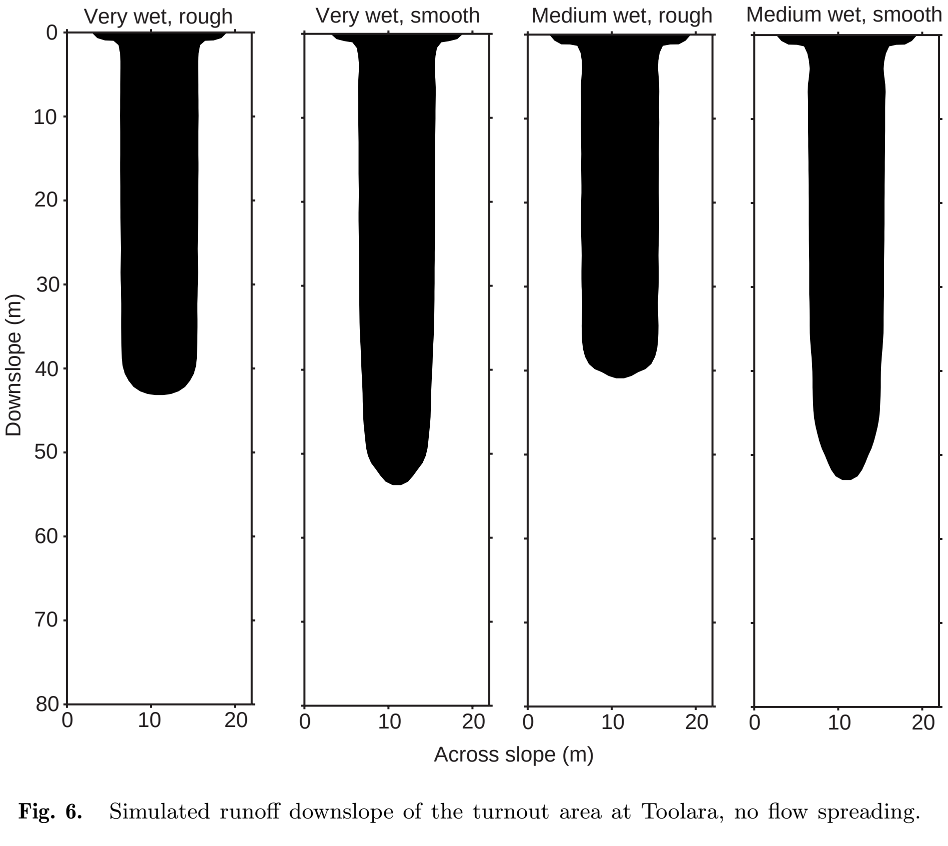

Fig. 6. Simulated runoff downslope of the turnout area at Toolara, no flow spreading.

Where large volumes of road runoff are allowed to discharge into either watercourses or their immediate environs, the levels of fine sediments reported in Tables 7 and 8 will threaten aquatic ecosystem values (see also Swift 1984; Bilby *et al.* 1989; Haydon *et al.* 1991), and potentially marine ecosystem values (see MacDonald *et al.* 1997). It is therefore necessary to avoid discharging large volumes of road runoff directly into watercourse systems.

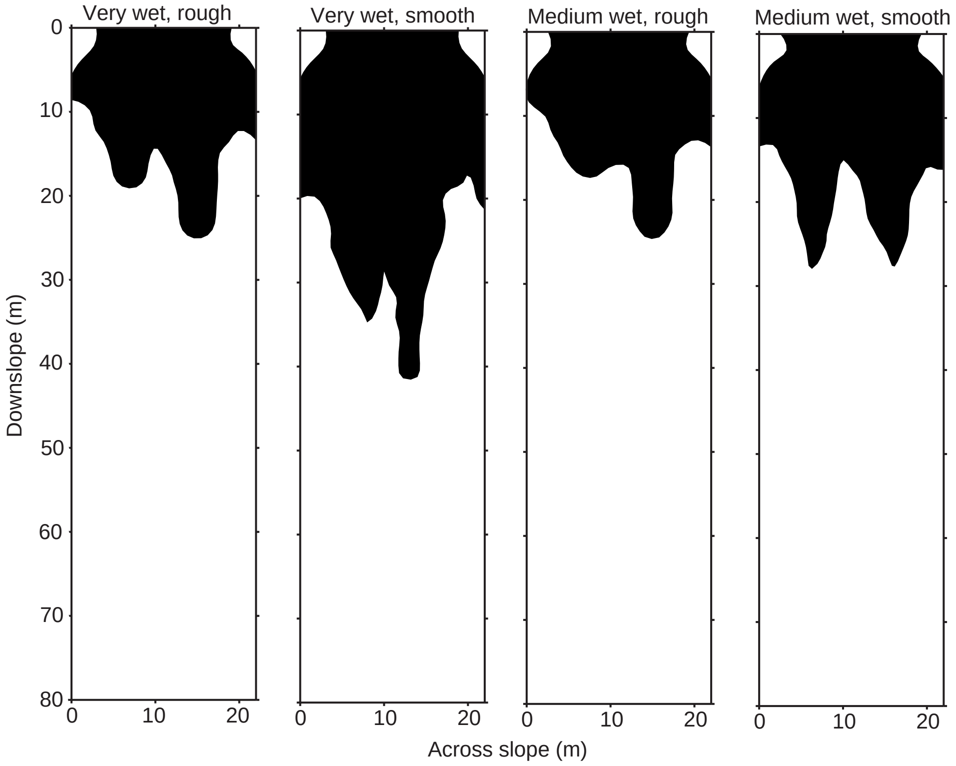

Fig. 7. Simulated runoff downslope of the turnout area at Imbil, with flow spreading.

Systems for avoiding sediment entrainment and concentration of road runoff water

With respect to the generation of sediment from forest roads, the key findings of our research for forest managers are: (*i*) sediment loads in runoff are directly proportional to road area generating runoff; (*ii*) road surface gravelling reduces sediment generation (Tables 7 and 8) (see also Swift 1984; Bilby *et al.* 1989); (*iii*) consolidated road drains produce less sediment than newly formed unconsolidated drains, (*iv*) grass regeneration on road surfaces reduces sediment production (Table 3); and (*v*) gravel type has a significant impact on the characteristics of generated sediment.

These findings reinforce well-known forest road design and maintenance practices, such as minimising road areas, avoiding the concentration of road runoff wherever possible, and stabilising road surfaces (see Anon. 1993). Our work indicates that forest roading could be further improved by:

- gravelling, regenerating, or consolidating (for example, by using road surface hardeners) sections of road that discharge directly into watercourse environs;
- timing maintenance and construction work during dry seasons;
- promoting rapid grass regeneration of tabledrains, for example, by leaving grass roots intact during maintenance and actively sowing grass in extremely sensitive areas.

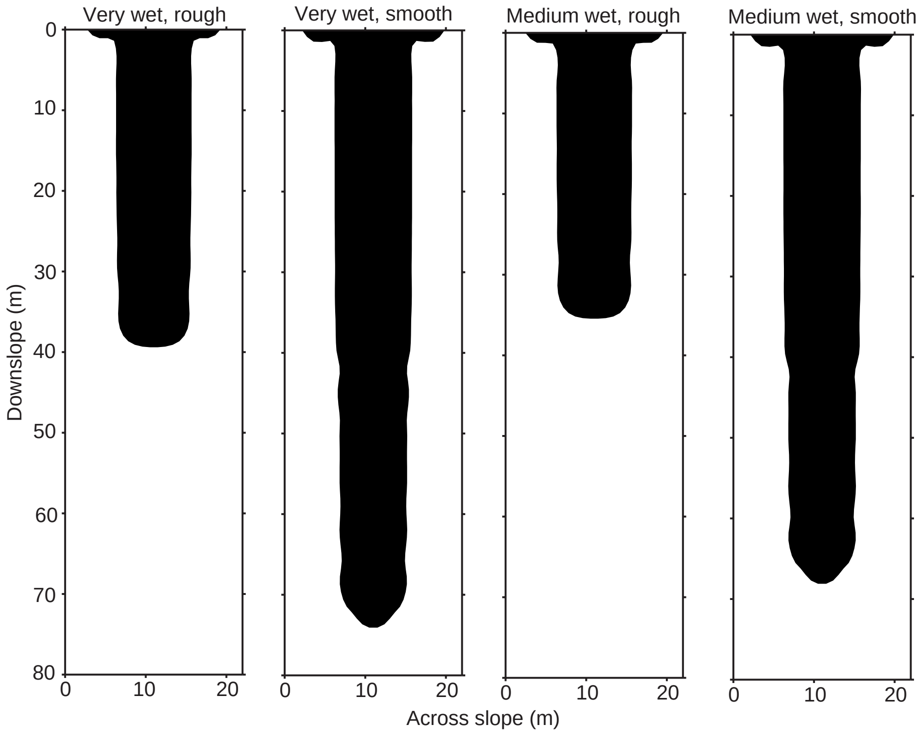

Fig. 8. Simulated runoff downslope of the turnout area at Imbil, without flow spreading.

The observed increase in sediment generation from newly formed drains has particular significance for upgrade and maintenance activities on roads that are poorly located, for example, by being too close to watercourse environs. In the authors' experience, these situations are common in older established plantations, where there is often pressure to realign and upgrade existing roads. If poorly located roads are stable in that surfaces have consolidated and/or re-vegetated and there is no evidence of table drain or road bank slump, they will ideally be managed without further destablisation. Typically, depending on safety needs, this will involve not widening and realigning the road, rather merely gravelling the surface and using vehicle control techniques, such as 1-way traffic flow and signage, to manage road use.

Using hillslopes to infiltrate runoff from turnout drains

A complementary study (Loch *et al.* 1999) has shown that standard design vegetation filter strips used in plantation forestry (Costantini *et al.* 1993), although effective in removing large sediment sizes from road runoff, were not effective at removing sediment fractions <0·05 mm in diameter. Settling ponds, and other engineered structures that pond runoff prior to its entry into watercourses, are also likely to be of limited utility in controlling fine sediment movement unless very long residence times can be designed.

From our research published here, and previously (Loch *et al.* 1999), we conclude that sediment-laden road runoff is best managed by hillslope infiltration, with vegetative filter strips only providing minor support. A requirement of this approach is that water be spread over a wide distance when it exits a table drain outlet. A problem with many forest drains is their concentrated outlets, with many ridge road drains having outlet widths of 1–2 m.

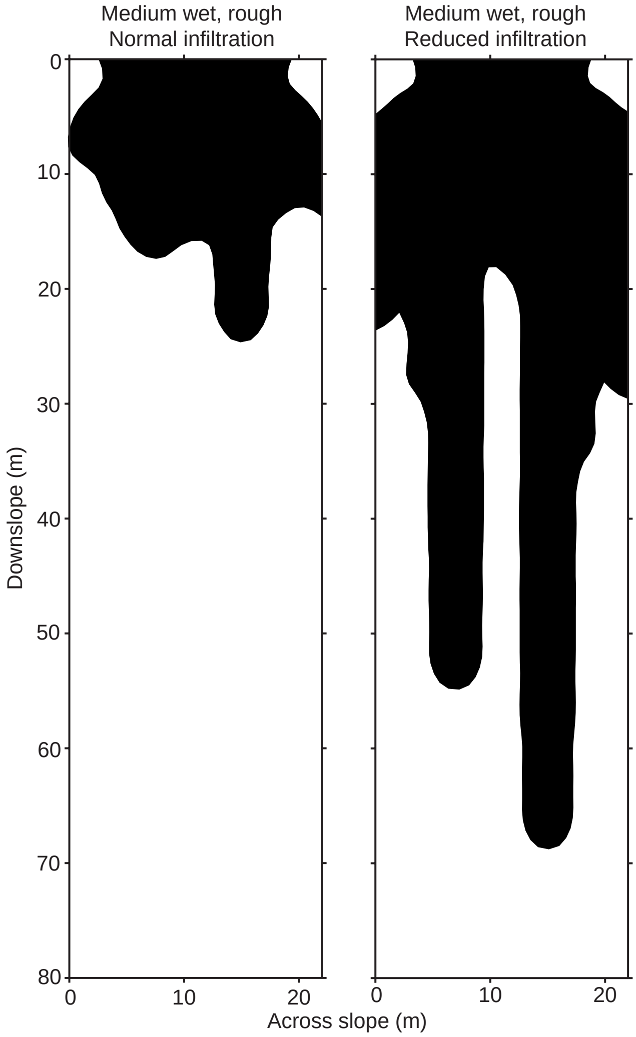

Fig. 9. Sensitivity of runoff distribution to a reduction in infiltration (Imbil, spreading flow, medium wet, rough, comparison of normal and reduced infiltration).

For the scenarios simulated here, only modest hillslope lengths, <40 m (Figs 5 and 7), were needed to absorb flows from forest road turnout drains. However, the wide range of scenarios that may contribute to the generation of runoff from road (particularly road width) or to the movement of runoff after leaving the turnout drain precludes the specification of more general guidelines. Further simulations would be advisable to identify critical hillslope lengths for infiltration of road drain flows in other situations.

For the conditions modelled in this study, road systems located >40 m from watercourse filter strips should, wherever possible, be drained onto hillslopes for infiltration, rather than being channelled to vegetative filter strips on the watercourse environs. Only short lengths of road surface approaching watercourse crossings, and those roads that approach watercourses through cuttings, should be drained into vegetative filter strips.

For hillslope infiltration to be effective, it is essential that turnout drain discharge areas be stable, have high infiltration capacities, and maximise the spread of flow. These can be achieved under normal forest plantation management by:

- constructing road systems prior to any forest operations that may destabilise hillslopes, such as compaction during harvesting (Fig. 9) and cultivation during site preparation;
- avoiding areas of unstable hillslope—including hillslopes where potential for landslips may be exacerbated by increased soil moisture contents;
- using residue retention practices (Costantini *et al.* 1997*a*, 1997*b*) during the inter-rotation period to maintain high roughness and high infiltration rates;
- designing turnout drains so that rather than discharge at a point, they discharge over a wide area of hillslope;
- strategically locating residue so that runoff spreads across the hillslope.

Although this study deals with managing sediments generated from forest roads, the results are likely to be similar for dirt and gravel roads in other parts of the rural landscapes.

Acknowledgments

Work reported in this paper formed part of the Queensland Department of Primary Industries, Forest Development Group work program. We thank Mr Keith Goodings for his supervision of the field rainfall simulation and overland flow study, and Mrs Irene Jacobsen for laboratory analyses.

References

Anon. (1993). ‘Unsealed Roads Manual: Guidelines to Good Practice.’ (Australian Road Research Limited: Victoria.)

Beasley, D. B., Huggins, L. F., and Monke, E. J. (1980). ANSWERS: a model for watershed planning. *Transactions of the ASAE* **23**, 938–44.

Bilby, R. E., Sullivan, K., and Duncan, S. H. (1989). The generation and fate of road-surface sediment in forested watersheds in southwestern Washington. *Forest Science* **35**, 453–68.

Bubenzer, G. D., and Meyer, L. D. (1965). Simulation of rainfall and soils for laboratory research. *Transactions of the ASAE* **8**, 73, 75.

Coaldrake, J. E. (1961). The ecosystem of the coastal lowlands (‘Wallum’) of southern Queensland. CSIRO Bulletin 283. 138 pp.

Coker, R. J., and Fahey, B. D. (1993). Road-related mass movement in weathered granite, Golden Downs and Motueka forests, New Zealand: A note. *Journal of Hydrology (NZ)* **31**, 65–9.

Coker, R. J., Fahey, B. D., and Payne, J. J. (1993). Fine sediment production from truck traffic, Queen Charlotte forest, Marlborough Sounds, New Zealand. *Journal of Hydrology (NZ)* **31**, 56–64.

Connolly, R. D., and Barton, N. (1990). 'KINCON Version 1 · 1. User's Manual.' (Soil Conservation Research Branch, Queensland Department of Primary Industries: Queensland.)

Connolly, R. D., and Silburn, D. M. (1995). Distributed parameter hydrology model (ANSWERS) applied to a range of catchment scales using rainfall simulator data. II. Application to spatially uniform catchments. *Journal of Hydrology* **172**, 105–25.

Connolly, R. D., Silburn, D. M., Rowland, P., and Barton, N. (1990). Improved evaluation and design of soil conservation structures using the runoff hydrograph model KINCON. *Australian Journal of Soil and Water Conservation* **3**, 270–4.

Costantini, A., Dawes, W., O'Loughlin, E., and Vertessy, R. (1993). Hoop pine plantation management in Queensland. I. Gully erosion hazard prediction and watercourse classification. *Australian Journal of Soil and Water Conservation* **6**, 35–9.

Costantini, A., Dunn, G. M., and Grimmett, J. L. (1997*a*). Towards sustainable management of forest plantations in south-east Queensland. II: Protection of soil and water values during second rotation *Pinus* plantation management. *Australian Forestry* **60**, 226–32.

Costantini, A., Grimmett, J. L., and Dunn, G. M. (1997*b*). Towards sustainable management of forest plantations in south-east Queensland. I: A review of logging and understorey residue management between rotations in steep country *Araucaria cunninghamii* plantations. *Australian Forestry* **60**, 218–25.

Duncan, M. J. (1972). The performance of a rainfall simulator and an investigation of plot hydrology. MAgrSc Thesis. Lincoln College, University of Canterbury, New Zealand.

Haydon, S. R., Jayasuriya, M. D. A., and O'Shaughnessy, P. J. (1991). The effect of vehicle use and road maintenance on erosion from unsealed roads in forests: The road 11 experiment. Melbourne Water Report MMBW-W-0018. 131 pp.

Knisel, W. G. (1980). CREAMS. A field scale model for chemicals, runoff and erosion from agricultural management systems. US Department of Agriculture, Conservation Research Report No. 26.

Loch, R. J. (1994). A method for measuring aggregate water stability of dryland soils with relevance to surface seal development. *Australian Journal of Soil Research* **32**, 687–700.

Loch, R. J., Espigares, T., Costantini, A., Garthe, R., and Bubb, K. (1999). Vegetative filter strips to control sediment movement in forest plantations: validation of a simple model using field data. *Australian Journal of Soil Research* **37**, 929–46.

Luce, C. H., and Cundy, T. W. (1994). Parameter derivation for a runoff model for forest roads. *Water Resources Research* **30**, 1057–69.

MacDonald, L. H., Anderson, D. M., and Dietrich, W. E. (1997). *Environmental Management* **21**, 851–63.

Pilgrim, D. H. (Ed.) (1987). 'Australian Rainfall and Runoff—A Guide to Flood Estimation.' Vol. 2. (The Institution of Engineers, Australia: Barton, ACT.) 159 pp.

Reid, L. M., and Dunne, T. (1984). Sediment production from forest road surfaces. *Water Resources Research* **20**, 1753–61.

Rosewell, C. J. (1986). Rainfall kinetic energy in eastern Australia. *Journal of Climate and Applied Meteorology* **25**, 1695–701.

Stephenson, D., and Meadows, M. E. (1986). Kinematic hydrology and modeling. *Advances in Water Science* **26**. 250 pp.

Swift, L. W. Jr (1984). Soil losses from roadbeds and cut and fill slopes in southern Appalachian Mountains. *Southern Journal of Applied Forestry* **8**, 209–16.

Manuscript received 9 September 1998, accepted 7 June 1999