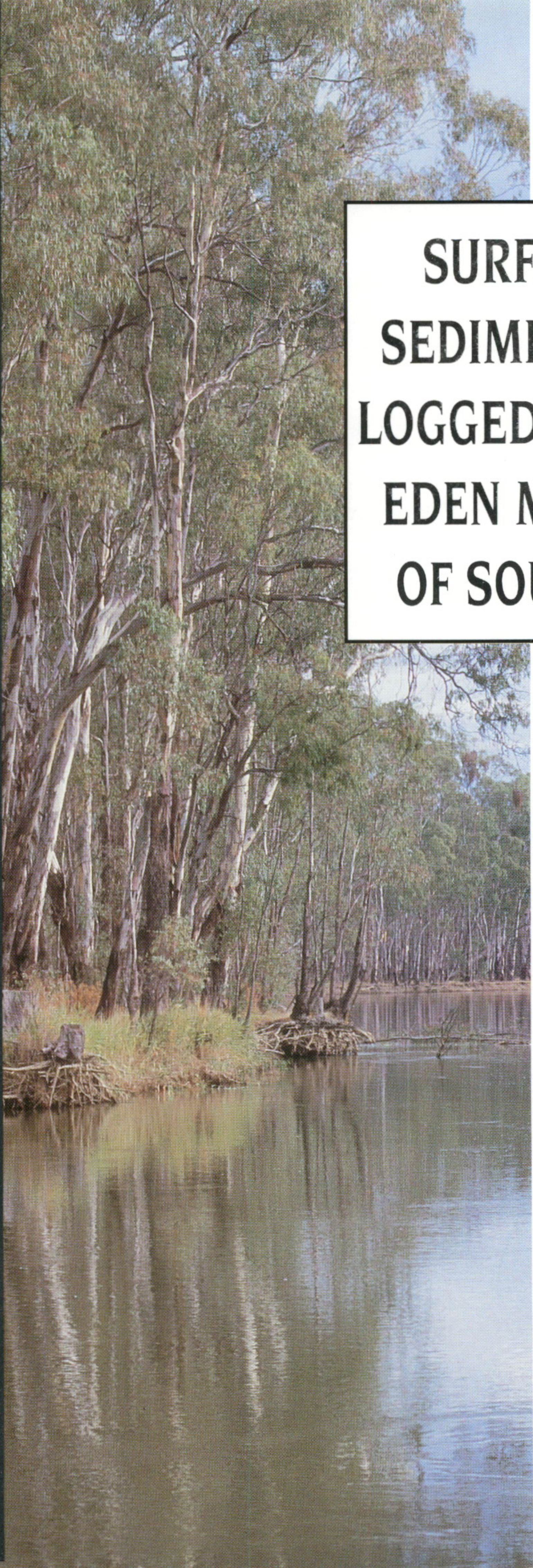

SURFACE RUNOFF AND SEDIMENT MOVEMENT ON LOGGED HILLSLOPES IN THE EDEN MANAGEMENT AREA OF SOUTH EASTERN NSW

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Soil (Types of)
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Infiltration

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PREFACE

The material in this report is a contribution to one of the core research projects in the Cooperative Research Centre for Catchment Hydrology (CRCCH), entitled "Sediment movement in forestry environments". The project aims to provide forest managers and environmental agencies with scientifically based guidelines for the protection of stream water quality.

An important facet of this work is to quantify rates of sediment movement in a variety of forest environments under a variety of forest management practices. Intensive field experiments are being conducted to achieve this aim. The aspect of the project reported here has involved input from CSIRO and the NSW Department of Land and Water Conservation.

This report summarises the application of a novel large scale rainfall simulator, developed by CSIRO, to forest sites managed by NSW State Forests. The results confirm the importance of compacted surfaces such as snig tracks as a major source of surface runoff and erosion in forest areas. Future CRCCH research will focus on improving the management of such sources in forestry environments.

Dr Rob Vertessy
Forestry Program Leader
Cooperative Research Centre for Catchment Hydrology

ABSTRACT

Timber harvesting activities can affect soil erosion and related water quality through the disturbance of catchment vegetation and soil. The basic parameters required to construct erosion hazard models, including relative erosion rates for different soil types, vegetation cover, and the degree of disturbance, are not available for most Australian catchments, particularly for forestry environments. This report investigates sediment and runoff generation on forested hillslopes within the Eden Management Area (EMA) of south eastern NSW using large scale rainfall simulator experiments. The experiments investigated a combined snig track and general harvest area system, where cross banks redirected runoff from the snig track into the general harvest area. Relative volumes of surface water and sediment from snig tracks and general harvesting areas are compared for three storm intensities, three soil types and three recovery periods since logging. The nature and extent of runoff and sediment re-distribution are also investigated.

These experiments confirm the importance of disturbed, compacted surfaces, such as snig tracks, as major sources of sediment and runoff in logged catchments. Snig tracks on recently logged sites generate, on average, seven times as much surface flow per unit area as general harvesting areas and, about 20 times more sediment, with maximum sediment yields in the order of 11 t/ha for a 1 in 100 year storm of 30 minute duration. General harvesting areas yield relatively small volumes of sediment and high infiltration rates predominate, with resultant patchy overland flow.

Highest on-site erosion rates were recorded on snig tracks developed on the granitic soils around Bombala in the west of the EMA, whilst those on the coastal Ordovician sediments produced relatively low erosion rates. However, these coastal sites actually delivered slightly higher sediment loads from the combined snig track and general harvest area. This is attributed primarily to their finer-grained texture and the sediments propensity to be transported further distances. Surface runoff and sediment yields decline over time so that within five years of logging, all three soil types behave similarly and yield little sediment. Cross banks were found to be effective measures to reduce sediment delivery rates to the general harvesting area, with between 40 and 90% of the eroded sediment being deposited at the base of the bank.

ACKNOWLEDGMENTS

Funding for this project was provided by the NSW Department of Land and Water Conservation (NSW DLaWC). The field experiments were conducted with the assistance of a great many people. We are particularly grateful to Merv Peden, Steve Dodds of NSW State Forests and Charlie Bell of the NSW DLaWC for providing us with harvesting plans and their knowledge of the logging history in the Eden Management Area. We are also grateful to Cathy Wilson for her contributions to the experimental design and use of the rainfall simulator equipment. The actual experiments required up to 14 people and included personnel from NSW DLaWC, the CSIRO Divisions of Water Resources and Soils and university vacation students. The following are gratefully thanked for their contributions: Rachel Butterworth, Neville Carrigy, Natasha Herron, Ian Prosser, Sue McIntyre, Nigel O'Shea, Colin Rosewell, Craig Smith, Tyron Venn, Deborah Weekes, Christoph Zierholz. We are particularly grateful to Rachel Butterworth for digitising the cover slides. We also thank Kent Rich for his assistance with the final production of this report. Ian Prosser and Eugene Wallensky are thanked for their helpful comments on the report.

1.0 INTRODUCTION

One of the most pressing problems in forest management today is the general lack of quantitative data that can be used to develop scientifically-based prescriptions for the environmental management of soil and water resources. Forest managers and environmental protection agencies are required to protect streams from increased sediment and nutrient delivery resulting from timber harvesting activities. In most states, practical guidelines for the protection of land and water resources are outlined in Codes of Forest Practices. Further regulation of forestry operations in NSW is provided by the Pollution Control Licence (1995) as administered by the NSW Environmental Protection Authority (EPA). The scientific rationale for these guidelines are subject to periodic review. However, the lack of quantitative data on the nature and scale of sediment and runoff generation in Australian catchments means that the predictive framework necessary to produce these guidelines is not readily available.

1.1 Background

The adverse effects of forest harvesting activities on soil and water values are commonly discussed in terms of on-site and off-site impacts. On-site impacts relate to soil erosion, compaction and the associated loss of nutrients within the general harvesting area (GHA) caused primarily by mechanical operations, road and track construction and poor vegetation cover as a result of fire, disturbance and nutrient depletion. The nature and severity of on-site disturbances have significant implications, not only for the land surfaces susceptibility to erosion, but also for future site productivity (Wert and Thomas, 1981; Lockaby and Virdine, 1984) and tree growth (Greacen and Sands, 1980; Incerti *et al.*, 1987; Farrish, 1990; Rab, 1992; King *et al.*, 1993). Off-site impacts refer to the potential for increased sediment and nutrient loads to enter the stream network and degrade the physical and biological qualities of streams. Numerous studies have identified increases in nutrient loads and suspended solids following clearing (Likens *et al.*, 1970; Brown and Krygier, 1971a, 1971b; Fredriksen, 1971; Fredriksen *et al.*, 1975; Graynoth, 1979; Martin and Pierce, 1980; Hewlett *et al.*, 1984; Cornish and Binns, 1987; Hopmans *et al.*, 1987; Olive and Rieger, 1987; Davies and Neilson, 1994). The specific impacts of both on-site and off-site disturbances are outlined in a number of scientific studies and government reports (see Campbell and Doeg, 1989 and Doeg and Koehn, 1990 for reviews; Cameron and Henderson, 1979; DWR, 1989; OCE, 1988; LCC, 1990; RAC, 1992).

Many studies, both in Australia and overseas, suggest that it is compacted surfaces, such as forest roads, that generate most surface runoff and sediment within a logged catchment (Megahan and Kidd, 1972; Kriek and O'Shaughnessy, 1975; Langford and O'Shaughnessy, 1980; Langford *et al.*, 1982; Reid and Dunne, 1984; Anderson and Potts, 1987; Haydon *et al.*, 1991; Grayson *et al.*, 1993). In hydrological terms, compacted surfaces intercept surface and subsurface flow and re-direct it along the road and track network within the catchment. Where these flow paths connect with the drainage lines, enhanced sediment and nutrient delivery to the stream network is inevitable. The hydrological impacts of logging within the general harvesting area are perceived to be less dramatic, where reductions in permeability are reported to only be about one-third those on mechanically compacted surfaces (Johnson and Beschta, 1980, Huang, *et al.*, 1996) and the degree of soil and vegetation disturbance is less severe. In terms of sediment production, the significance of roads and tracks as the major source of sediment in forestry environments has been outlined in a number of studies (Kreik and O'Shaughnessy 1975; Langford and O'Shaughnessy, 1980; Langford *et al.* 1982; Reid and Dunne, 1984; Davies and Neilson 1993). Grayson *et al.*, (1993), for example, found that the annual sediment production from forest roads was in the range of 50-90 t/ha of road surface per year. However, data on the relative contributions of snig tracks and general harvesting areas, in terms of runoff and sediment production are lacking.

Many forest planning agencies and research organisations perceive the need for erosion hazard models which are capable of evaluating the impact of forest management practices on soil and water values at the catchment, or even regional scale. The use of empirical or physically-based models as predictive tools for erosion hazard mapping is often hampered by the complexity of runoff and sediment re-distribution patterns in logged catchments. In addition to natural variations in soil hydraulic properties and vegetation, there are also water pollution control measures that re-route discharge and promote sediment deposition. Cross banks constructed at regular intervals on snig tracks are designed to reduce flow velocities and divert excess runoff onto vegetated areas. There are few studies where the nature and scale of runoff and sediment re-distribution has been investigated. These data are essential, however, for the meaningful application of many erosion prediction models. One of the major limitations of the widely used Universal Soil Loss Equation (USLE; Wischmeier and Smith, 1978), for example, is its inability to predict sediment deposition and the implications for this in terms of accurately predicting sediment yield.

Thus, while in general terms it is known that forest activities can affect water quality through the disturbance of catchment vegetation and soil, there are scant data available on the relationship between timber harvesting activities and environmental parameters such as soil erosion rates, in-stream water quality and biota. The basic parameters required to construct erosion hazard models, such as relative erosion rates for different soil types, vegetation cover and degree of disturbance, are not widely available for Australian catchments. The potential usefulness of existing studies for constructing general prescriptions on a state wide or even regional scale is limited by the fact that specific impacts will be influenced by the type of soil, topography, climate and the quality of management practices present in any given catchment.

Further cause for concern is the accuracy and suitability of the water quality indicators used in many studies and the short duration over which monitoring was conducted (Doeg and Koehn, 1990). In particular, many studies report the difficulty of linking high, on-site erosion rates with relatively low in-stream water quality indicators such as turbidity. This is largely a function of the complexity of sediment re-distribution within the catchment where sediment delivery rates vary according to changes in soil type, vegetation, and the quality of management practices employed, including placement of buffer strips and road drainage structures. Sediments remain stored for considerable periods of time in adjacent areas and may not enter the river systems during the period of in-stream water quality monitoring, which in many studies is often quite short. Likewise, there are a number of studies which found increased suspended loads in the river immediately after logging but few can identify the source of this sediment directly, and in particular, whether it has been derived from hillslope or in-channel sources. Increases in the magnitude and/or frequency of runoff events following clearing may be sufficient in some catchments to cause enhanced bank erosion, contributing to the increased sediment load recorded. Experimental work currently underway in CSIRO Land and Water is investigating the potential for radio-nuclide tracers, such as caesium and lead (Pb 210) to identify the relative importance of a range of sediment sources within a logged catchment.

1.2 The Project

A joint research project between the CRC for Catchment Hydrology and the NSW Department of Land and Water Conservation (NSW DLaWC) was initiated in July 1995 to investigate sediment and runoff production and re-distribution on forest hillslopes. The overall aim of the project was to examine the impact of forest practices on surface runoff and erosion rates across a range of soil types and on forest compartments of varying age since logging. The specific objectives of the experiments were:

- to measure sediment and runoff generation on forest snig tracks and general harvesting areas for a range of storm intensities;
- to examine the relationship between runoff and sediment yield, soil type and time since logging;
- to measure the extent of nutrient movement associated with soil and vegetation disturbance;
- to quantify runoff and sediment re-distribution; and
- to examine the effectiveness of cross banks for controlling sediment delivery rates to the general harvesting area.

The purpose of this report is firstly, to describe the nature of the rainfall simulator experiments and secondly, to summarise the major findings of this work in terms of runoff and sediment generation and their interaction with soil type, rainfall intensity and time since logging. The nutrient data are not reported here. These results form the early stages of our analyses and more detailed consideration of certain aspects will appear in later publications.

2.0 STUDY AREA

Nine sites were selected in the Eden Management Area (EMA in Fig. 1) of south eastern NSW, an area of approximately 7,800 km^2 from Bombala and Nimitabel in the west to Bermagui and Eden along the coast comprising of State Forest and other Crown-timber lands (Fig. 1). Six of the sites lie on the edge of the Southern Tablelands near the town of Bombala (Fig. 1). The remaining three are located on the coastal lowlands between Tathra and Bermagui (Fig. 1). Elevation lies between 680 m ASL (above sea level) in the west and <130 m ASL along the coast, while local relief is of the order of 100 m. Experiments were conducted on sites with a mean slope of 15^0, which was regarded as a modal slope for logging operations within the EMA.

Mean annual rainfall in the EMA ranges from 650 mm in the west to 900 mm along the coast. The summer months (December-March) are generally wetter than winter months, but intense rainfall and thunderstorm activity is common from September to mid-January.

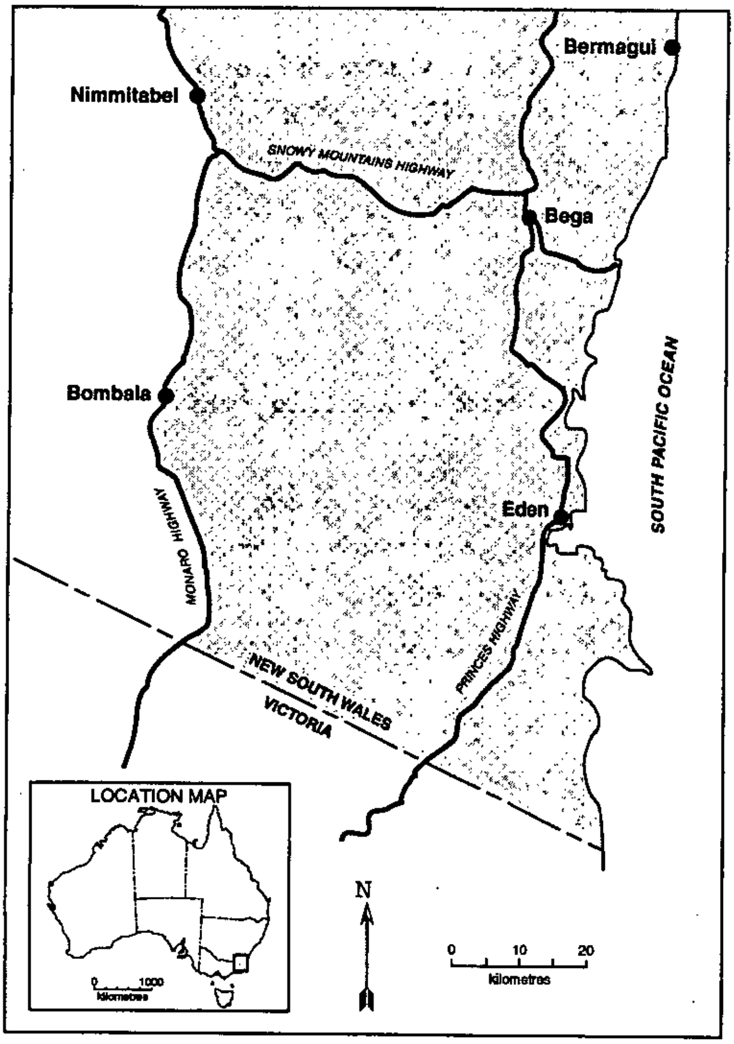

Figure 1. Location of the Eden Management Area in south eastern NSW.

Integrated harvesting of native eucalypt as well as pine plantation (*Pinus Radiata*) forests for both woodchip and sawlog production typifies the regions forestry operations. Silvertop Ash (*Eucalyptus sieberi*) was the dominant species before logging on each of the sites, with associated canopy species of Grey Gum (*E. cypellocarpa*), Brown Barrel (*E. fastigata*) and Stringy Bark (*E. obliqua.*). Following logging, middle storey re-growth vegetation consisted primarily of Blanket Bush (*Bedfordia arborescens*), Musk Daisy Bush (*Olearia argophylla*) and tree fern (*Cyathea australis*). Undergrowth vegetation at the time of the experiments was generally open but included pockets of dense *Daviesia sp, Allocasuarina sp, Acacia sp*. Fallen, fire-killed, mature trees also contributed to the understorey cover at some sites.

2.1 Site Characteristics

2.1.1 Geology and Soil

The area is dominated geologically by the igneous intrusive Bega Batholith which occupies about 45% of the EMA. The Batholith consists of three major igneous rock types; granite-adamellite, adamellite and quartz diorite-granodiorite (Reinson, 1976). The remaining part of the EMA is dominated by Ordovician metasediments. Descriptions of the three soil types selected, henceforth referred to by their parent geologies as light granite soils (LG), red granite soils (RG), and metasediment soils (MS) are described in Table 1. The two granite soils predominate in State Forests around the Bombala region (Coolangubra SF, Bondi SF and Nalbaugh SF). The metasediment soils are prevalent in the coastal forests (Murrah SF and Mumbulla SF).

Table 1. Description of the three soil types selected in the EMA.

Lithology	**Soil Code**	**Soil Description**	**Average Particle Size**			**Munsell Colour**
			% sand	**% silt**	**% clay**	
Granite/adamellite	LG	Light coloured, uniformly coarse textured and weakly structured (orthic tenosol, Isbell, 1996; U_c 5.22, Northcote, 1971)	67	16	17	7.5YR4/4
Granite	RG	Red coloured, strongly aggregated duplex soil (red chromosol, Isbell, 1996; D_r 4.21, Northcote, 1971)	62	23	15	5YR5/8
Ordovician metasediment	MS	A gravelly yellow duplex clay loam (yellow chromosol, Isbell, 1996; D_y 2.41, Northcote, 1971)	42*	17	27	7.5YR6/4

* 14% > 2mm (sand)

State Forest's operational staff perceived the light granite soils to have higher erosion rates based on field evidence of rill development and batter failures. The red granite and metasediment soils were regarded as relatively stable on the basis of little field evidence of surface wash erosion in the logging compartments. The Water Pollution Hazard categories developed by the NSW EPA, Pollution Control Licence (1995), as based on modified USLE procedures, rank the soils in the reverse order with the metasediment soils classified as the highest risk (Fig. 2). This ranking is primarily a product of the higher rainfall erosivity R (Rosewell and Turner, 1992) of these coastal sites (3500), compared with an R value of 1800 for the granite sites around Bombala. The finer grained texture of the metasediment soils makes them more susceptible to surface compaction than the coarser-grained granites (Fig. 2).

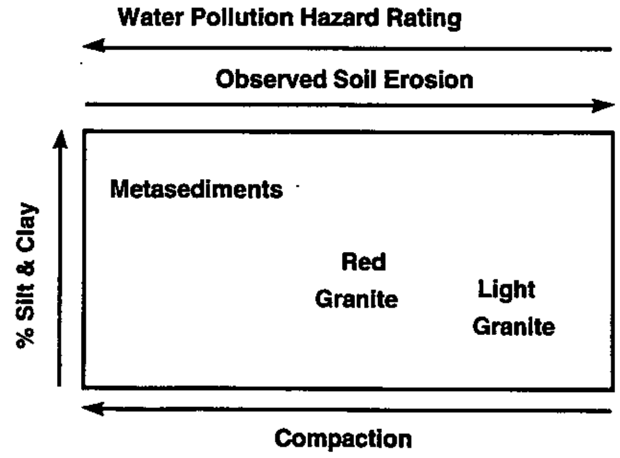

Figure 2. Perceived erosion hazards of three soil types.

2.1.2 *Post-Logging Age Classes*

Forest coupes representing three age classes were selected across these soil types. The youngest age class of 6-7 months represents the extent of disturbance during the early stages of site recovery after the post-harvest burn (Table 2). Younger age classes would have been desirable but in NSW the post-harvest burn is completed in cooler months and by the time site selection occurred, most suitable sites were already 3-4 months old. The remaining age classes were approximately one and a half years and five years since the post-harvest burn (Table 2).

Table 2. Logging history and dimensions of experimental plots at each of the selected sites.

Code	Age Class (years)	Logging Date	Burning Date	Date of Exper.	Dimensions				Mean Slope (%)	
					Plot m^2	% Snig	% GHA	% Sub-GHA	GHA	Snig
LG	4.7	Dec-90	May-91	Jan-96	257	26	59	15	29	29
	1.5	Mar-94	Jun-94	Nov-95	263	27	57	16	25	25
	0.6	Dec-94	Jun-95	Jan-96	257	39	48	13	23	25
RG	4.6	Nov-90	May-91	Nov-95	289	16	65	19	29	24
	1.7	Jul-93	Jun-94	Jan-96	256	24	61	15	27	25
	0.6	Jun-94	Jun-95	Jan-96	256	28	53	19	30	29
MS	4.7	Oct-90	Apr-91	Dec-95	262	23	61	16	28	29
	1.5	Apr-94	Jul-94	Dec-95	246	27	54	19	30	29
	0.4	Mar-94	Jul-95	Dec-95	262	34	51	15	22	20

2.1.3 *Degree of Disturbance*

Each of the sites had been subject to an integrated harvesting operation with timber used for both sawlog and woodchip production. The nature of timber extraction was similar across all sites and included the use of a bulldozer or rubber-tyred skidder to create snig tracks and haul logs to the log landings or log processing area. Cross banks were constructed at regular intervals on snig tracks to divert runoff upon completion of log extraction.

Each experimental plot included two broad levels of disturbance: a snig track and a general harvesting area. The snig track was highly disturbed by bulldozers or skidders during the logging operation. The pattern of disturbance of this area was often relatively uniform as reflected in the near-complete removal of the organic-rich, O horizon and a portion of the A horizon. Well-defined rills were present in the lower 5 m of the majority of snig tracks indicating prior concentrated overland flow. In contrast, disturbance in the general harvesting areas was highly variable. In some instances, the topsoil had been displaced or removed but in other instances, only ground cover vegetation and litter had been disturbed and removed to varying degrees. No attempt was made to quantify the spatial pattern of disturbances within the general harvesting areas.

3.0 EXPERIMENTAL DESIGN

3.1 Collection of Field Data

Rainfall was generated in these experiments using CSIRO's large, field-based, rainfall simulator. A description of the simulator's design and configuration is presented in Appendix 1. The experimental layout of the plot was designed to measure surface water generation on both snig track and general harvesting area, whilst allowing measurement of runoff and sediment redistribution within each of the hillslope elements. Three rainfall intensities were selected according to procedures outlined in Pilgrim (1987), corresponding to 1:2, 1:10 and 1:100 year events for the region. These events produce average rainfall intensities of 45 mm h^{-1}, 75 mm h^{-1} and 110 mm h^{-1}. Appendix 1 outlines the calibration of rainfall intensities with the rainfall simulator configuration and nozzle sizes.

The long axis of each plot was orientated perpendicular to the contour and standardised to include, approximately, a 5 x 15 m area of snig-track and a 10 x 20 m area of general harvesting area (Fig 3). A representative portion of the general harvesting area (Sub-GHA in Fig. 3), approximately 10 m x 5 m, was partitioned off towards the top of the plot. Specific areas are listed in Table 2. Sidewalls made of sheet metal were installed parallel to the direction of flow and between the snig track and general harvesting area and were sealed in place using liquid petroleum jelly (Fig. 3).

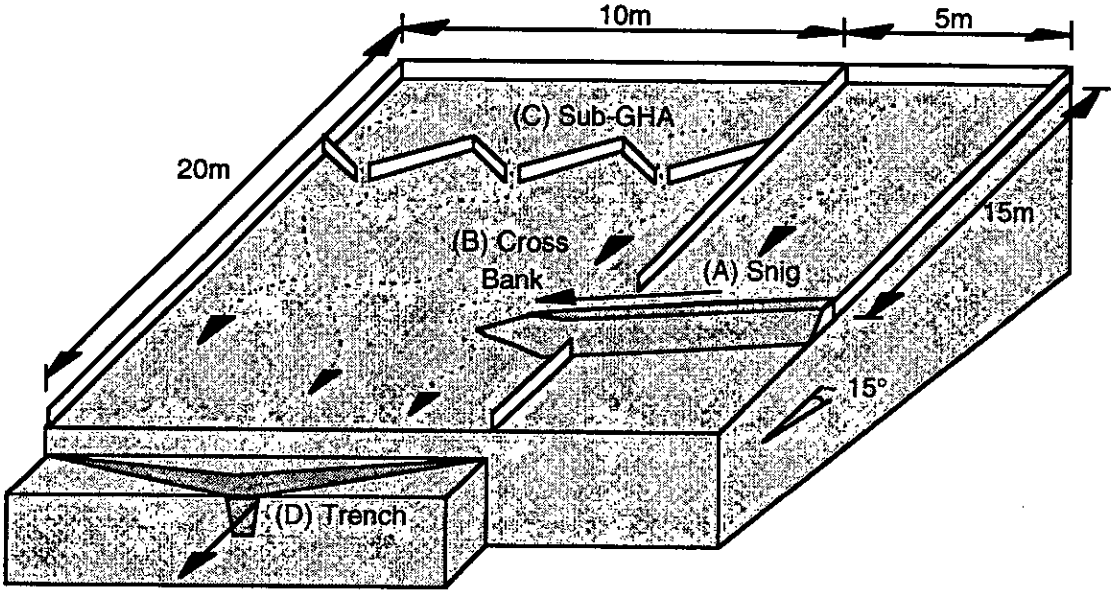

Figure 3. Plot layout indicating the location of the four sample collection points.

Runoff and sediment samples were collected at four sample locations on the plot (Fig. 3).

1. *Snig -track* (A in Fig. 3): Surface runoff samples were collected on the snig track in an area immediately upslope of the channel formed by the crossbank. Sampling typically occurred within an area of concentrated flow, such as a rill, towards the base of the snig track and visual estimates were made of the percentage flow sampled. Samples were taken at approximately

three minute intervals using a suction sample device attached to 1 or 2 litre sample bottles and a wet vacuum cleaner.

2. *Cross-bank outflow* (B in Fig. 3). Runoff samples were collected at the outlet of the crossbank channel, immediately before flow entered the general harvesting area. At this location a V-notch flume and stage recorder were installed to monitor overland flow at one second intervals. The runoff samples were collected at the outlet of the flume at approximately three minute intervals and they sampled all of the flow.
3. *General Harvest Area* (C in Fig. 3): Flow from a representative portion of the general harvesting area (Sub-GHA) was confined by metal plates arranged in three continuous 'V' shaped collection points (Fig. 3). Artificial concentration of flow due to sampling was minimised by locating the sample area towards the top of the plot, ensuring that flow would diverge as soon after collection as possible in the remaining 15 m of hillslope. Representative runoff and sediment samples were obtained by timed sampling using a suction sampler at each of the three outlets across the width of the general harvesting area.
4. *Base of the plot* (D in Fig. 3): A plastic lined trench at the bottom of the hillslope fitted with a V-notch flume and stage recorder were used to catch surface runoff and sediment from the contributing upslope area of the plot. This trench receives runoff and sediment from the lower boundary of the general harvesting area, including a component which has flowed through the cross-bank outlet and across the lower general harvesting area. Timed samples were also collected at 3 minute intervals.

Rainfall simulations were, in all but one run, applied for 30 minutes with intervening periods of approximately 1-hour between applications. A maximum of ten runoff samples were collected at each of the sample locations during each of the simulations. Methods for calculating parameters such as discharge, total runoff and sediment yield are outlined in Appendix 2. Variations in the spatial distribution of rainfall during each of the simulations are illustrated in Figures 19-28 in Appendix 3.

At the end of each run, one sample from each of the sample locations was stored in a freezer for subsequent nutrient analysis and one was sieved to determine aggregate particle size distribution. Sediment aggregate size distribution was determined according to the principles outlined in Kemper and Rosenau (1986). The remaining eight samples were returned to the laboratory for determination of total solids and volume.

Ground cover was photographed within a 1.0 x 1.0 m quadrat immediately prior to the experiments at approximately 10 locations at each of the sites. These slides were digitally scanned to produce quantitative estimates of ground cover. Mean values of total[1] and contact cover for both the snig track and general harvest area are reported in Table 3.

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[1] Total cover refers to both projected vegetation cover and contact cover (all objects including stones, leaf litter etc. in contact with the soil surface) within the 1m^2 grid.

4.0 RESULTS

The results from the experiments described above are summarised here in three parts:

- 4.1 outlines surface runoff generation as related to soil type and recovery age;
- 4.2 examines soil erosion rates on both snig track and general harvesting areas and investigates relationships with soil and age; and
- 4.3 summarises the nature and scale of sediment re-distribution and examines the effectiveness of erosion control structures such as cross banks.

Whilst all data are presented in the accompanying tables, many of the figures are chosen to illustrate a worst-case scenario, using maximum rainfall intensities from a 1:100 year storm and runoff and sediment data from the most recently logged sites.

4.1 Runoff Production

Because overland flow is the major detachment and transporting mechanism of sediment and chemicals to our water bodies, it is essential that we understand the nature of runoff development and re-distribution in disturbed forests. There are a number of factors which affect the type and volume of surface runoff produced in logged catchments. These relate primarily to the material and hydraulic properties of the soil, in particular, its texture, *hydraulic conductivity* [2] and *infiltration capacity* [3]. Additional factors include the degree of soil disturbance, as reflected in changes to the soil structure and vegetation cover. Changes in soil structure due to compaction are often assessed in terms of increased bulk density and reductions in porosity. The measured bulk densities, total porosity and organic content of topsoils (0-10 cm) on snig tracks in the EMA sites were significantly different (probability, $p > 0.0001$) from those on the general harvesting areas (Table 3). The bulk density of the snig track soils was approximately 1.25 times higher than those on the general harvesting area (Table 3). This is due partly to compaction but also to the loss of more porous surface soil during cross bank construction. The surface 10 cm of soil on the snig track has approximately 80% of the total porosity, and 40% of the organic matter of the equivalent surface sample on the general harvesting area (Table 3). On average, snig tracks in this study only have 60% of the total cover of general harvest areas (Table 3). A protective cover of vegetation is important for providing hydraulic roughness and thereby reducing the velocity of surface flows, increasing detention and

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[2] Hydraulic conductivity (also called permeability) is the rate at which water moves through the soil under a unit potential energy gradient. Under saturated conditions, the rate is largely determined by the soil-grain size while for unsaturated flows it is determined by grain size and the degree of saturation.

[3] Infiltration capacity is the maximum rate at which water arriving at the soil surface can be transmitted down the soil profile.

depression storage, so that more water is available for infiltration. The following section examines how management- related disturbances affect surface runoff production and how it varies across the three soil types and recovery ages.

Table 3. Measured properties of surface soils (0-10 cm) across the selected sites in the EMA.

Soil Code	Age Class (yrs)	Area of Disturbance	Initial Saturation (%)	Bulk Density (g/cm3)	Total Porosity (cm3/cm3)	Organic Matter (%)	Total Cover (%)	Contact Cover (%)
LG	5	GHA	43.3	1.24	0.53	11.5	58.2	40.1
LG	1	GHA	42.6	1.33	0.5	8.6	49.9	38.6
LG	0	GHA	31.7	1.13	0.57	7.9	57.1	43.3
LG	5	Snig Track	57.9	1.44	0.46	3.1	49.6	38.1
LG	1	Snig Track	66.1	1.61	0.39	1.7	27.9	27.9
LG	0	Snig Track	34.9	1.20	0.55	5.9	30.7	20.7
RG	5	GHA	ND	0.98	0.63	12.2	80.0	75.0
RG	1	GHA	35.2	1.06	0.60	3.0	49.2	29.4
RG	0	GHA	57.4	1.11	0.58	3.5	60.1	43.7
RG	5	Snig Track	ND	1.44	0.46	3.3	54.0	43.0
RG	1	Snig Track	65.0	1.47	0.45	2.1	21.4	17.7
RG	0	Snig Track	89.4	1.46	0.49	2.8	26.7	26.7
MS	5	GHA	27.0	1.06	0.59	21.8	66.3	40.6
MS	1	GHA	59.7	1.57	0.4	11.6	45.2	18.3
MS	0	GHA	17.6	1.19	0.54	22.5	34.1	34..00
MS	5	Snig Track	64.0	1.62	0.38	8.1	40.3	37.6
MS	1	Snig Track	47.8	1.41	0.46	2.4	57.6	37.2
MS	0	Snig Track	25.4	1.43	0.45	7.9	46.9	45.0

4.1.1 Nature of Overland Flow and Time to Runoff

There are a number of flow mechanisms which produce runoff responses within a forested catchment, including saturation excess or "wet area" runoff. This hillslope study is primarily concerned with *Horton overland flow,* defined as that which results from saturation from above when rainfall intensity exceeds the infiltration rate of the soil (Horton, 1933). On the flat, bladed surfaces of the snig tracks, surface runoff occurred as relatively uniform sheet flow, except at sites where rills had developed towards the base of the track. On the snig track, incipient ponding and partial area runoff occurred within 3-4 minutes of rainfall during the 1:2 year events, decreasing to about 90 seconds for the 1:10 and 1:100 year storms (Table 4). The entire surface generated runoff during the higher intensity storms.

Table 4. Time in seconds to commencement of 'global runoff [4]' at each of the sample locations.

		Time to Runoff								
		0.5 years since logging			1 year since logging			5 years since logging		
Sampling Location	**Run Number**	**Meta-sediment**	**Red Granite**	**Light Granite**	**Meta-sediment**	**Red Granite**	**Light Granite**	**Meta-sediment**	**Red Granite**	**Light Granite**
GHA	1	150	327	NRO	540	746	0	NRO	NRO	0
	2	90	102	400	420	249	0	210	0	0
	3	80	85	220	155	120	0	210	115	0
Snig	1	180	240	150	240	270	0	390	210	270
	2	90	60	90	150	60	0	165	120	120
	3	60	30	60	90	60	0	120	120	90
Trench	1	150	NRO	663	221	990	480	525	240	580
	2	90	570	150	0	120	0	240	180	0
	3	50	160	130	0	60	0	165	140	0
Xbank	1	420	420	270	1380	315	0	NRO	NRO	NRO
	2	120	120	120	150	60	0	1020	660	1500
	3	90	60	80	90	60	0	600	480	440

NRO = No global runoff occurred

The nature of overland flow within the general harvesting area is more difficult to describe. Fine-scale variations in infiltration between bare and vegetated areas produced patchy overland flow during the majority of simulations. Our visual observations of dye traces suggest that only 20-30% of the general harvest area produced runoff during the lower intensity events, increasing to about 50-60% during the higher intensity rainfall. Some of this runoff completely infiltrated within the plot, and so did not connect to the outlet measurement point. During the high intensity, 1:100 year storm, well defined flow paths developed from bare areas and continued downslope deviating around vegetation, logs and leaf litter. Generally, increased rainfall intensity led to increases in the area contributing runoff, and an increased fraction of this runoff reaching the trench.

4.1.2 *Infiltration Characteristics of the Soils*

The *apparent infiltration capacity* [5] of soils on the snig track and general harvesting areas was determined by subtracting the steady state runoff rate for the last five minutes of each simulation from the mean rainfall rate. Apparent infiltration capacities for the snig track and general harvesting areas are outlined in Table 5. There is no statistical difference between apparent infiltration capacities across the three soil types (Table 5). However, infiltration rates are significantly different for the snig track and general harvesting area for all three rainfall intensities (probability, p=0.001). The dominant factor in explaining differences in infiltration

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[4] Global runoff is defined here as the elapsed time between the commencement of rainfall and runoff through the outflow of the cross bank flume. Global runoff from the bottom trench is similarly defined.

[5] The apparent infiltration capacity is an inferred property from the steady state runoff rate minus the rainfall rate. It takes no account of the redistribution of runoff within the plot area associated with variability in soil hydraulic properties and ponded water availability.

capacity, therefore, is the relative degree of disturbance between snig track and general harvesting area, and not differences in soil type.

Table 5. Apparent infiltration capacity of the three soil types for varying rainfall intensities.

Sampling Location	Run Number	Apparent Infiltration Capacity (mm/h)								
		0.5 years since logging			1 year since logging			5 years since logging		
		Meta-sediment	Red Granite	Light Granite	Meta-sediment	Red Granite	Light Granite	Meta-sediment	Red Granite	Light Granite
Sub- GHA	1	38.9	43.8	NRO	49.3	39.6	51.1	NRO	NRO	41.7
	2	55.5	64.8	64.6	52.9	56.6	69.4	49	51.3	69.8
	3	90.2	85	66.3	80.8	89	na	87.8	74.8	108
Trench	1	38	NRO	43.5	45.9	41.8	32.8	57.4	37.3	41.2
	2	36.2	55.1	50.2	27.4	36.5	43	61.2	53.2	60.6
	3	90.8	79.8	58		92.7			71.3	90.9
Snig	1	26	17.2	45.1	42.5	28.1	8.4	NRO	NRO	NRO
	2	21.6	15.4	46	0.9	9.2	14.7	37.4	45	56.9
	3	41.5	6.8	9.4	na	14.1	na	67.6	47.8	36.2

na = not available from discharge data. NRO = no runoff occurred

There is no significant trend in apparent infiltration capacity of the snig track with rainfall rate. This is consistent with the assumption that the snig track has a pre-existing compacted layer of soil at the surface which acts to limit infiltration at all experimental intensities. Estimates of saturated hydraulic conductivity on the snig track using the drip infiltrometer method (Bridge and Ross, 1985) also indicated that infiltration rates were relatively uniform (mean 12.40 mm/h ± 1.68 SD). This result is consistent with the removal of the organic O horizon and partial removal of the A horizon and the near- uniform application of shear and compressive stress during trafficking. Thus once surface runoff commences, flows transmit relatively quickly downslope in the absence of areas of higher infiltration which can absorb larger volumes of surface flow. In contrast, on the general harvest area, the apparent infiltration capacities increased with increasing rainfall across all age classes (Fig. 4). The general harvesting area was characterised by a higher variance of infiltration rates within the plot (mean 39.82 mm/h ± 37.99 SD) reflecting areas of varying hydraulic conductivity and vegetation cover. These results suggest that areas of very high infiltration potential are operating well below their potential for low rainfall intensities and as rainfall intensity is increased, some of this potential is taken up through the infiltration of runoff from upslope.

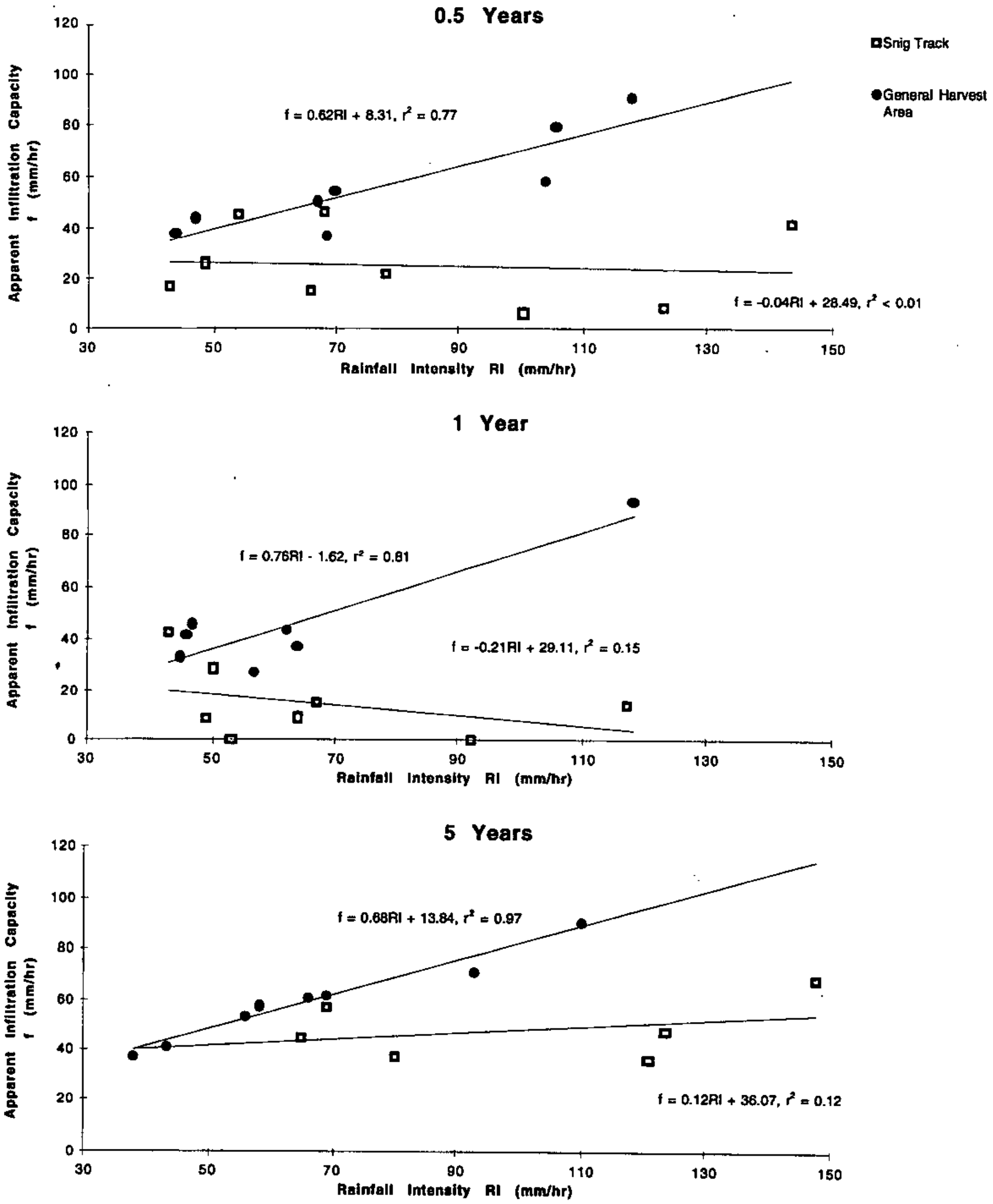
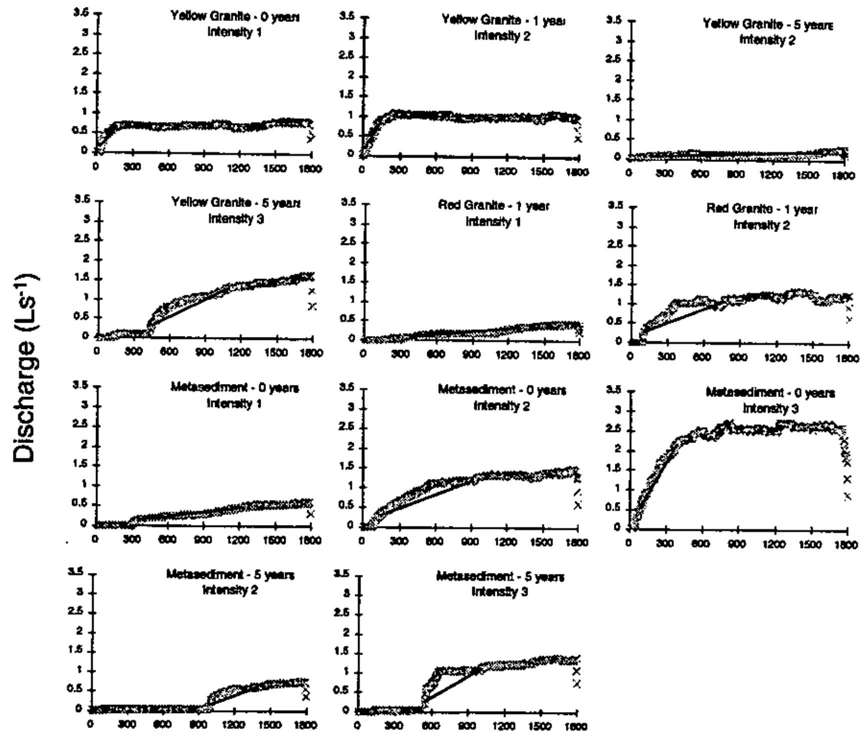


Figure 4. Variations in apparent infiltration capacity (f) with increasing rainfall intensity (RI) on snig tracks and general harvesting areas of varying age.

4.1.3 *Rates of Overland Flow on Snig Tracks and General Harvesting Areas*

Runoff hydrographs from the cross bank and the bottom trench stage recorders are illustrated for selected sites in Figure 5. Three broad hydrological responses can be recognised; an initial phase of low surface runoff reflecting high rainfall infiltration and/or depression storage and poor connection to the measuring point; a second stage of rising discharge reflecting increasing ponding and developing connection between runoff patches; and an equilibrium period when zones of runoff and the degree of connection is steady (Fig. 5).

Cross Bank Flume



Trench Flume

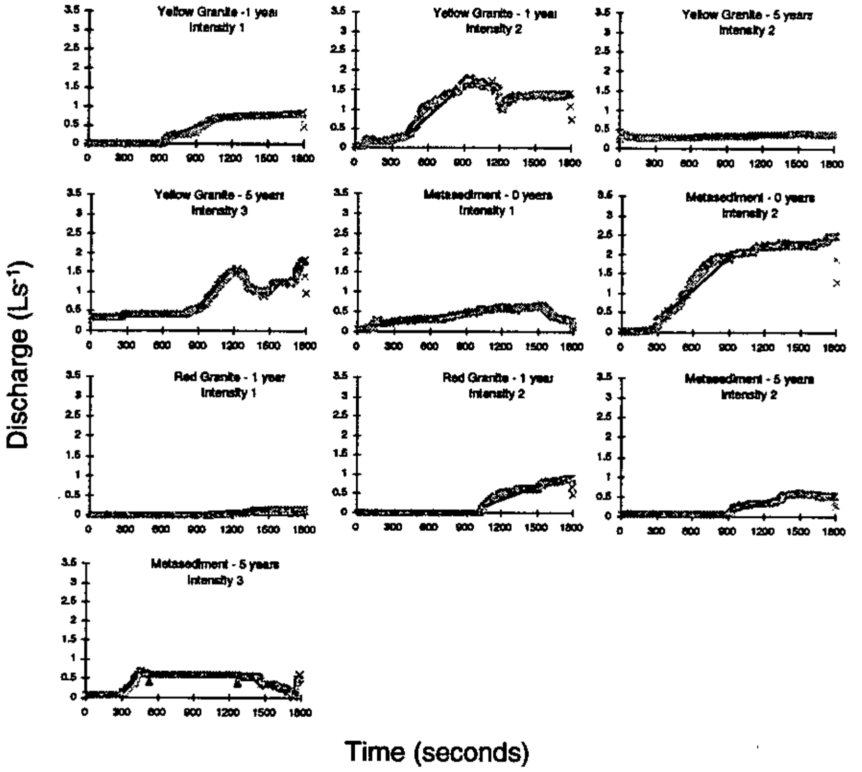


Figure 5. Representative runoff hydrographs from the snig track and general harvesting area.

Steady state runoff developed more gradually on the general harvesting area, where 80% of the maximum discharge was reached, on average, 200 seconds after it was reached on the snig track (Table 6).

Table 6. Hydrograph characteristics of selected sites across each of the soil types.

Site	Location	Run #	Years Since Logging	Soil Type	Flow Rate (Litres/Second)				Time (Seconds)			Slope Fit to Data		
					Max.	20% x Max.	80% x Max.	Discharge Change	20% x Max.	80% x Max.	Duration	Slope	r^2 (Adj.)	N
1	Cross Bank	1	1	Light Granite	0.83	0.17	0.66	0.50	35	165	130	0.00	94.19	27
1	Cross Bank	2	1	Light Granite	1.09	0.22	0.87	0.65	30	150	120	0.01	99.49	25
1	Trench	1	1	Light Granite	0.82	0.16	0.65	0.49	670	1045	375	0.00	87.12	75
1	Trench	2	1	Light Granite	1.81	0.36	1.45	1.09	435	830	395	0.00	91.37	80
2	Cross Bank	2	5	Light Granite	0.28	0.06	0.22	0.17	170	1620	1450	0.00	51.53	292
2	Cross Bank	3	5	Light Granite	1.63	0.33	1.30	0.98	450	1095	645	0.00	90.66	130
2	Trench	2	5	Light Granite	0.41	0.29	0.38	0.09	370	1415	1045	0.00	95.33	210
2	Trench	3	5	Light Granite	1.79	0.56	1.49	0.92	895	1155	260	0.00	98.99	53
5	Cross Bank	2	5	Metasediment	0.76	0.15	0.61	0.46	990	1395	405	0.00	75.98	82
5	Cross Bank	3	5	Metasediment	1.41	0.28	1.13	0.85	535	1010	475	0.00	54.98	96
5	Trench	2	5	Metasediment	0.60	0.12	0.48	0.36	925	1340	415	0.00	85.19	84
5	Trench	3	5	Metasediment	0.69	0.14	0.55	0.41	320	425	105	0.00	94.48	22
6	Cross Bank	1	0.4	Metasediment	0.59	0.12	0.47	0.35	345	1240	895	0.00	96.34	182
6	Cross Bank	2	0.4	Metasediment	1.49	0.30	1.19	0.89	140	915	775	0.00	90.00	156
6	Cross Bank	3	0.4	Metasediment	2.71	0.54	2.17	1.63	85	385	300	0.01	97.35	61
6	Trench	1	0.4	Metasediment	0.67	0.13	0.54	0.40	125	1010	885	0.00	90.80	178
6	Trench	2	0.5	Metasediment	2.50	0.50	2.00	1.50	390	925	535	0.00	93.32	108
8	Cross Bank	1	1	Red Granite	0.42	0.08	0.34	0.25	375	1305	930	0.00	83.76	187
8	Cross Bank	2	1	Red Granite	1.35	0.27	1.08	0.81	100	765	665	0.00	68.77	134
8	Trench	1	1	Red Granite	0.15	0.03	0.12	0.09	1165	1415	250	0.00	88.41	51
8	Trench	2	1	Red Granite	0.90	0.18	0.72	0.54	1055	1535	480	0.00	81.24	97

4.1.4 *Runoff Production on Snig Tracks and General Harvesting Areas*

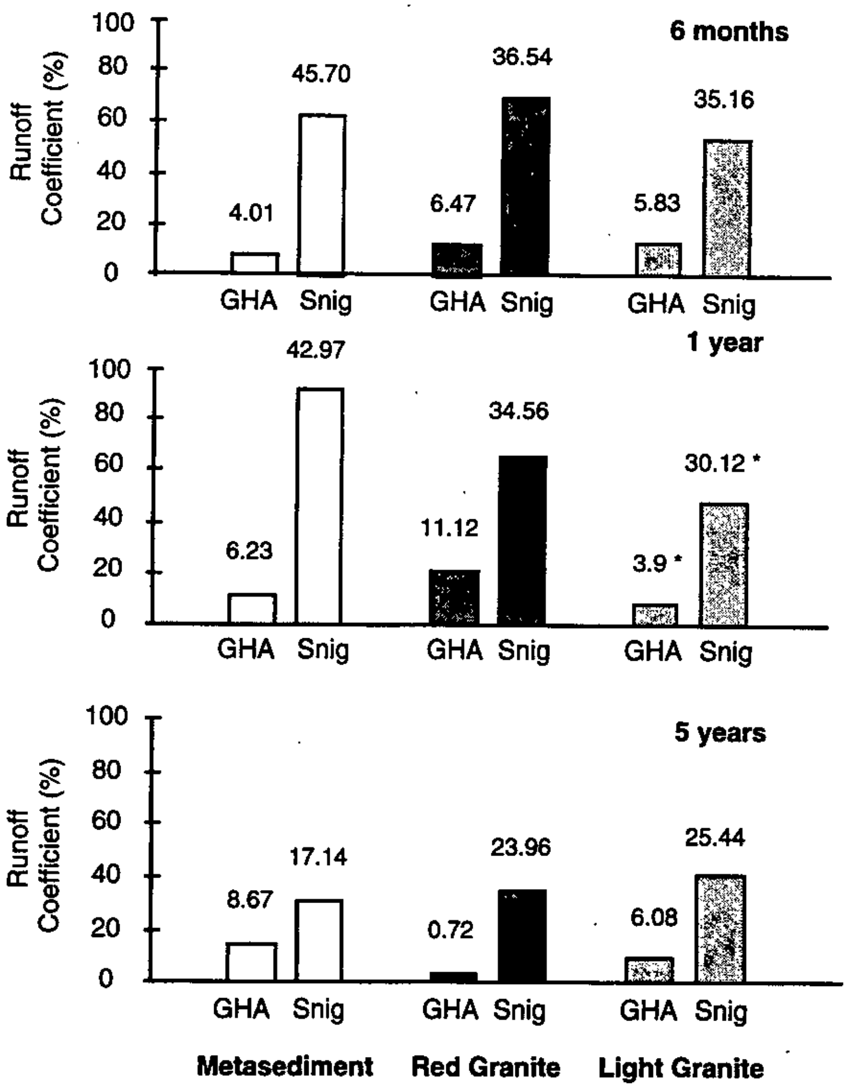
Total runoff volumes, per unit contributing area, are significantly higher (probability, p=0.001) on snig track surfaces than those produced on the general harvesting areas for each rainfall intensity (Table 7). For the 1:2 and 1:10 year storms, snig tracks generate approximately seven times more surface runoff per unit contributing area than general harvesting areas on recently logged sites (Table 7). The relative difference in runoff production declines to about two fold with increasing recovery age (Fig. 6).

Table 7. Total runoff volumes (mm per contributing area) and coefficients for each soil and age class.

Sampling Location	Data	Run Number	Runoff (mm) and Runoff Coefficient (%)								
			0 years since logging			1 year since logging			5 years since logging		
			Meta-sediment	Red Granite	Light Granite	Meta-sediment	Red Granite	Light Granite	Meta-sediment	Red Granite	Light Granite
Sub-GHA	Runoff (mm)	1	0.52	0.63	0.00	0.08	0.66	1.05	0.00	0.00	1.53
	Runoff Coefficient[1] (%)		2.56	2.76	n/a	0.32	2.89	4.04	n/a	n/a	6.80
	Runoff (mm)	2	1.90	1.38	2.97	1.60	2.79	2.11	3.51	0.07	2.63
	Runoff Coefficient (%)		6.13	3.82	8.37	5.41	7.73	5.70	11.49	0.27	6.92
	Runoff (mm)	3	4.01	6.47	5.83	6.23	11.12	3.90	8.67	0.72	6.08
	Runoff Coefficient (%)		7.96	11.87	13.88	12.12	20.40	5.78	15.45	1.82	9.73
Trench	Runoff (mm)	1	2.72	0.00	1.56	0.60	0.29	2.73	0.24	0.00	0.71
	Runoff Coefficient (%)		12.42	n/a	6.64	2.56	1.30	12.13	0.83	n/a	3.30
	Runoff (mm)	2	10.47	3.35	6.76	8.87	1.87	7.24	1.72	0.27	2.36
	Runoff Coefficient (%)		30.62	9.61	20.18	31.23	5.37	23.35	5.00	0.97	7.15
	Runoff (mm)	3	12.31	9.43	17.13	11.17	10.65	6.12	8.33	5.03	5.62
	Runoff Coefficient (%)		20.88	17.86	32.94	24.26	20.17	11.33	13.17	10.82	10.22
Snig	Runoff (mm)	1	6.31	5.79	2.75	0.06	6.13	17.29	0.00	0.00	0.00
	Runoff Coefficient (%)		25.91	26.99	10.19	0.28	28.58	73.35	n/a	n/a	n/a
	Runoff (mm)	2	21.23	18.06	8.60	15.84	29.41	24.39	8.70	4.74	3.44
	Runoff Coefficient (%)		54.51	54.81	25.29	59.66	89.26	72.81	21.70	14.63	9.97
	Runoff (mm)	3	45.70	36.54	35.16	42.97	34.56	30.12	24.47	23.96	25.44
	Runoff Coefficient (%)		63.60	72.79	57.17	93.41	68.84	53.31	33.11	38.77	42.05

[1] Runoff coefficient is the percentage of rainfall which became surface runoff during each of the 30 minute simulations

The average runoff coefficient for snig track surfaces, across all soil and age classes, is 22% for the 1:2 y storm, 39% for the 1:10 y storm and 51% for the 1:100 y storm. This compares with overall means of 6%, 10% and 14% from general harvesting areas for the same rainfall intensities (Fig. 6). A two-factor ANOVA indicates that runoff coefficients are significantly different for snig tracks and general harvesting areas (probability, p=0.042; 0.0001 and 0.0001) for all three intensities, although confidence levels improve once rainfall rates exceed 45 mm h^{-1}



values over bar = Total Runoff in mm

Figure 6. Runoff coefficients and total runoff volumes for general harvesting areas and snig tracks on the most recently logged sites across all three soil types for the 1:100 year storm. (*= estimated total volume for the 30 minutes from a 10 minute simulation).

4.1.5 *Runoff and Soil Type*

There is no simple relationship between runoff volumes and soil type. Total volumes of surface runoff vary inconsistently with rainfall intensity across each age class (Table 7). For example, snig tracks on the recently logged and 1 year metasediment soils produce slightly higher runoff volumes than the granite soils for all three rainfall intensities (Table 7). In the case of the 5 year sites, all three soil types produce similar runoff values for the 1:10 and 1:100 year storm simulations (Table 7).

4.1.6 Runoff production with age

Total runoff declines on the snig track surfaces with age across all three soil types (Fig. 7). The nature of runoff decline is best described by a linear function with r^2 values ranging from 0.87 to 0.99 (Fig. 7). The rate of decline over the five year period on the snig track is steepest on the Ordovician sites where the slope of the linear function is -4.35 years, compared to -1.7 years on the light granite soils for the 1:100 year storm (Fig. 7). Runoff volumes for snig tracks on the three 5 year old compartments converge towards a similar value of 28 mm, suggesting that controlling factors such as variations in the degree of disturbance and protective cover are similar across all three sites of this age class.

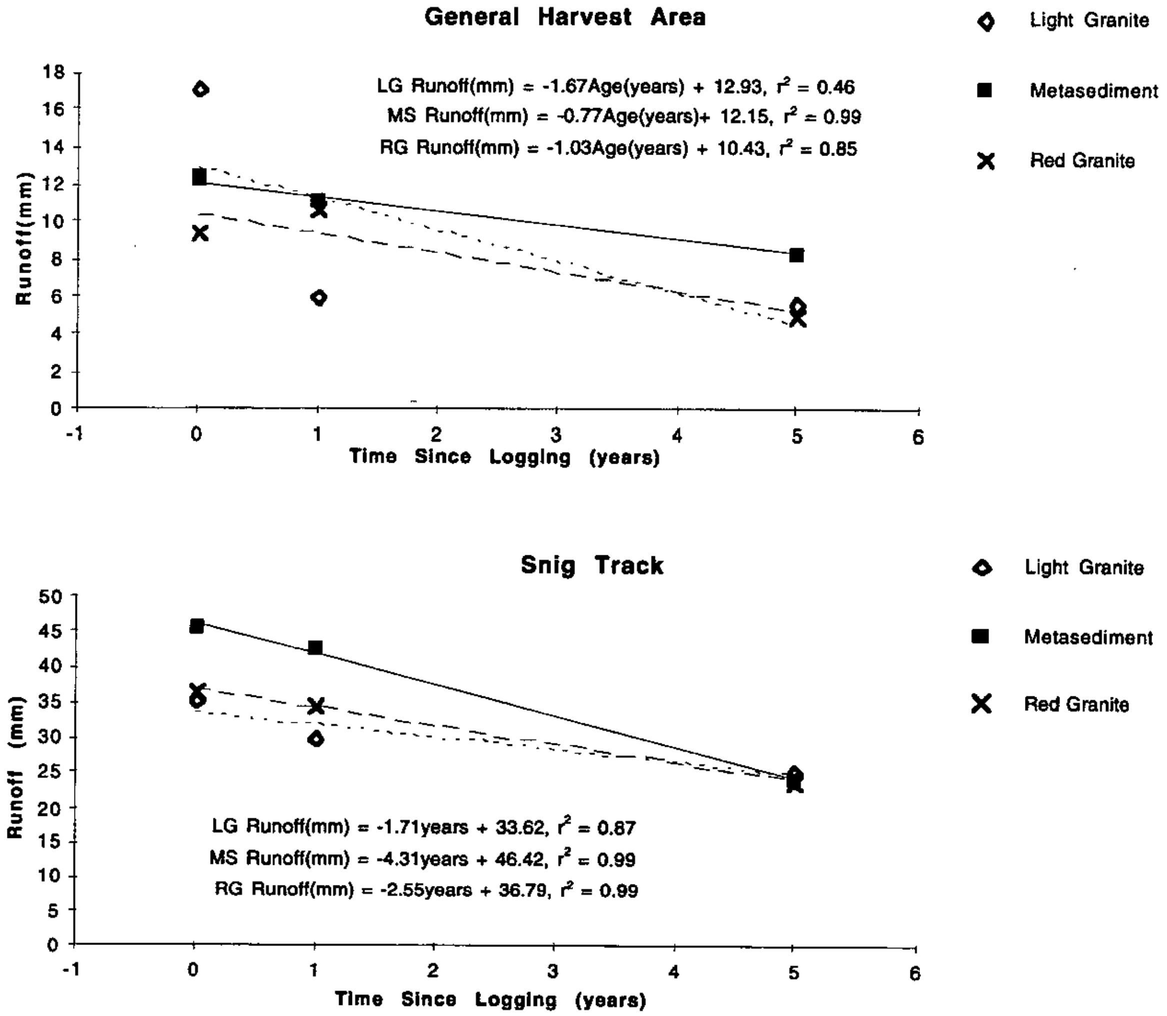


Figure 7. Relationship between total runoff (mm) and time since logging for the 1:100 year storm across each soil type.

Surface runoff production from the general harvesting area generally declines with time since logging across all three soil types (Fig. 7). The rate of runoff decline is slower than that observed on the snig tracks, as reflected in the lower coefficients (Fig. 8). Runoff decline on the general harvesting areas of the light granite soils occurs most rapidly within the first year after the post harvest burn, where there is almost a 30% reduction in runoff volume. In contrast, surface runoff volumes from the general harvesting areas does not change significantly between the one and five years on both the light granite and metasediment soils (Fig. 7).

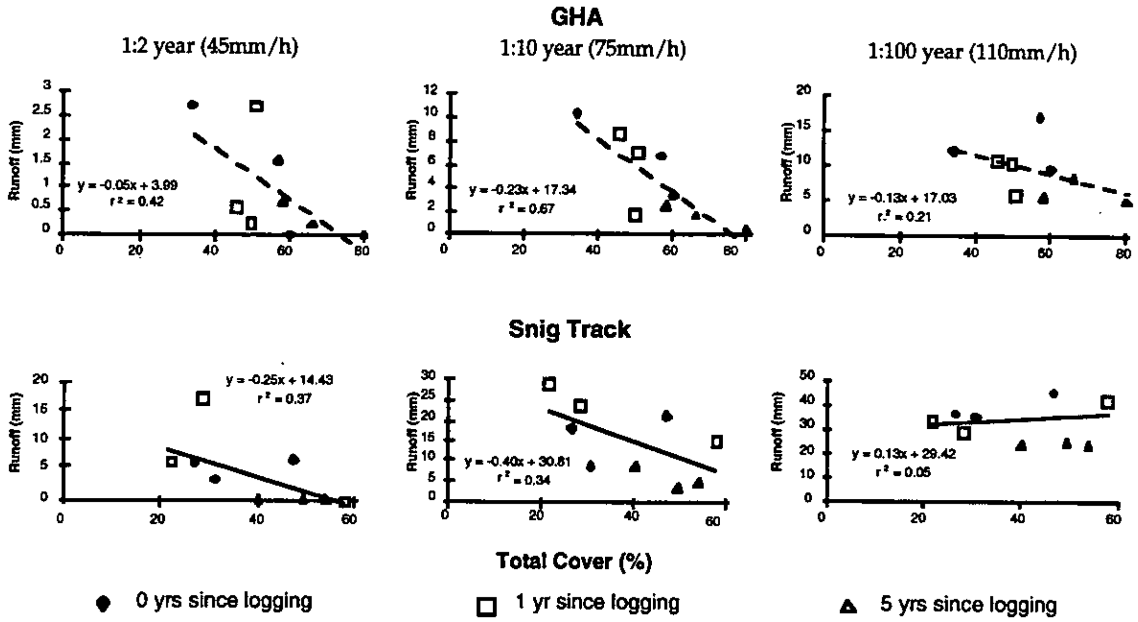


Figure 8. Relationship between surface runoff and mean percentage total cover on snig tracks and general harvest areas for 1:2, 1:10 and 1:100 year storms.

Changes in the volume of surface runoff also occurs in response to increases in vegetation cover, organic matter and reductions in soil compaction caused by biological activity and physical processes over time. Surface runoff production on the snig tracks declines with increasing total cover across all sites (Fig. 8). The relationship between surface runoff and total cover varies with rainfall intensity as reflected in coefficients of variance of 36%, 34% and 5% for the 1:2, 1:10 and 1:100 year storms. This suggests that the effect of total cover in reducing runoff volumes is greater for low to medium events, but that once rainfall intensity exceeds some threshold value, the influence of cover on surface runoff weakens as a greater percentage of the general harvesting area produces runoff and vegetated areas become saturated. Regression coefficients were higher using total cover as opposed to contact cover which produced r^2 values of 0.13, 0.20 and 0.02 for the three storm events. This suggests that the role of cover in protecting the soil surface from raindrop impact may be more important than the role of contact cover in reducing the velocity of overland flow.

Similar trends are evident between surface runoff and cover on the general harvesting area although the fit of the relationship was better with r^2 values of 0.42, 0.67 and 0.21 for the three storms. The effect of total cover on surface runoff is better for the 1:2 and 1:10 year storms. As on the snig track, the relationship between runoff and cover was better using total cover rather than contact cover where r^2 values ranged from 0.06 to 0.32. The relationship between surface runoff and percentage organic matter is weak for all three rainfall intensities with coefficients of variation ranging between 0.1% and 9% on the snig track and 0.2% and 8% on the general harvesting area.

5.0 Surface Erosion

Raindrop impact and overland flow are the dominant detachment and transport mechanisms for sediment and nutrients in forested environments. The previous section illustrated how management related practices such as snig track construction can affect runoff rates and volumes in logged catchments. This section examines how these practices affect the land surface's inherent susceptibility to surface erosion. This will be influenced by factors such as the soil's resistance to detachment processes, its aggregate stability and soil hydraulic properties, and the degree of soil disturbance and vegetation disturbances during logging operations.

5.1 Sediment Production

5.1.1 Sediment Concentrations in Runoff

Sediment concentration is a measure of the intensity of the erosion processes. When combined with runoff rate and duration it gives an estimate of sediment yield, as described in section 5.1.2. Highest sediment concentrations are found in the surface runoff on snig tracks (Table 8). The recently logged site on the red granite soil contains the highest values with mean concentrations in the order of 27-30 kg/m^3 (Fig. 9). These compare with mean values of between 4-6 kg/m^3 on the general harvesting areas for the same soil type (Fig. 9). On the 5 year old red granite site, the general harvesting area actually produces higher mean sediment concentrations than the snig track during rainfall intensities of 75 mm h^{-1} and 110 mm h^{-1}. The snig track at this site contains a high percentage of surface rock cover including large boulders reducing the amount of sediment available for transport.

Sediment concentrations in runoff discharged from the cross bank outlet are considerably lower than those on the snig track with mean values ranging from 2 to 6 kg/m^3 on the recently logged sites (Table 8). A further reduction in mean sediment concentration occurs in runoff from the basal trench where mean values on the recently logged sites are of the order of 0.2 to 3 kg/m^3 (Table 8). The implications for this in terms of sediment re-distribution are discussed in more detail in Section 5.2 below.

Table 8. Mean sediment concentrations in surface runoff for the four sample locations at each site.

		Mean Sediment Concentration (kg/m³)								
		0.5 years since logging			**1 year since logging**			**5 years since logging**		
Sampling Location	**Run Number**	**Meta-sediment**	**Red Granite**	**Light Granite**	**Meta-sediment**	**Red Granite**	**Light Granite**	**Meta-sediment**	**Red Granite**	**Light Granite**
GHA	1	3.19	6.61	NRO	1.83	0.62	1.55	NRO	NRO	1.54
	2	2.80	4.97	0.31	1.92	0.53	2.34	0.57	2.64	1.09
	3	6.41	4.24	0.24	0.77	0.61	2.77	0.32	1.84	0.68
Snig	1	5.35	27.11	13.18	2.00	12.62	11.98	0.38	0.32	0.68
	2	5.58	29.45	14.72	1.34	25.24	16.52	0.18	0.20	0.75
	3	5.51	28.82	17.35	3.13	20.21	26.29	0.25	0.23	3.04
Xbank	1	2.13	NRO	1.12	0.65	0.52	0.46	0.03	NRO	0.24
	2	2.61	0.30	2.06	0.98	1.03	0.94	0.10	0.20	1.02
	3	2.89	0.49	2.46	1.14	1.20	1.45	0.09	0.11	0.44
Trench	1	2.42	1.74	2.32	0.45	2.20	2.52	NRO	NRO	NRO
	2	2.10	2.24	4.06	0.41	3.13	3.61	0.17	0.15	0.32
	3	1.91	4.54	6.36	0.46	3.65	7.98	0.17	0.16	0.50

NRO = no runoff occurred

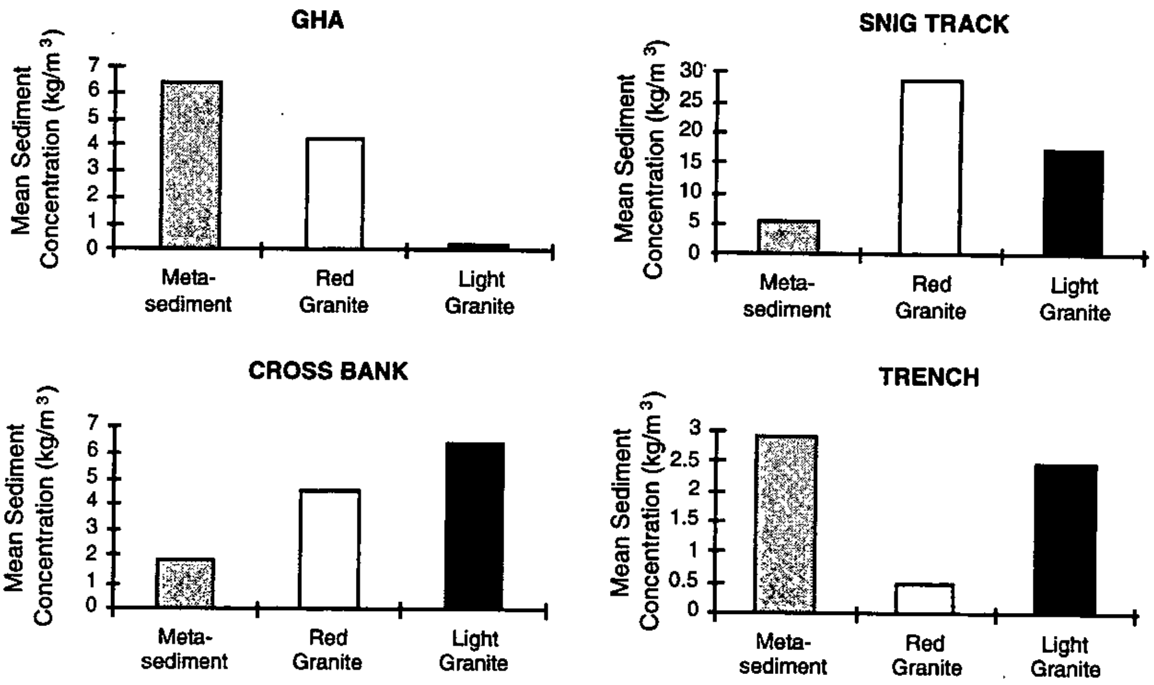


Figure 9. Mean sediment concentrations in runoff at each of the sample locations for the 1:100 year storm.

5.1.2 *Total Sediment Yield*

Sediment yield is the mass of sediment per unit contributing area arriving at the sample point summed over the duration of the experimental run. Maximum sediment yields are produced on snig tracks (Table 9). For the most recently logged sites, sediment yield is in the order of 2 to 11 t/ha for the 1:2 year and 1:100 year storms (Table 9). Snig tracks on these recently logged sites generate, on average, 20 times more sediment than the general harvesting areas for the 1:100 year storm intensities, where average sediment yield ranges from 0.05 to 0.35 t/ha (Table 9).

Table 9. Total Sediment Yields (t/ha) for each soil and age class.

		Sediment Yield (t/ha)								
		0.5 years since logging			**1 year since logging**			**5 years since logging**		
Sampling Location	**Run Number**	**Meta-sediment**	**Red Granite**	**Light Granite**	**Meta-sediment**	**Red Granite**	**Light Granite**	**Meta-sediment**	**Red Granite**	**Light Granite**
GHA	1	0.01	0.04	NRO	0.00	0.00	0.01	NRO	NRO	0.02
	2	0.05	0.07	0.01	0.02	0.02	0.05	0.02	0.00	0.03
	3	0.26	0.25	0.01	0.05	0.07	0.04	0.03	0.01	0.04
Snig	1	0.38	1.77	1.16	0.06	0.88	2.10	0.01	0.03	0.01
	2	1.64	6.70	3.58	0.40	6.08	4.23	0.02	0.03	0.04
	3	2.30	11.08	5.88	1.75	7.65	4.03	0.06	0.07	0.96
Xbank	1	0.12	0.10	0.23	0.00	0.12	0.44	NRO	NRO	0.00
	2	0.49	0.45	0.94	0.10	0.64	1.00	0.01	0.01	0.00
	3	0.69	1.62	1.94	0.20	1.24	1.06	0.04	0.04	0.11
Trench	1	0.05	NRO	0.01	0.00	0.00	0.01	NRO	NRO	NRO
	2	0.29	0.01	0.18	0.05	0.08	0.08	0.00	0.00	0.00
	3	0.35	0.05	0.27	0.12	0.11	0.04	0.01	0.00	0.03

NRO = no runoff occurred

5.1.3 *Sediment Yield and Rainfall Intensity*

Sediment yields on the two youngest age classes, increased with increasing rainfall intensity with r^2 estimates in the order of 0.45 (Fig. 10), sediment yield on the snig tracks show a very weak relationship with increasing rainfall intensity by five years after logging, with a lower coefficient of variation of 16% (Fig. 10). On the general harvest area, there is a weak relationship (r^2= 0.23) between sediment yield and rainfall intensity (Fig. 10)..

Erosion rates on the two granite soils appear particularly sensitive to changes in rainfall intensity between the 1:10 and 1:100 year storm events. Sediment generation rates on the most recently logged, red granite site almost double between the 1:10 and 1:100 year storms with average rainfall intensities of 75 mm h^{-1} and 110 mm h^{-1} respectively (Fig. 10).

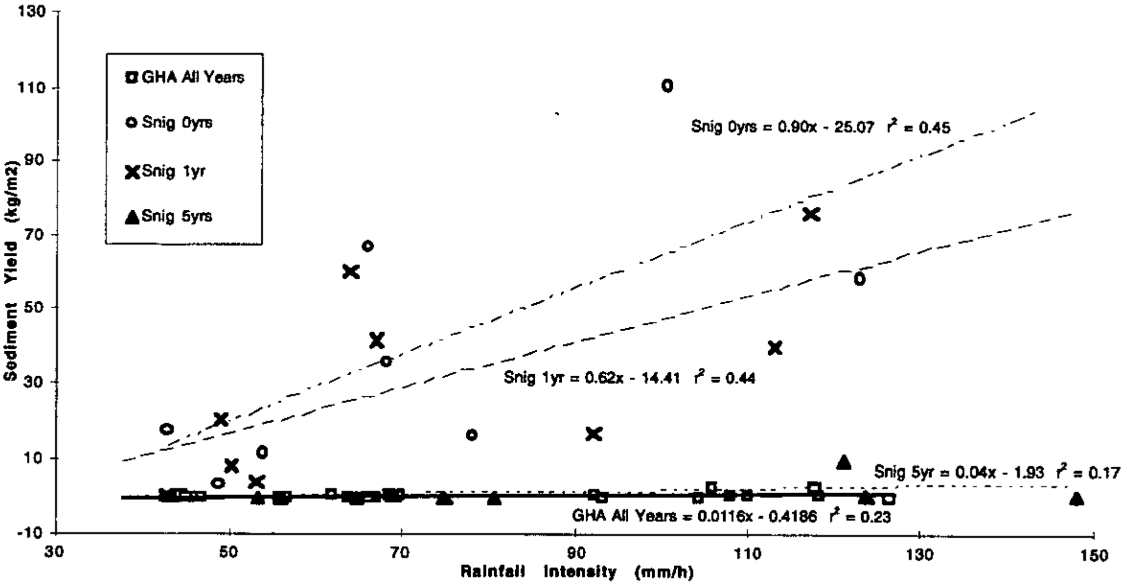


Figure 10. Relationship between sediment yield and rainfall intensity for sites of varying age.

5.1.4 *Sediment Yield and Soil Type*

There is no simple relationship between total sediment yield and soil type across each age class (Table 9). For the recently logged and one-year sites, the red granite soils produce the highest yields for all three rainfall intensities (Fig. 11). Five years after logging, all three soil types produced similar volumes of sediment on the snig track with a slightly higher yield from the light granite site (Table 9). The two granite soils appear more susceptible than the metasediment soils to higher on-site erosion rates in the period immediately after logging.

This trend is reversed, however, in terms of sediment production rates and soil types on the general harvesting area where the metasediment soils tend to produce the highest yields across all age classes (Fig. 11). After five years, there is no significant difference in sediment yields across the three soil types (Table 9).

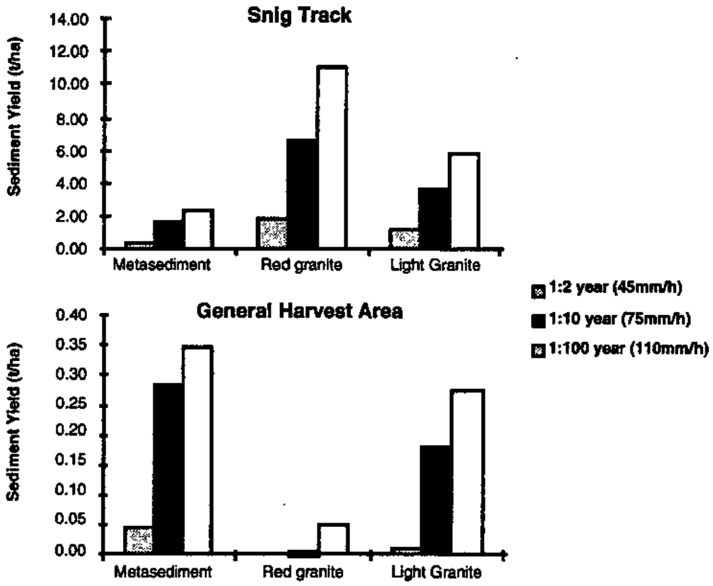


Figure 11. Total sediment yield from the snig tracks and general harvesting areas on the most recently logged sites across each of the soil types. Note differing scales on the two parts of this diagram.

5.1.5 *Sediment Production with time since logging*

Total sediment yield declines on the snig tracks and general harvesting areas over time across all three soil types (Fig. 12). On the snig tracks, the rate of decline over the five year period is steepest for the two more erodible granitic soils (LG and RG in Fig. 12). Snig tracks across all three soil types display a rapid reduction in total sediment yield within the first year after the post-harvest burn and rates decline to a similar value of 0.2 kg/m² five years after logging. This trend is also evident in yield changes with time on the general harvesting areas (Fig. 12).

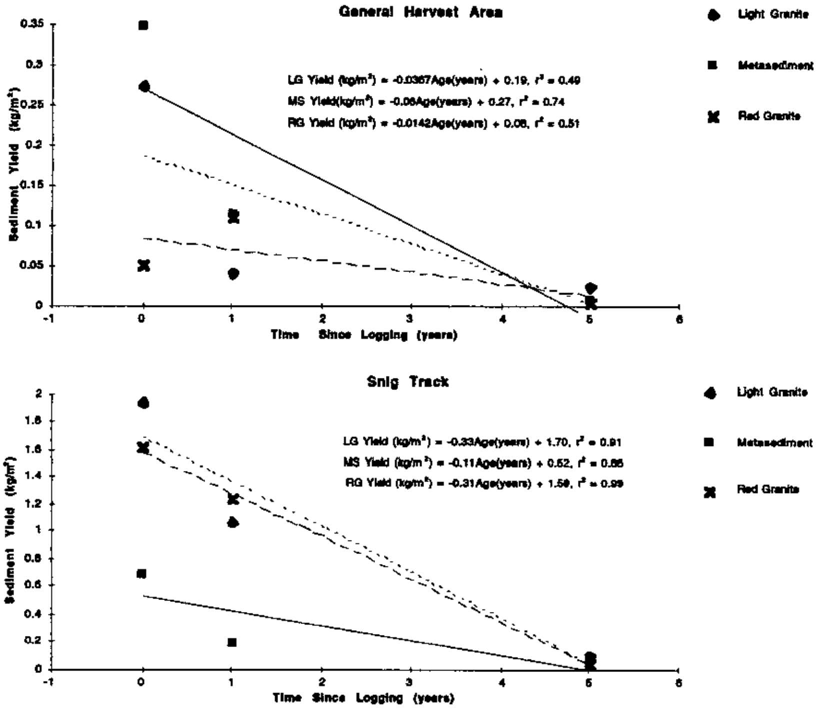


Figure 12. Relationship between total sediment yield and time since logging for the 1:100 year storms. Note differences in scale between two parts of the diagram.

Sediment yield on the snig tracks declines with increasing total cover with r^2 values ranging from 0.63 to 0.80 for the three rainfall intensities (Fig. 13). The 1:10 year storm with rainfall intensities of 75 mm h^{-1} produces the best co-efficient of variation (80%) suggesting that cover is most effective in reducing sediment yield at this intensity. As in the case of surface runoff, the relationships between sediment yield and cover are better for total cover as opposed to contact cover where r^2 values reduce to between 0.44 and 0.66.

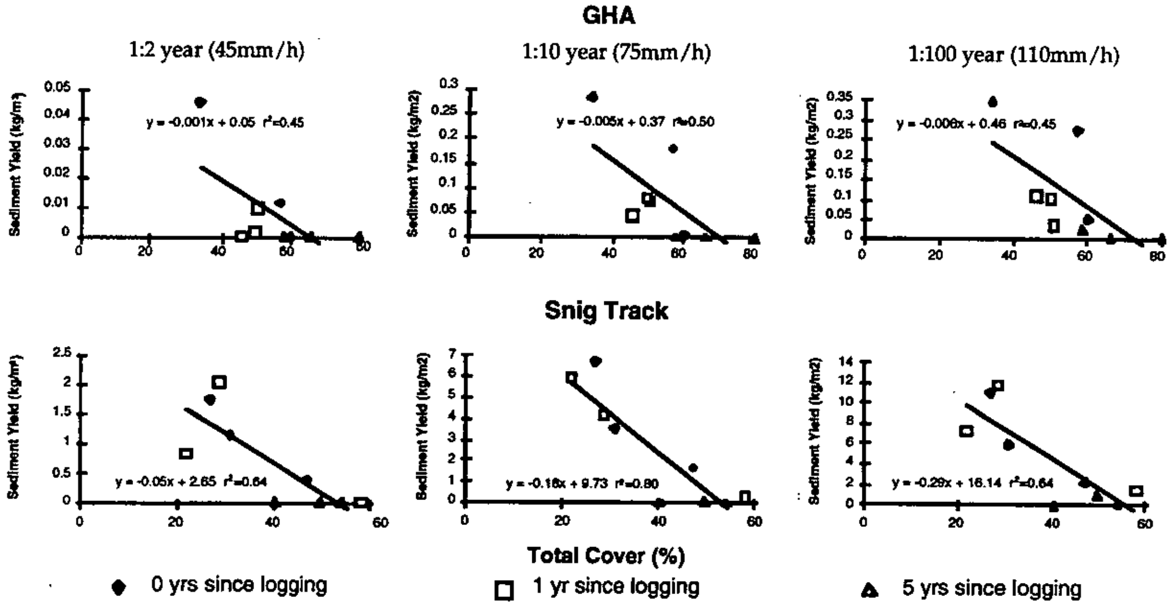


Figure 13. Relationship between sediment yield and total cover on the snig track and general harvest area for the 1:2, 1:10 and 1:100 year storms.

5.2 Sediment Re-distribution

Erosion undoubtedly occurs in forestry environments and, in particular, on disturbed, areas such as snig tracks. The transportation and delivery of this material to the drainage lines depends upon a number of factors. These include the prevailing slope, topography, soil texture, and trapping efficiency of drainage structures and protection features, such as buffer strips, within the catchment. The rainfall simulator experiments used in this study cannot comment specifically on the delivery of eroded sediments to the water course. All of the experimental plots where several hundred metres upslope of any appreciable drainage line. However, we can quantify sediment re-distribution within the 300 m^2 area of forest hillslope. This provides some insight into the nature and extent of sediment re-distribution between the snig track and general harvest area and changes in delivery rates as a result of erosion control structures such as cross banks.

5.2.1 Sediment re-distribution within the experimental plot

Sediment re-distribution on two recently logged and two, 5 year old compartments is illustrated in Figure 14. The most obvious changes in sediment yields on all plots occurs in the vicinity of the cross bank features. The type of cross banks present at each of the nine sites were similar in nature and in their quality of construction. They were on average 5 m wide and 50 cm high with a relatively gentle cross slope of 2^0. In the majority of cases they were constructed to promote runoff discharge into the general harvesting area. A well defined depositional fan was present at the exit of the bank illustrating previous episodes of sediment deposition from natural rainfall events.

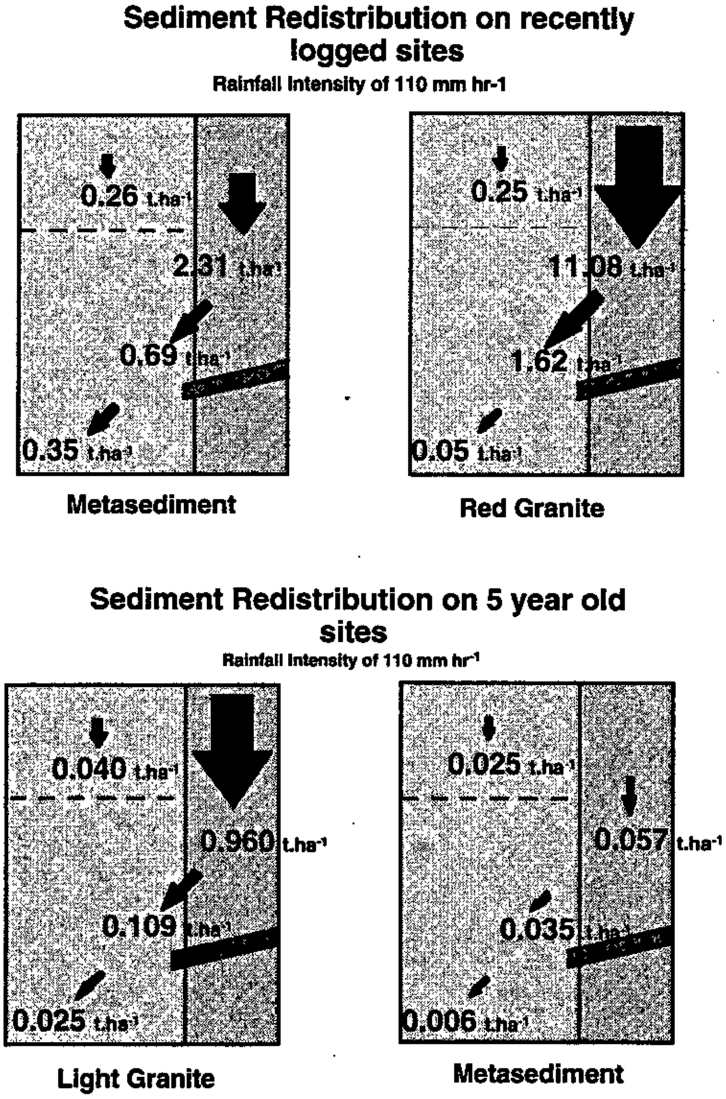


Figure 14. Sediment re-distribution at the plot scale for the recent and 5 year old sites. Values shown are sediment yield per unit contributing area summed over the duration of the run [6].

The percentage of sediment deposited at each of the cross banks varies from 40% to 100%[7] across all soil and age classes (Table 10). On the most recently logged sites, the percentage deposited ranges between 65 and 94% (Fig. 15). The particle size distribution of the eroded sediment from the snig

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[6] Because the trench receives discharge from the snig track and general harvesting areas, values of sediment yield for the trench have been calculated using the combined contributing area of approximately 250 m^2.

[7] Where 100% deposition is recorded, runoff failed to occur through the crossbank flume and all eroded sediment from the snig track was deposited at the bank.

track and the cross bank outlet indicates the propensity for the coarser sediment to be deposited in this area, leaving a predominance of fine materials to be transported into the general harvesting area (Fig. 16).

Table 10. Percentage sediment deposited, and exiting the cross banks across each soil and age class.

Rainfall Intensity	**Location**	**Percentage Sediment Deposited**								
		Metasediment			**Red Granite**			**Light Granite**		
		0.5 yrs	**1 yr**	**5 yrs**	**0.5 yrs**	**1 yr**	**5 yrs**	**0.5 yrs**	**1 yr**	**5 yrs**
45mm/h	Deposited in Cross Bank	65	99	100	94	84	100	78	76	100
	Exited Cross Bank	35	1	0	6	16	0	22	24	0
75mm/h	Deposited in Cross Bank	67	73	46	93	88	71	72	73	98
	Exited Cross Bank	33	27	54	7	12	29	28	27	2
110mm/h	Deposited in Cross Bank	67	88	43	84	82	33	65	70	87
	Exited Cross Bank	33	12	57	16	18	67	35	30	13

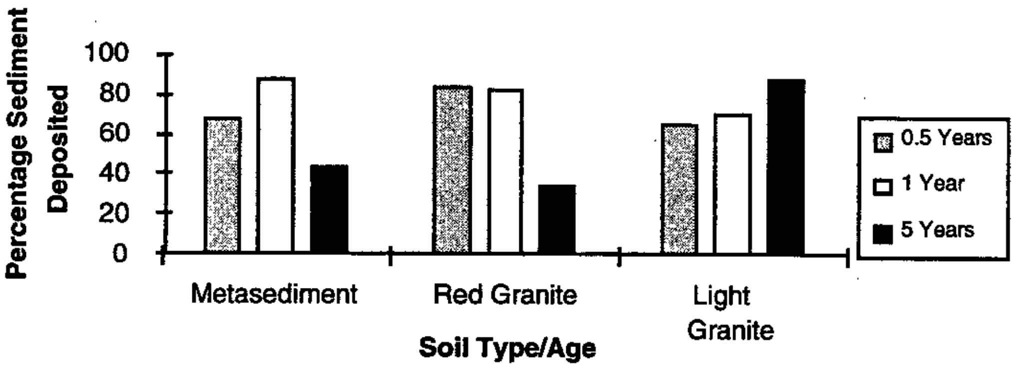


Figure 15. Percentage material deposited at the cross bank outlet during the 1:100 year storm across all soil types.

Cross banks in the 5 year sites on both the metasediment and red granite soils, where sediment deposition ranges from 32% to 70%, would appear to be less effective in promoting sediment deposition (Table 10). In the case of the 5 year site on the metasediment soils, the effectiveness of the bank is reduced because almost 50% of the eroded snig track sediment is less than 0.125 mm in size and even the reduced velocities in the cross bank area are sufficient to transport this material into the general harvesting area. In the case of the 5 year old red granite site, the presence of logs within the cross bank structure promoted some throughflow of runoff and associated sediment downslope so that overall, the cross bank construction was less effective.

The second area of noticeable differences in sediment yield occurs at the exit of the plot from the bottom trench. On the most recently logged sites, for example, the finer grained metasediment soils actually produced a slightly higher total sediment yield than the red granite soil (Fig. 14). Thus, while the granite soils are more erodible and produce higher sediment volumes on the snig track, much of this sediment appears to be deposited when flow velocities reduce either due to erosion control measures such as cross banks or due to increased roughness on the general harvesting area. In contrast the metasediment soils, once mobilised and in suspension, appear to be transported further. Relative differences in sediment yield from the cross bank outlet to the trench, a distance of about 5-7m, suggest that approximately 50% of the sediment eroded on the metasediment sites reached the hillslope trench. Although this is not an absolute measure of sediment deposition within the general harvesting area since it is not possible to differentiate the snig track sediment from that derived from the general harvesting area upslope, our visual observations from dye traces suggest that the discharge plume from the cross bank outlet formed the dominant sediment source reaching the bottom trench. Additional field experiments will attempt to partition the snig track runoff from that produced on the general harvesting area to investigate this relationship further.

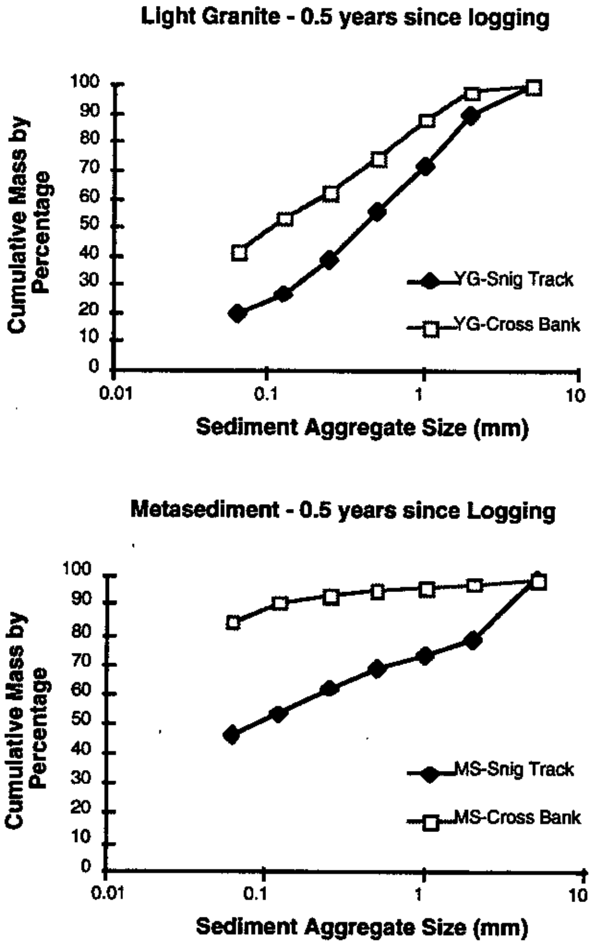


Figure 16. Sediment aggregate size distribution of the eroded sediment on the snig track and exiting the cross bank outlet.

5.3 Summary and Conclusions

The results of a series of rainfall simulator experiments have been reported in which the experimental variables were time since logging, rainfall intensity and soil type. The experimental design allowed runoff, sediment yield and sediment delivery to be measured for a hillslope containing both a snig track and general harvest area. This report provides a summary of the data and initial interpretation.

These experiments confirm the importance of compacted surfaces, such as snig tracks, as major sources of sediment and runoff in logged catchments. Sediment yields reported here for snig tracks and general harvesting areas are for simulated rainfall events of 30 minute duration. Comparisons with other values reported in the literature are difficult due to differences in the experimental design and the use of simulated storms of 30 minute duration.

Field evidence of rill and gully development particularly on the granite soils confirms the susceptibility of these soils to surface wash erosion. Although snig tracks on the five year old compartments produced relatively low volumes of runoff, our observations suggest that the majority of this was rill flow. Thus once gullies or rills have formed it is difficult to reduce surface runoff and sediment volumes by the natural regeneration processes which occur on the interrill areas. The degree of compaction and disturbance caused by the relative usage of tracks and access roads will also enhance sediment and runoff generation rates. In addition, sediment delivery will increase significantly when major flow paths connect with other disturbed areas such as forest roads or access tracks. It is imperative, therefore, that these features and other compacted surfaces are accounted for in the planning stages of forestry operations to ensure the protection of watercourses in logged catchments.

General harvesting areas yielded relatively small volumes of sediment and high infiltration characteristics resulted in patchy overland flow. The dominance of partial area runoff processes in this area, caused primarily by spatially variable soil hydraulic properties, is seen as a major factor in reducing runoff and sediment yields. Unlike the snig track surfaces where sheet flow and rill development were commonly observed, surface runoff on the general harvesting area was always observed to be patchy, so that it is less likely to connect to drainage lines. Sediment delivery rates through these areas are also reduced due to the increased roughness of remaining understorey vegetation which promotes sediment deposition. Limiting the degree of disturbance on these areas, and in particular, that of compaction and topsoil removal, is crucial to managing sediment production and delivery. General harvesting areas are very important for absorbing excess runoff generated on the more disturbed, compacted surfaces and for promoting sediment deposition due to the increased hydraulic roughness of more abundant vegetation cover.

Cross banks were found to have two important functions in this type of forest harvesting system. Firstly the cross banks redirect overland flow into the general harvest area with the benefits which have been discussed above. Secondly they provide an effective sediment trap of coarse sediment, thereby, reducing sediment delivery to the general harvesting area. All findings of this research emphasise the importance of careful cross bank construction immediately after logging has ceased.

- Soil type was not a major factor in explaining relative differences in runoff and sediment production in this study. In contrast, the degree of disturbance between the snig track and general harvesting area produced significant differences in both surface runoff and sediment erosion rates between these surfaces.
- Runoff and sediment yield were highest on the compacted snig track surfaces across all soil and age categories. On recently logged sites, snig tracks generated, on average, 7 times more surface runoff and 20 times more sediment per unit area than the general harvesting areas.
- The highest on-site erosion rates occurred on the coarse grained red granite soils around the Bombala region where maximum yields were in the order of 11 t/ha on the snig track surface in a 30 minute 1:100 year event. Lowest sediment yield was measured on snig tracks on the metasediment sites.
- Runoff and sediment yields declined over time and with increasing vegetation cover across all soil types. The granites showed the greatest susceptibility to high on-site erosion in the early stages of site recovery after logging, but all three soils produced similar volumes after five years.
- The nature of sediment re-distribution within the plots revealed that the more stable, metasediment soils actually yielded higher total soil losses from the plots due to their finer-grained texture. These soils may pose a greater threat, therefore, to in-stream water quality than the coarser granite soils which are likely to have longer residence times.
- Cross banks were effective measures of reducing sediment delivery to the general harvesting areas across all soil and age classes.

5.4. Future Research

The CRC for Catchment Hydrology have recently initiated a new core Program of Forest Hydrology research to be funded for three years (1996-1999). ***Project F01**: 'Sediment Movement in Forestry Environments; managing the important pathways to streams'* forms a core project within this Program. It aims to continue investigating the nature and scale of sediment movement in logged catchments with the objective of providing quantitative data to be used in reviewing the scientific rationale for Codes of Forest Practices and pollution control licences. The Eden Management Area data have recently be augmented by rainfall simulator experiments on three sites in the East Gippsland forests of eastern Victoria. In addition, the project is currently developing an experimental design using the rainfall simulator to investigate the rate of sediment production on forest roads in south eastern NSW. This study will also investigate the trapping efficiency of road drainage structures and their sediment delivery rates to drainage lines. These data will be used in association with GIS and physically-based erosion prediction models to develop summary models and nomograms for the development of 'Best Management Practices' in these environments.

BIBLIOGRAPHY

Anderson, B. and Potts, D. F. (1987) Suspended sediment and turbidity following road construction and logging in western Montana. Water Resources Bulletin, 23, 681-690.

Bridge, B. J., and Ross, P. J. (1985) A portable microcomputer -controlled drip infiltrometers field measurement of sorptivity, hydraulic conductivity and time to ponding. Australian Journal of Soil Research, 23, 393-404.

Brown, G. W. and Krygier, J. T. (1971a) Effects of clearcutting on stream temperatures, In Studies on effects of watershed practices on streams. School of Forestry, Oregon State University, Corvallis, Oregon, 1-14.

Brown, G. W. and Krygier, J. T. (1971b) Clearcut logging and sediment production in the Oregon Coast Range. Water Resources Research, 7, 1189-1198.

Cameron, A. L. and Henderson, L. E. (1979) Environmental considerations for forest harvesting. The Harvesting Research Group, CSIRO Division of Forestry, Canberra and Melbourne, 71pp.

Campbell, I. C. and Doeg, T. J. (1989) Impact of timber harvesting and production on streams: A review. Australian Journal of Marine and Freshwater Research 40, 519-539.

Cornish, P. M. and Binns, D. (1987) Streamwater quality following logging and wildfire in a dry sclerophyll forest in south eastern Australia. Forest Ecology and management, 22, 1-28.

Davies, P. and Neilson, M. (1993) The effect of steep slope logging on fine sediment infiltration into the beds of ephemeral and perennial streams of the Dazzler Range, Tasmania, Australia. Journal of Hydrology, 150, 481-505.

Doeg, T. J. and Koehn, J. D., (1990) A review of Australian studies on the effects of forestry practices on Aquatic values. SSP Technical Report No 5, Melbourne Department of Conservation and Environment, Victoria.

Dunne, T., Zhang, W. and Aubry, B. F., (1991) Effects of rainfall, vegetation, and microtopography on infiltration and runoff. Water Resources Research, 27, 2271-2285.

DWR (1989) Water Victoria: An environmental Handbook. Department of Water Resources, Melbourne.

EPA (1995) Pollution Control Licence, Environment Protection Authority, New South Wales, 75pp.

Farrish, K. W., (1990) Effects of soil loss on emergence and growth of loblolly pine. Journal of Soil and Water Conservation, 45, 415-417.

Fredriksen, R. L. (1971) Comparative chemical water quality- natural and disturbed streams following logging and slash burning. *In* Krygier, J. T. and Hall, J. D. (eds.) Proceedings of a Symposium on Forest land use and the stream environment. Oregon State University, Corvallis, Oregon, 125-137.

Fredriksen, R. L., Moore, G. C., and Norris, L. A. (1975) The impact of timber harvest, fertilization and herbicide treatment on streamwater quality in western Oregon and Washington. *In* Bernier, B. and Winget, C. H. (eds.), Forest Soils and Forest Land management, Quebec, 283-313.

Graynoth, E. (1979) Effects of logging on stream environments and faunas in Nelson. New Zealand Journal of Marine and Freshwater Research, 13: 79-109

Grayson, R. B., Haydon, S. R., Jayasuriya, M. D. A., and Finlayson, B. L. (1993) Water quality in mountain ash forests- separating the impacts of roads from those of logging operations. Journal of Hydrology, 150 p459-480

Greacen, E. L., and Sands, R. (1980) A review of compaction of forest soils. Australian Journal of Soil Research, 18, 163-189.

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, Melbourne Victoria, Report MMBW-W-0018 131p

Hewlett, J. D., Post, H. E., and Doss, R. (1984) Effect of clear cut silviculture on dissolved ion export and water yield in the Piedmont. Water Resources Research, 20, 1030-1038

Hopmans, P., Flinn, D. W., and Farrell, P. W. (1987) Nutrient dynamics of forested catchments in south eastern Australia and changes in water quality and nutrient exports following clearing. Forest Ecology and Management, 20, 209-231.

Horton, R. E. (1933) The role of infiltration in the hydrological cycle. Transactions of the American Geophysical Union, Reports and papers, Hydrology, 189-202.

Huang, J., Lacey, S.T., and Ryan, P. J. (1996) Impact of forest harvesting on the hydraulic properties of surface soil. Soil Science, 161, 79-86.

Incerti, M., Clinnick, P. F., and Willatt, S.T., (1987) Changes in the physical properties of a forest soil following logging. Australian Forest Research, 17, 91-108.

Johnson, G.M. and Beschta, R.L., (1980) Logging, infiltration capacity and surface erodibility in western Oregon. Journal Forestry, 78, 334-337.

Kemper, W.D., and Rosenau, R. C., (1986) Ch.17. Aggregate stability and size distribution *In* (ed. Klute, A.), Methods of Soil Analysis Part 1: Physical and mineralogical methods, American Soil Science Society, Madison.

King, M., Rab, A. and Baker, T. (1993) The regeneration of Eucalyptus Regnans under alternative silvicultural systems : Effect of seedbed on seedling growth. VSP Internal Report No. 24, DNRE, Victoria.

Kriek, P. N. and O'Shaughnessy, P. J. (1975) Some initial effects of water quantity and quality of an experimental reading and timber harvest in operation in a Victorian Mountain catchment. 7th Triennial Conference of the Institute of Foresters of Australia.

Langford, K. J. and O'Shaughnessy, P. J. (1980) Second Progress Report-Coranderrk. MMBW, Catchment Hydrology Research Report No. MMBW-W-0010.

Langford, K. J., Moran, R. J., and O'Shaughnessy, P. J. . (1982) The Coranderrk Experiment- the effects of roading and timber harvesting in a mature Mountain Ash forest on streamflow yield and quality. First National Symposium on Forest Hydrology, 11-13, p92-102

Lemin, H. and Brophy, J. (1992) Rainfall Simulator experiments for Tasmanian rainfall Experiment. CSIRO Division of Water Resources, Internal Report, pp20.

Likens, G. E., Bormann, F. H., Johnson, N. M., Fisher, D. W. and Pierce, R. S. (1970) Effects of forest cutting and herbicide treatment on nutrient budgets in the Hubbard Brook watershed-ecosystem. Ecological Monographs, 40, 23-47

Lockaby, B. G., and Virdine, C. G. (1984) Effect of logging equipment traffic on soil density and growth and survival of young loblolly pine. Journal of applied Forestry, 8, 109-112.

Martin, C. W. and Pierce, R. S., (1980) Clearcutting patterns affect nitrate and calcium in streams of New Hampshire. Journal of Forestry 78(5), 268-272

Megahan, W. F., and Kidd, W. J., (1972) Effects of logging and logging roads on erosion and sediment deposition from steep terrain. Journal Forestry, 70, 136-141.

Northcote, K. H., Hubble, G. D., Isbell, R. F., Thompson, G. H., and Bettenay, E., (1975) A description of Australian soils. CSIRO, Australia. 170pp.

OCE (1988) Victoria's Inland Waters. Office of the Commissioner for the Environment, Victoria

Olive, L. J. and Rieger, W. A., (1987) Variation in suspended sediment concentration during storms in five small catchments in south east NSW. Australian Geographical Studies, 23, 38-51

Pilgrim, D. H., (1987) Australian rainfall and Runoff- A Guide to Flood Estimation. Volume 1, The Institution of Engineers, Australia.

Rab, M. A., (1992) Impact of timber harvesting on soil disturbance and compaction with reference to residual log harvest in East Gippsland. Victoria: A Review. VSP Technical Report No. 13, DNRE, Victoria.

R.A.C., (1992), Forest and Timber Inquiry Final Report. Resource Assessment Commission, Australian Government Publishing Service, Canberra.

Reid, L. M. and Dunne, T., (1984) Sediment production from forest road surfaces. Water Resources Research, 20, 1753-1761.

Reinson, G. E., (1976) Hydrogeochemistry of the Genoa River basin, NSW-Victoria. Australian Journal of Marine and Freshwater Research, 27, 165-186.

Rosewell, C. W., and Turner, J. B., (1992) Rainfall Erosivity in NSW. Technical Report No. 20, department of Conservation and Land Management, Sydney, NSW.

Wert, S., and Thomas, B. R., (1981) Effects of skid roads on diameter, height, and volume growth in Douglas fir. Soil Science American Journal, 45, 629-632.

Wischmeier, W.H., and D. D., Smith (1978) Predicting rainfall erosion losses- A guide to conservation planning. Agricultural Handbook, 537, U.S. department of Agriculture, Washington, D.C.

APPENDIX 1

EXPERIMENTAL DESIGN

Rainfall was generated in these experiments using CSIRO's large, field-based rainfall simulator. A more detailed description of the simulator's design and development is described in Wilson *et al.* (in prep) and this report will confine itself to the specific modifications and refinements used in the collection of runoff and erosion data in the EMA experiments of 1995-1996. The report by Lemin and Brophy (1992) outlines in detail the methods of raindrop size calibration and illustrates the range of rainfall distributions obtained using this simulators sprinkler configuration.

Selection of Storm Intensities:

Intensity frequency curves for storms of 30 minute duration and with recurrence intervals of 1:1, 1:2, 1:5, 1:10, 1:20, 1:50 and 1:100 years were calculated according to the procedures outlined in 'Australian Rainfall and Runoff' (Pilgrim, 1987). Rainfall intensities are listed for these events in Table 3 using rainfall estimates from three locations across the study area. These included White Rock Mountain representing rainfall conditions in the region around Bombala, Murrah State Forest representing the coastal sites and Araluen PO, the closest station containing long term rainfall records within the study area. Rainfall intensities from these three locations were averaged to derive 'representative' intensities for selected recurrence interval storms.

A series of preliminary field simulations were conducted on-site at CSIRO to match these intensities with the sprinkler nozzles and pump pressures used with this rainfall simulator. Previous field tests by Lemin and Brophy (1992) indicated that the two sprinkler-nozzle sizes, HH 3/4 7 and HH 1/10 produced a median drop size of 2.5 mm and so our field tests were confined to these two nozzle sizes. Field tests confirmed that a 1 in 1 year storm using the smallest nozzle size of HH 3/47 could not be simulated accurately at pump pressures of 10 psi or more. The average value of 45 mm h-1 measured during the field tests proved higher than that required for an event of this recurrence interval (Table 10). Once the pump pressure was reduced to less than 10 psi, the raindrop size reduced considerably to a fine spray and produced poor spatial coverage. A 1:2 year event was simulated accurately using this sprinkler nozzle and this event was chosen, therefore, to represent our lowest recurrence interval storm. The larger nozzle size of HH 1/10 produced a mean rainfall intensity of 75 mm h-1 which represented on average, a 1:10 year event in the region. By combining the outflow from both nozzles, HH 3/4 7 and HH 1/10 we were able to simulate a 1:100 year event with an average rainfall intensity of 110 mm h-1.

Table 11. Intensity Frequency Duration values (mm h^{-1}) for a selection of storm events of 30 minute duration in the EMA.

Location	*1:1*	*1:2*	*1:5*	*1:10*	*1:20*	*1:50*	*1:100*
Coastal	42. 13	55.15	73.97	86.24	102.20	120. 41	141.54
Granites	30. 50	40.36	55.58	66.22	80.08	94.60	115.79
Araluen	35.95	46.72	61.47	70.74	82.88	97.11	112.12
Mean	36.19	47.41	63.67	74.4	88.38	104.04	123.15

Table 12. Pre-experiment results of rainfall intensities from different size sprinkler nozzles.

Nozzle Size	Pressure psi	Run 1 mm/h	Run 2 mm/h	Run 3 mm/h	Distribution
HH 1/10	10 psi	74.6	64.2	66.4	Drop size variable
HH 1/10	20 psi	75.8	74.2	74.6	Good cover
HH 1/10	40 psi	101.8	84.2	108.2	Fine spray
HH 3/4 7	10 psi	48	50.2	49.8	Good Cover
HH 3/4 7	40 psi	115	91	91	Drop size variable

Rainfall Distribution

Rainfall was provided by ten 'Spraying Systems' sprinklers mounted so as to spray upwards on top of 3 m tall risers placed in parallel rows, 6 m apart, and arranged in equilateral triangles approximately 6 m on each side (Fig. 18). Design intensities were compared with the collected volumes from eighteen rain gauges during the experiments and produced a coefficient of variation of 7.8%. Rainfall distribution maps were produced for each rainfall intensity using the location reference for each of the rain gauges and the volumes recorded (Fig. 20-29). Wind speed and directions were variable, but not extreme, throughout the experiments and the spatial distribution is considered good. Major variations in distribution are more likely a function of slight variations in the location of the rainfall gauges, and in particular, the presence of vegetation or sudden changes in wind speed or direction, than problems with the sprinkler configuration.

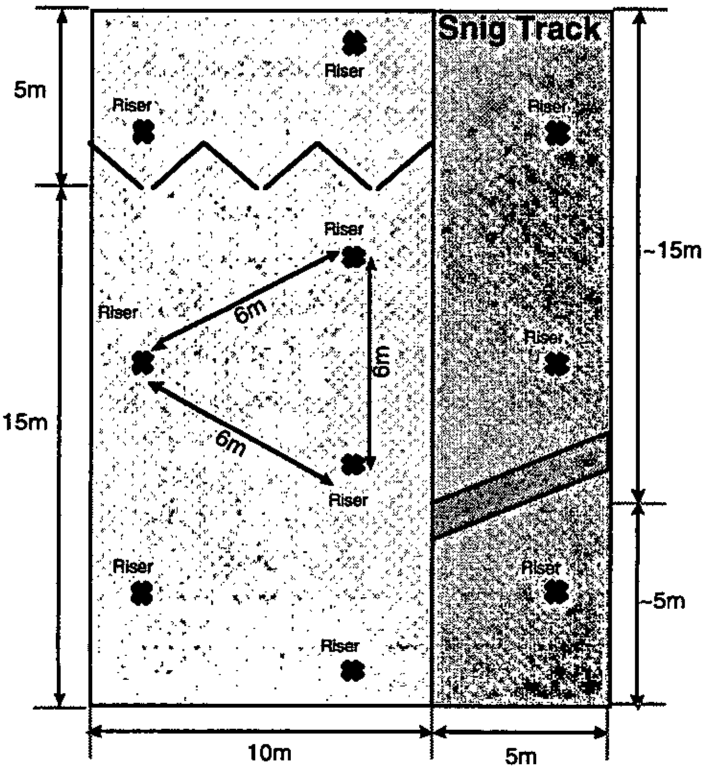


Figure 17. Configuration of rainfall risers within the 300m^2 plot

APPENDIX 2

PARAMETER CALCULATIONS

Rates and total volumes of surface runoff

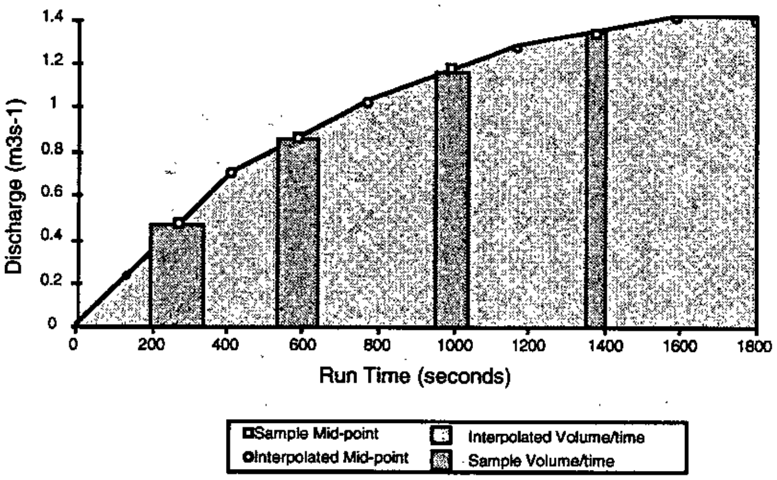
Discharge, g, (m^3 s^{-1}) was calculated using two methods. For all sample locations discharge was estimated at the time of sampling by dividing runoff volume of the sample by time, which was measured at each sample location to an accuracy of ±0.5 seconds. A calibration equation for the appropriate sample container was then applied to convert depth of sample to volume of sample. Note that for the snig track sample discharge was not calculated by this method as the sample was only a fraction of the total flow. At this location the discharge was assumed to be equal to the cross bank discharge. The second method of obtaining measures of discharge was used at the cross-bank outlet and base of the plot where flumes and associated continuous loggers were located. For the majority of simulations, hydrographs were produced using the flume data. In some instances, however, coarse sediment is believed to have become lodged in the flume and disrupted the stage readings. Timed samples were used to construct hydrographs in these instances.

Volumetric water flux, q, (m^3 m width^{-1} s^{-1}), which is the rate of volume flow of water per unit strip width, was calculated for each sample by dividing discharge by the unit width of the snig track.

Total runoff per unit area (mm) was calculated for each of the sample stations using flume data where available, or by plotting the time variable, volumetric water flux and calculating the area beneath the curve using the modified trapezoidal rule method (Fig 18). Total runoff volumes,

$\int_{t_0}^{T} g\,dt$ where obtained using the modified trapezoidal rule method given in equations [A1] and [A2].

Where possible, the results from the two runoff rate methods were compared and produced a co-efficient of variation of 4.5 %. Contributing areas were calculated from topographic surveys of each plot.



Total runoff volume for an event is approximately given by :

$$\int_{t_0}^{T} g\,dt \approx \frac{1}{2}\begin{bmatrix} (g(t_0)+g(t_1))(t_1-t_0) \\ +(g(t_1)+g(t_2))(t_2-t_1) \\ +\ldots \\ +(g(t_T)+g(t_{T-1}))(t_T-t_{T-1}) \end{bmatrix} \qquad [A1]$$

where: t_0 = the time at the beginning of a run (normally 0 seconds)

T = the duration of simulated rainfall during a run (normally 1800 seconds)

n = the number of discharge measurements

$g(t_n)$ = discharge ($m^3 s^{-1}$) at time, t_i

if $t_{last} \geq T$, then

$$g(t_T) = g(t_{last-1}) + T\left(\frac{g(t_{last}) - g(t_{last-1})}{t_{last} - t_{last-1}}\right) \qquad [A2]$$

if $t_{last} < T$, then

we assume $g(t_T) = g(t_{last})$,

where t_{last} = time of last sample

Figure 18. Calculation of total runoff volumes using a modified version of the trapezoidal method.

Runoff Coefficients (%) for the snig track and general harvesting areas were calculated by expressing surface runoff volume (mm) as a percentage of the mean rainfall applied over the duration of the event (mm). Actual values of rainfall amounts were used as opposed to the design intensity and this allowed for fluctuations in rainfall due to changes in wind, pump pressure etc to be accommodated for in the calculation.

Sediment Concentrations and Total Sediment Yields

Sediment concentration, c (kgm^3) was obtained by oven drying the collected runoff samples and weighing the sediment mass remaining. Sediment weight was then divided by the sample volume to produce sediment concentrations.

Sediment Flux, q_s (kgm^3 s^{-1}), defined as the mass of sediment flowing per unit time across a unit width perpendicular to the direction of the flux, is calculated for each of the samples as the product of sediment concentration, c, and discharge, g. Sediment flux per unit width (kg m^3 m^{-1} s^{-1}) was calculated by dividing the combined product of sediment concentration and discharge by the width of the snig track, or general harvesting area.

Sediment Yield (kgm^2) estimates for the snig tracks and general harvesting areas were produced by summing the time variable sediment flux (kg m^3 m s^{-1}) and calculating the area under the curve using the modified trapezoidal rule method (Fig. 18). The total sediment mass per unit width was then multiplied by the length of the snig track to produce sediment yield in Kg m^2. This was also converted to tonnes per hectare (t/ha) for ease of comparison with published sediment yield values in the literature.

Soil Loss (kgm^2 or t/ha) for the experimental plots is calculated by summing the time-variable sediment flux (q_s) at the exit of the flume installed at the base of the plot.

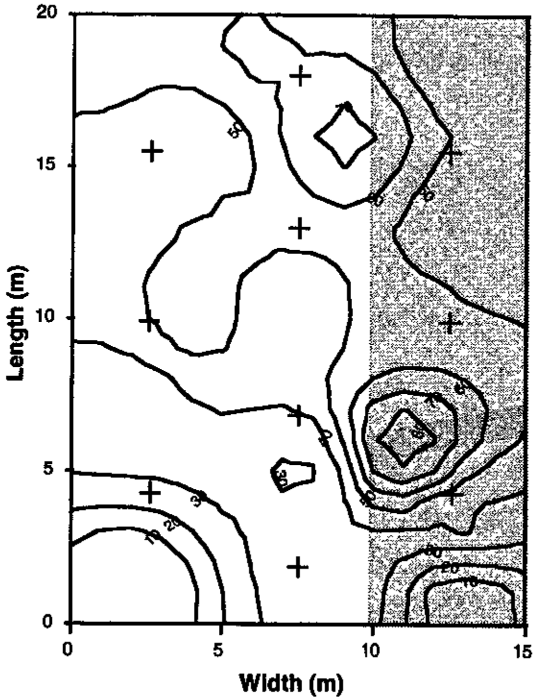
Statistical Analyses

The experimental design used in this investigation consisted of three major factors; rainfall intensity, soil type and recovery age, each with three sub-levels to include three rainfall intensities, three soil types and three recovery ages. This design produced a data matrix suitable for use with descriptive statistics. The absence of replications for any soil or age class makes the use of discriminative statistical analyses, such as analysis of variance (ANOVA) tenuous. However, we use these tests to highlight differences in runoff and sediment yield for similar rainfall intensities *between* sites of equivalent age, and soil type. We acknowledge that the sample population is small and additional data are required to improve the accuracy of the analyses. However, given the spatial and temporal heterogeneity of major controlling factors such as soil physical and hydraulic properties, vegetation cover and degree of disturbance, it is highly unlikely that 'true' replication of site characteristics can ever be found in forestry environments.

APPENDIX 3

Light Granite - 0 years - Bombala
(Compartment Number : 1709 - Site 7)

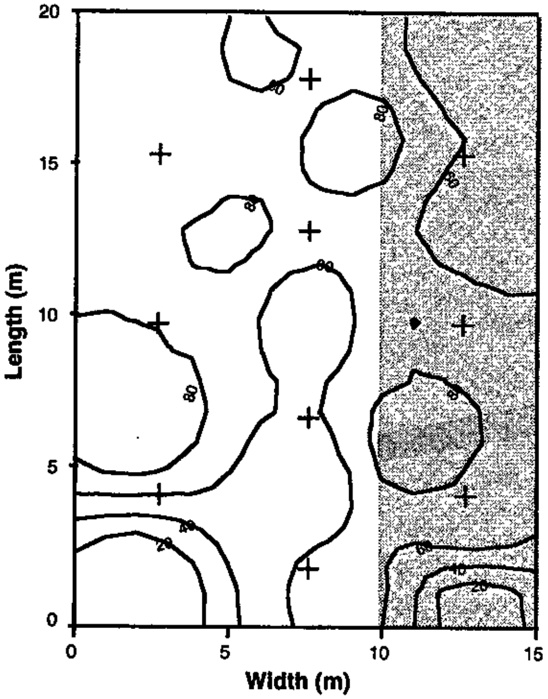
+ Riser
▨ Snig Track
▨ Cross Bank
Isohyet (mm/hr)



Run Number 1

Simulated Rainfall Intensity 45mm/hr

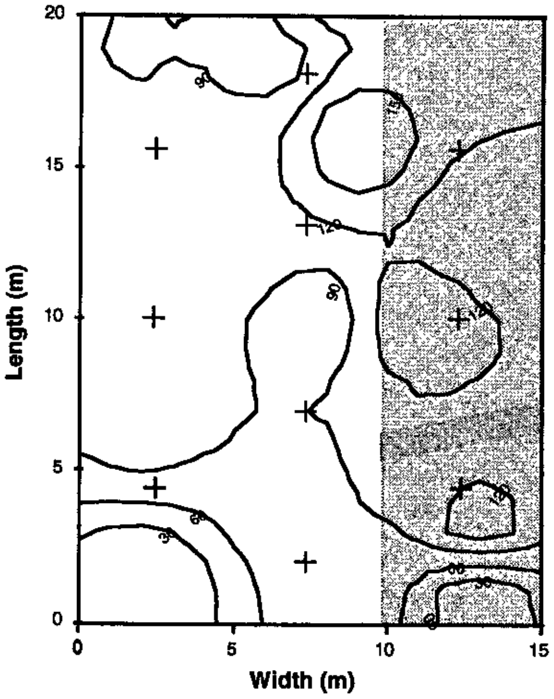
Observed Intensity (mm/hr)
Mean: 43.55
Standard Error: 0.86
Max: 84.20
Min: 0.40



Run Number 2

Simulated Rainfall Intensity 75mm/hr

Observed Intensity (mm/hr)
Mean: 63.62
Standard Error: 1.05
Max: 95.80
Min: 4.20



Run Number 3

Simulated Rainfall Intensity 110mm/hr

Observed Intensity (mm/hr)
Mean: 96.08
Standard Error: 1.75
Max: 171.20
Min: 1.40

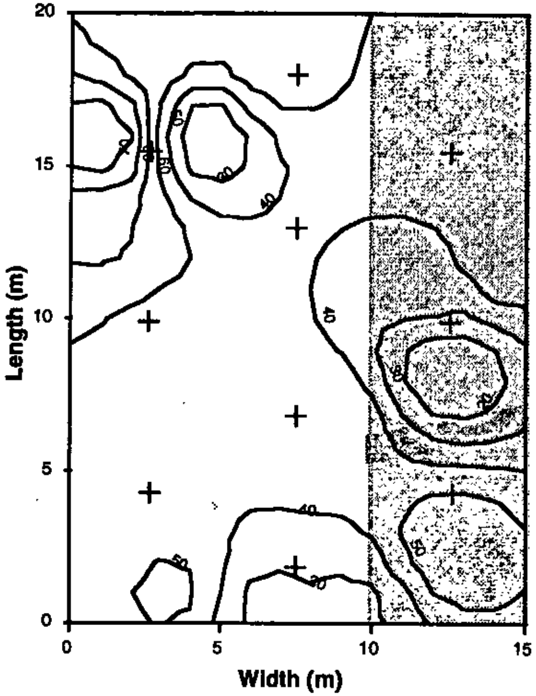
Light Granite - 1 year - Bombala
(Compartment Number : 1226 - Site 1)

+ Riser

▨ Snig Track

▨ Cross Bank

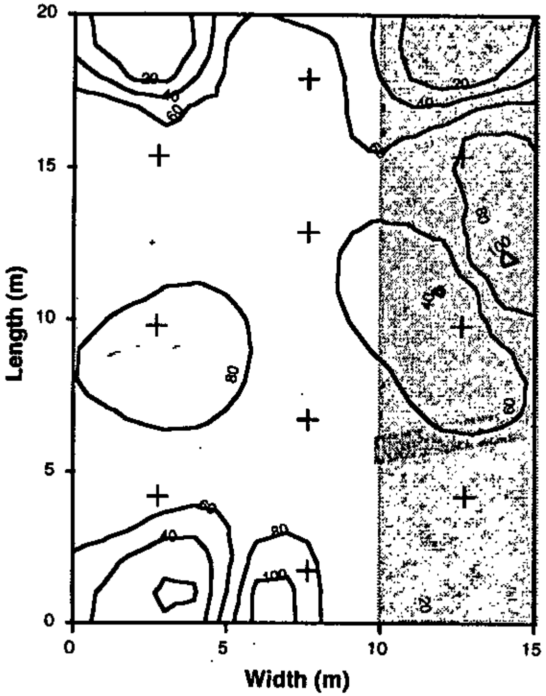
Isohyet (mm/hr)



Run Number 1

Design Intensity: 45mm/hr

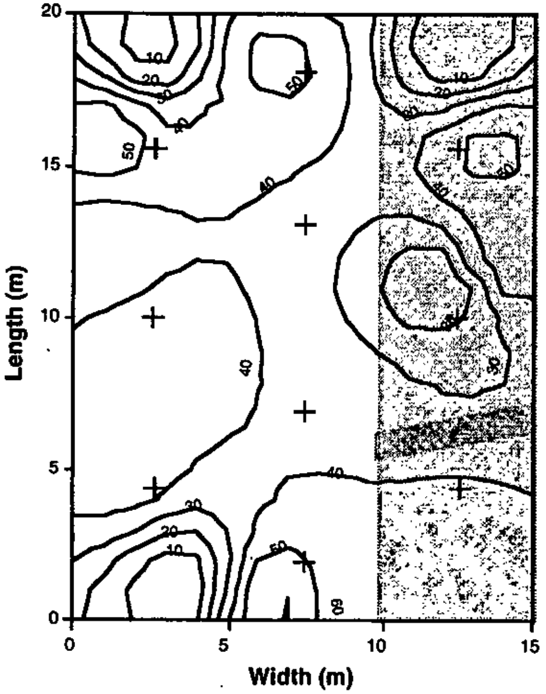
Observed Intensity (mm/hr)
Mean: 44.86
Standard Error: 0.61
Max: 86.40
Min: 12.33



Run Number 2

Design Intensity: 75mm/hr

Observed Intensity (mm/hr)
Mean: 62.92
Standard Error: 1.12
Max: 106.75
Min: 0.38



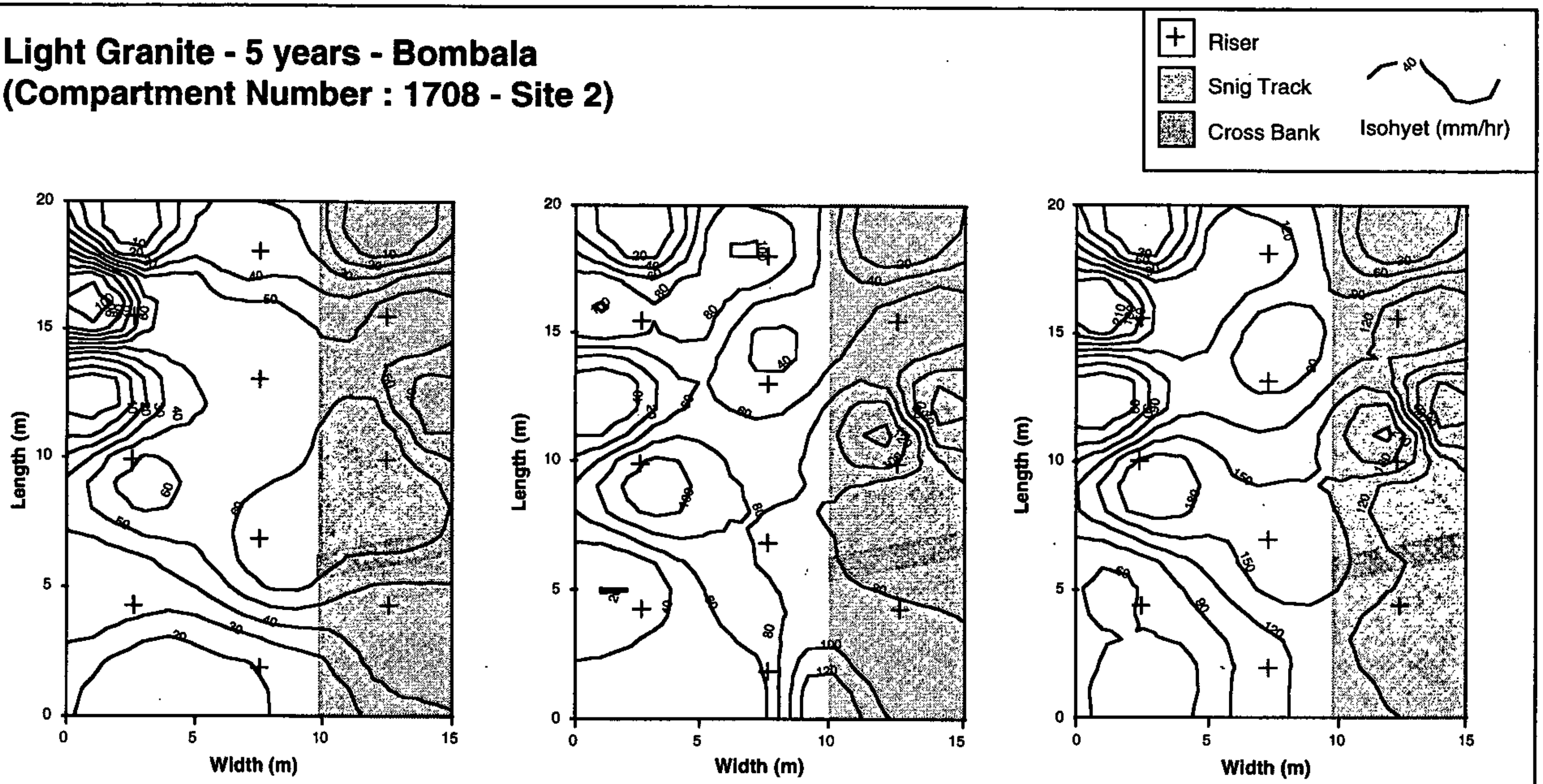
Run Number 3

Design Intensity: 110mm/hr

Observed Intensity (mm/hr)
Mean: 35.96
Standard Error: 0.64
Max: 60.06
Min: 3.02

(NB: 10 minute run, hence 1/3 design intensity)

Light Granite - 5 years - Bombala
(Compartment Number : 1708 - Site 2)



Run Number 1

Simulated Rainfall Intensity 45mm/hr

Observed Intensity (mm/hr)
Mean: 42.28
Standard Error: 1.05
Max: 106.80
Min: 0.67

Run Number 2

Simulated Rainfall Intensity 75mm/hr

Observed Intensity (mm/hr)
Mean: 63.43
Standard Error: 1.51
Max: 132.54
Min: 0.38

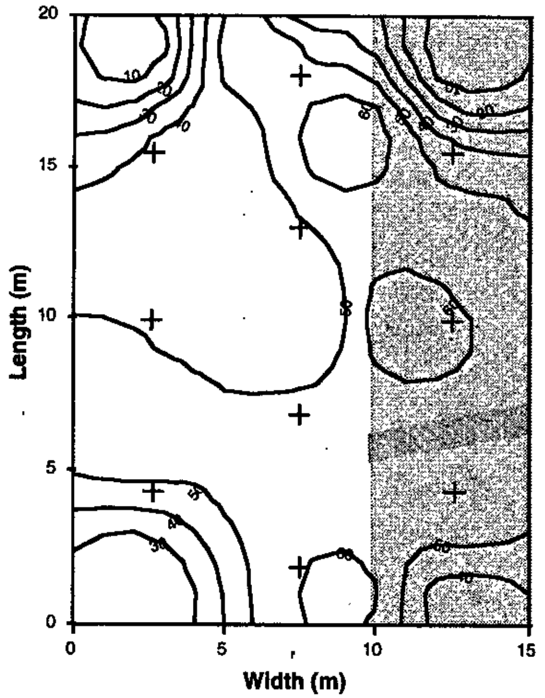
Run Number 3

Simulated Rainfall Intensity 110mm/hr

Observed Intensity (mm/hr)
Mean: 107.61
Standard Error: 2.62
Max: 239.40
Min: 0.69

Red Granite - 0 years - Bombala
(Compartment Number :1312 - Site 9)

+ Riser
▨ Snig Track
▩ Cross Bank
Isohyet (mm/hr)

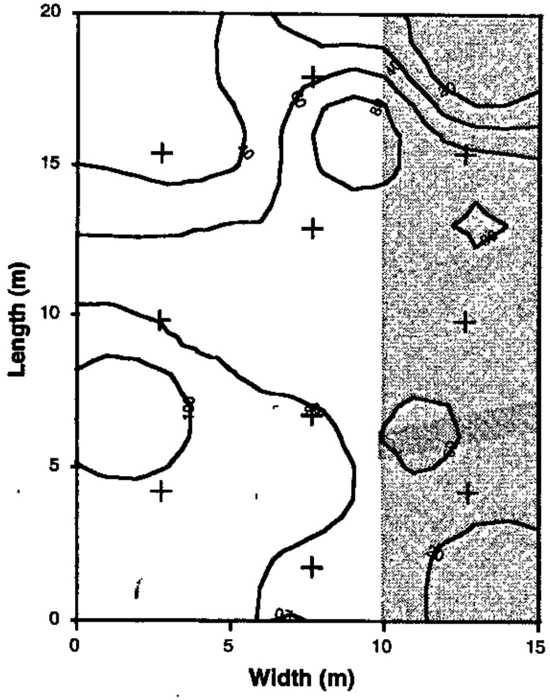


Run Number 1

Simulated Rainfall Intensity 45mm/hr

Observed Intensity (mm/hr)

Mean:	45.54
Standard Error:	0.79
Max:	66.40
Min:	2.80

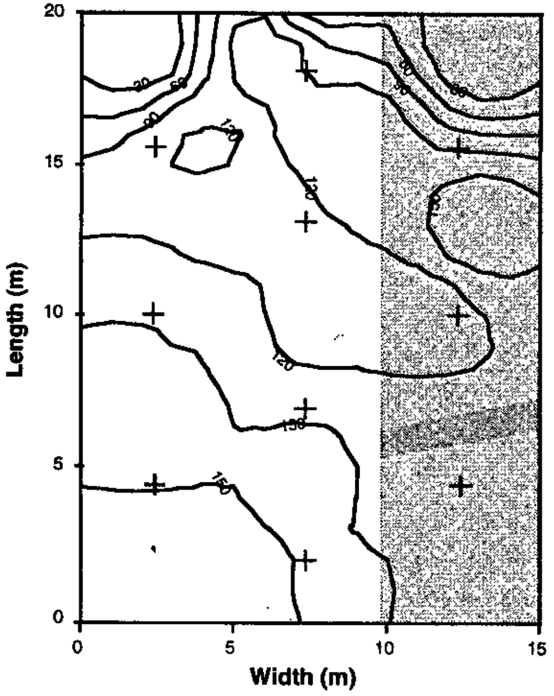


Run Number 2

Simulated Rainfall Intensity 75mm/hr

Observed Intensity (mm/hr)

Mean:	65.27
Standard Error:	1.38
Max:	111.20
Min:	0.40



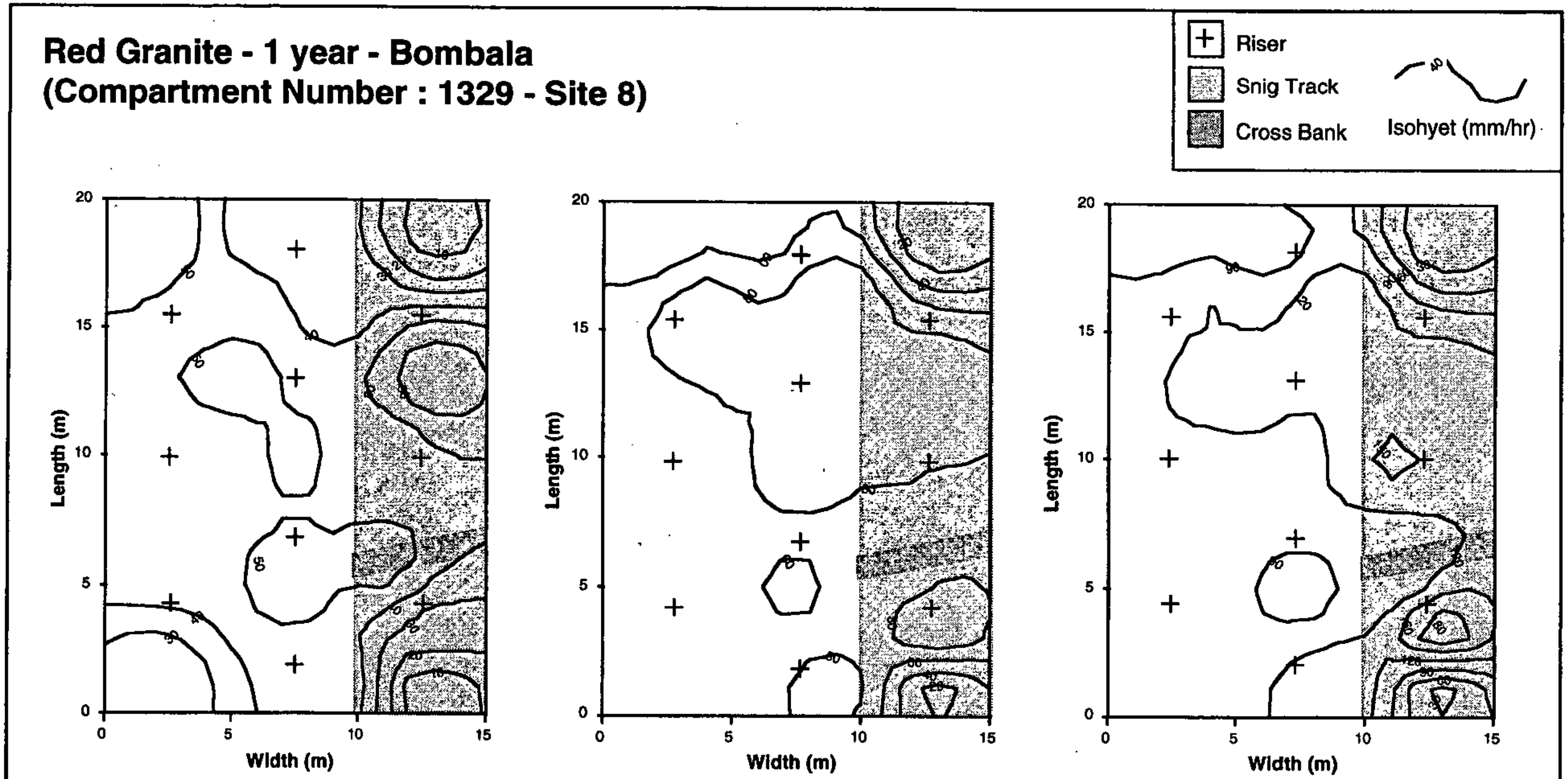
Run Number 3

Simulated Rainfall Intensity 110mm/hr

Observed Intensity (mm/hr)

Mean:	119.67
Standard Error:	2.14
Max:	176.60
Min:	1.20

Red Granite - 1 year - Bombala
(Compartment Number : 1329 - Site 8)



Run Number 1

Simulated Rainfall Intensity 45mm/hr

Observed Intensity (mm/hr)	
Mean:	41.98
Standard Error:	0.69
Max:	65.40
Min:	1.80

Run Number 2

Simulated Rainfall Intensity 75mm/hr

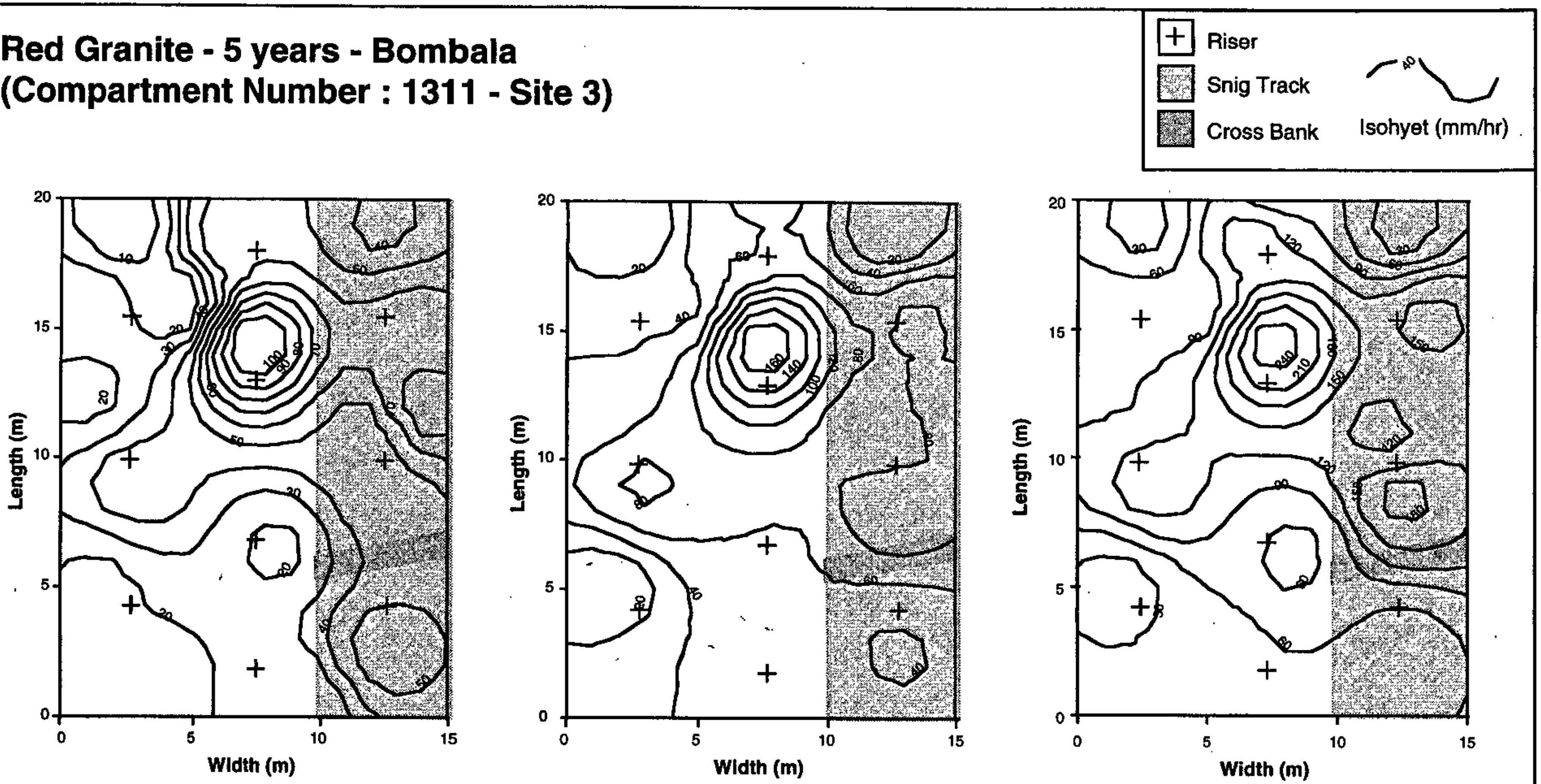
Observed Intensity (mm/hr)	
Mean:	68.98
Standard Error:	1.01
Max:	99.20
Min:	3.80

Run Number 3

Simulated Rainfall Intensity 110mm/hr

Observed Intensity (mm/hr)	
Mean:	107.50
Standard Error:	1.60
Max:	198.00
Min:	9.00

Red Granite - 5 years - Bombala
(Compartment Number : 1311 - Site 3)



Run Number 1

Simulated Rainfall Intensity 45mm/hr

Observed Intensity (mm/hr)
Mean: 39.31
Standard Error: 1.12
Max: 109.89
Min: 0.30

Run Number 2

Simulated Rainfall Intensity 75mm/hr

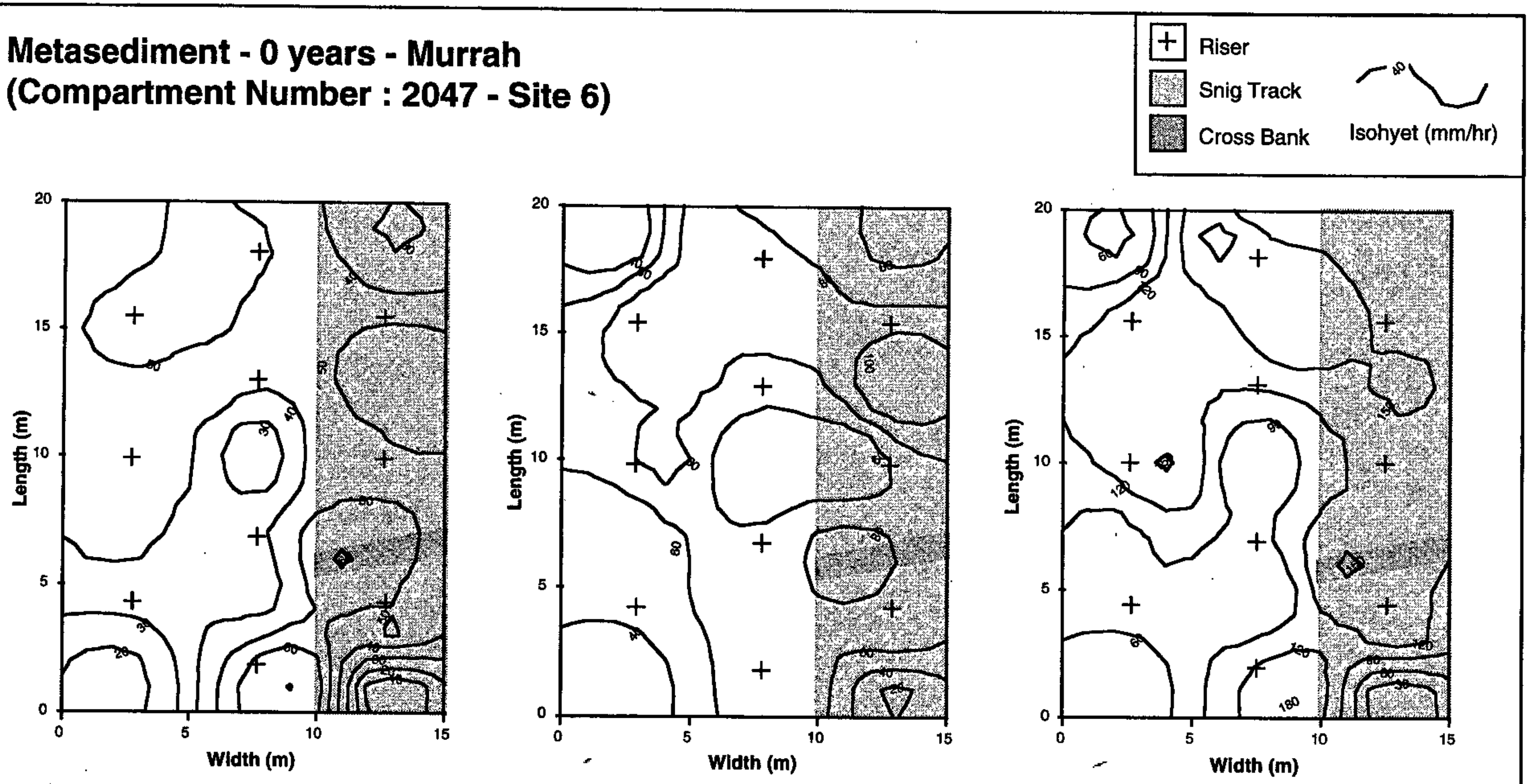
Observed Intensity (mm/hr)
Mean: 57.23
Standard Error: 1.66
Max: 171.20
Min: 0.38

Run Number 3

Simulated Rainfall Intensity 110mm/hr

Observed Intensity (mm/hr)
Mean: 92.46
Standard Error: 2.74
Max: 251.39
Min: 18.25

Metasediment - 0 years - Murrah
(Compartment Number : 2047 - Site 6)



Run Number 1

Simulated Rainfall Intensity 45mm/hr

Observed Intensity (mm/hr)	
Mean:	42.97
Standard Error:	0.62
Max:	70.20
Min:	1.00

Run Number 2

Simulated Rainfall Intensity 75mm/hr

Observed Intensity (mm/hr)	
Mean:	65.89
Standard Error:	1.09
Max:	115.60
Min:	16.00

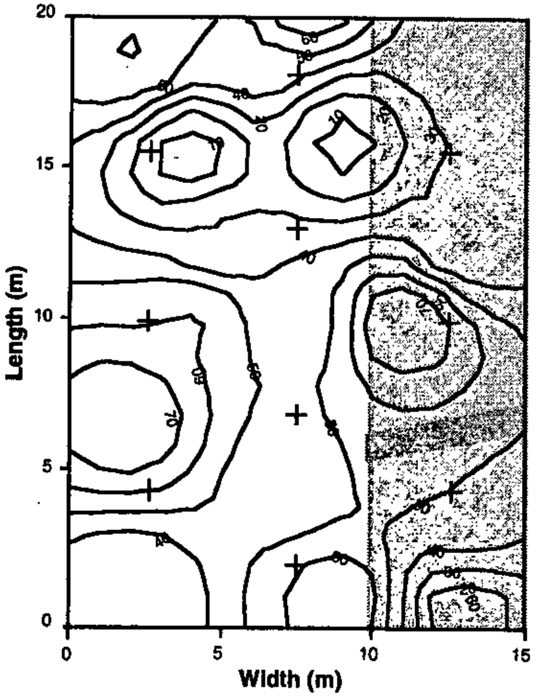
Run Number 3

Simulated Rainfall Intensity 110mm/hr

Observed Intensity (mm/hr)	
Mean:	112.62
Standard Error:	1.94
Max:	186.40
Min:	3.80

Metasediment - 1 year - Murrah
(Compartment Number : 2128 - Site 4)

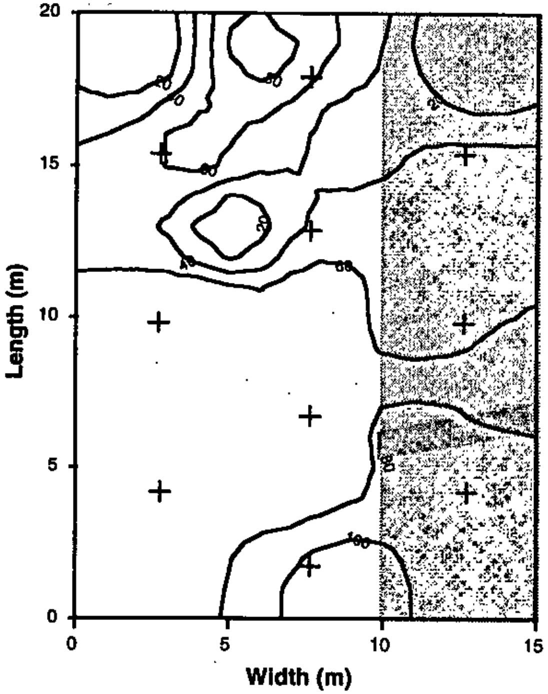
- + Riser
- ▨ Snig Track
- ▨ Cross Bank
- Isohyet (mm/hr)



Run Number 1

Simulated Rainfall Intensity 45mm/hr

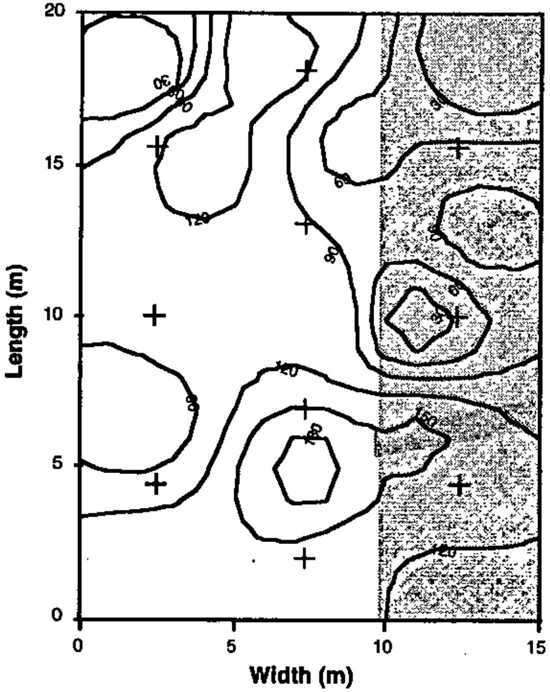
Observed Intensity (mm/hr)	
Mean:	44.46
Standard Error:	0.86
Max:	79.40
Min:	5.68



Run Number 2

Simulated Rainfall Intensity 75mm/hr

Observed Intensity (mm/hr)	
Mean:	61.43
Standard Error	1.34
Max:	113.00
Min:	0.80



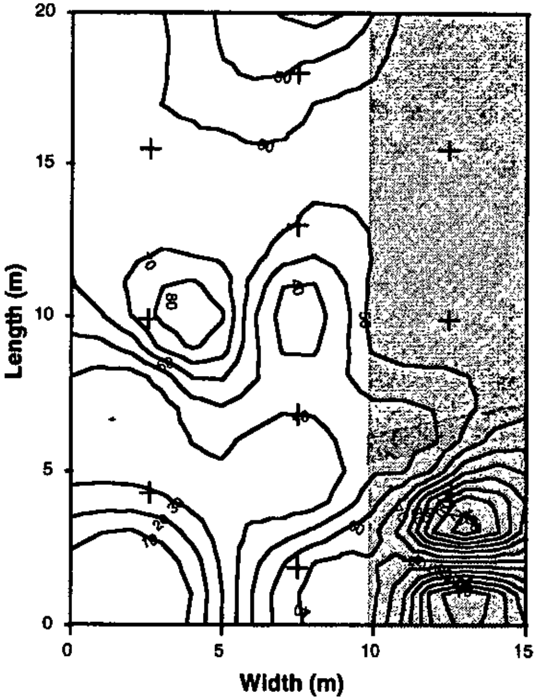
Run Number 3

Simulated Rainfall Intensity 110mm/hr

Observed Intensity (mm/hr)	
Mean:	99.67
Standard Error:	2.16
Max:	188.03
Min:	3.00

Metasediment - 5 years - Murrah (Compartment Number : 2061 - Site 5)

+ Riser
▨ Snig Track
▨ Cross Bank
Isohyet (mm/hr)

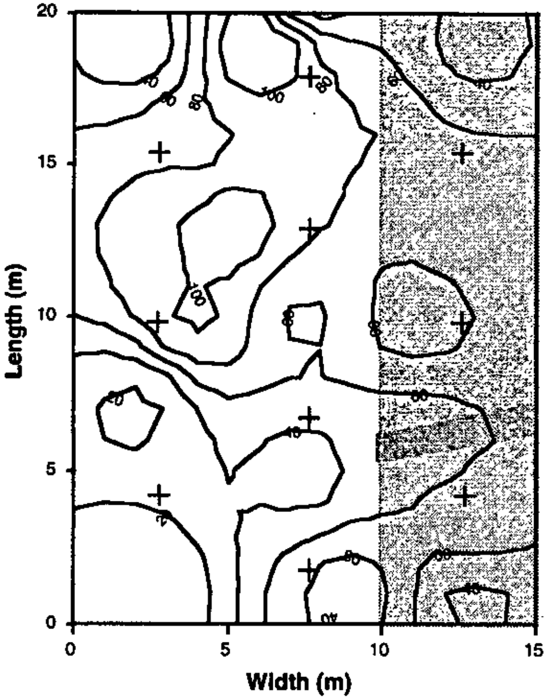


Run Number 1

Simulated Rainfall Intensity 45mm/hr

Observed Intensity (mm/hr)

Mean:	54.64
Standard Error:	1.12
Max:	136.40
Min:	0.40

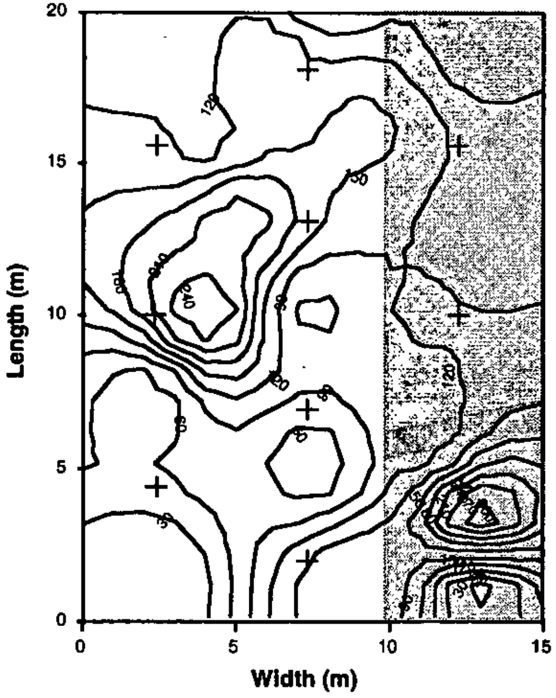


Run Number 2

Simulated Rainfall Intensity 75mm/hr

Observed Intensity (mm/hr)

Mean:	60.39
Standard Error:	1.36
Max:	120.00
Min:	0.74



Run Number 3

Simulated Rainfall Intensity 110mm/hr

Observed Intensity (mm/hr)

Mean:	118.51
Standard Error:	2.96
Max:	316.60
Min:	1.57

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