SUSPENDED SEDIMENT TRANSPORT IN THE NORTH ESK RIVER

by

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This thesis contains no material which has been accepted for the award of any other higher degree or diploma in any tertiary institution, and to the best of my knowledge and belief, this thesis contains no material previously published or written by another person, accept when due reference is made in the text of the thesis.

signed ....

W. J. Skirving

It was sometime in 1983 during low tide on the Tamar River, the place was the Launceston Yacht Club. A proud owner of a lovely yacht had decided to go for a leisurely sail. However, his efforts were thwarted by a very smelly obstacle......mud! Even if he could have forded the mud between himself and his yacht, he still had to contend with the fact that there was no water under the yacht on which to sail! What could he do? Naturally, he went and told his local member of parliament about his predicament, and so began the Government's concern over the siltation of the Tamar River.

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ABSTRACT

This thesis investigated the suspended sediment transportation of the North Esk River, Tasmania. The investigation was divided into two sections, the origins and the quantity of sediment transported. With respect to the origins, it was found that the main contributors to the suspended sediment load were recently denuded areas, i.e. recently logged areas and ploughed farmland. For example, 761t of sediment was estimated to have come from a 50ha logging coupe in only 320hours.

A single beam turbidity meter, based on light attenuation, was designed and constructed to monitor the sediment concentrations of the river. The results from this turbidity meter were used in conjunction with discharge data to derive a sediment rating curve. This curve was applied to daily discharge records to derive long term estimates of sediment transport.

The mean annual suspended sediment transport of the North Esk River was estimated to be 7225t. This estimate was extrapolated to the whole Tamar River catchment. It was estimated that the average annual suspended sediment input to the Tamar Estuary from its tributaries is 56,900 t/year.

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LIST OF SYMBOLS AND UNITS

SYMBOLS

u^*	shear velocity
wo	fall velocity of a particle
d	particle size
D	depth of flow
C	sediment concentration
t'o	ratio of grain shear stress
toc	critical shear stress
La	sediment transport
Q	discharge
T	total sampling time
Δt	sampling interval
Ø	scattering angle
PVC	polyvinyl chloride
LDR	light dependent resistor

UNITS

nm	nanometre
µm	micrometre
mm	millimetre
m	metre
km	kilometre
ha	hectare
t	tonne
v	volt
pF	picofarad
µF	microfarad

Ω	ohm
kΩ	kilo-ohm
mg	milligram
g	gram
l	litre
min.	minute
s	second
°C	degree Celsius
cumec	cubic metre per second

CHAPTER 1: INTRODUCTION

In June 1984, Unisearch Ltd and the Water Research Laboratory of the University of New South Wales, were commissioned to undertake a two year investigation into the causes of siltation within the Tamar River, in particular its upper reaches near Launceston. The study was directed by Professor D. N. Foster and was supervised by the Tamar River Improvement Committee, established by the Government of Tasmania to examine and report on problems related to the development and beautification of the Tamar River.

As part of this study, the University of Tasmania was contracted by the Water Research Laboratory to investigate the quantities and origins of suspended sediment entering the Tamar River from its tributaries. Consequently, a project was set up to investigate the suspended sediment load of the North Esk River (Figure 1), considered to be representative of the whole Tamar Basin. The main aim of this project was to estimate the annual suspended sediment load of the North Esk River, with a view to extrapolating the findings to the entire Tamar catchment. A lesser aim of the project was to investigate suspended sediment provenance within the North Esk Basin.

The Tamar River is a large estuary located in North Eastern Tasmania (Figure 1). It extends for 69.5 km from Bass Strait at Low Head to Launceston where it terminates at the confluence of the North and South Esk Rivers. Tidal effects extend one kilometre up the South Esk River and two kilometres up the North Esk River. Its drainage basin is one of the largest in the state, approximately 11,000 km^2. Eighty-seven percent of the Tamar catchment is drained by only two of its tributaries; the North Esk River which has a catchment area of 1067 km^2, and the South Esk River which has a catchment area of 24,680 km^2.

The Tamar River Estuary was formed during the post glacial marine transgression which commenced approximately 13,000 years ago and concluded 6,500 to 5,000 years ago (Jennings, 1971 and Thom and Roy, 1985). During this

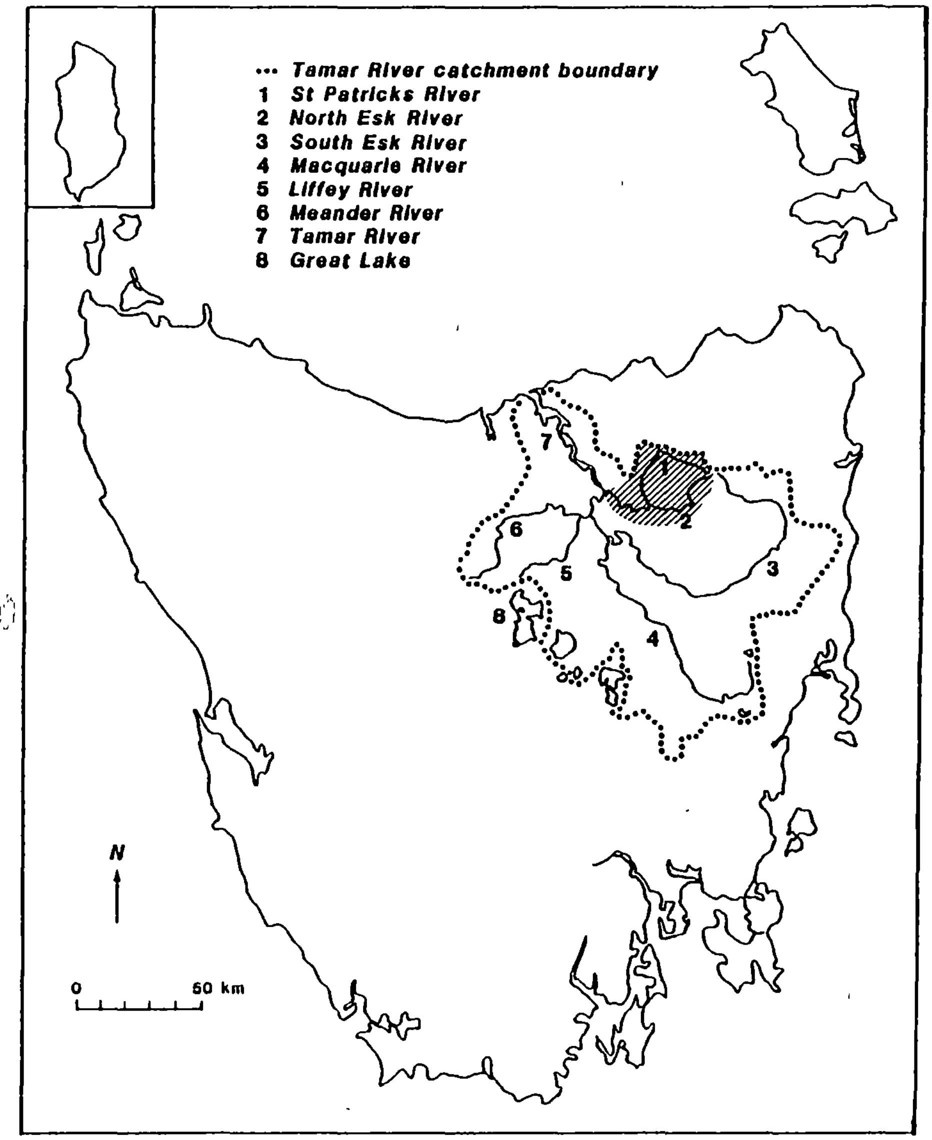


Figure 1: The Tamar River drainage basin, with the North Esk River drainage basin (shaded).

period sea level rose by approximately 60 m to about its present level, resulting in the flooding of the Tamar River and the formation of the drowned river valley which is now the Tamar Estuary. Since the sea level reached its present level, the estuary has been gradually filled in with sediments brought down by its tributaries, particularly the North and South Esk Rivers which drain approximately one seventh of the total area of Tasmania. This infilling has been largely restricted to the upper half of the estuary. The lower reaches still retain many of the characteristics of a drowned valley. (Foster, *et al.,* 1986)

The Tamar River has three distinct periods of usage. The first period was between 1804 and 1890, when the river retained much of its natural state. Water depths were sufficient to meet the needs for the type and size of ships using the river. During this period, port works were primarily concerned with navigational aids and tugs to assist the movement of ships. (Foster, *et al.,* 1986)

The second period (1890 to 1965) was a period in which continuous and increased dredging was needed to meet the requirements of larger and larger ships using the Port of Launceston. This dredging increased the channel depth in the upper reaches of the estuary by redistributing the silt from the upper to the lower half. Also during this period, the advent of steam powered vessels meant that the need for tugs was disappearing. (Foster, *et al.,* 1986)

The third period began in 1965 and has continued to the present. At the beginning of this period, the major port facilities were shifted down river to meet the requirements for larger ships. As a result of this shift, the need for dredging was reduced. (Foster, *et al.*, 1986)

The above mentioned reduction in dredging prompted the hypothesis upon which the Water Research Laboratory's study (part of which forms this thesis) is based. In this study it was hypothesized that; "since 1965 the river has been gradually reverting to the conditions which existed prior to the turn of the century. Since the dredging has only been redistributing the sediment within the estuary, it is thought that the silt which is accumulating in the estuary near Launceston is coming from two sources. The tidal flow is bringing sediment from the lower half of the estuary, and the tributaries are providing 'new' sediment from the upstream catchment." This thesis provides information about the tributaries' contribution to the suspended sediment within the Tamar Estuary.

A. SEDIMENT TRANSPORT

Whether or not a river has the competence to move the materials that it encounters depends on its speed and turbulence (Cooke and Doornkamp, 1974). A river may carry material as bed load, saltation load, suspended load, or as solution load. Bed load is composed of material too large to be carried upwards in turbulent eddies, but in times of high discharge it may be moved along the river bed by sliding, rolling or saltation. Saltation load is the part of the bed load which may in periods of very high-energy conditions in the river, be bounced along the channel floor. The material is never able to stay in suspension for long.

Some authors prefer to include the saltation load within the bed load (Einstein *et al.*, 1940; Chorley, 1969; Hall, 1984; and Rodda, 1985), since the saltating particles from time to time supplement the bed load. Suspended load is carried in the body of the current. The degree of coarseness of suspended particles varies with velocity, and especially with the degree of turbulence. (Chorley, 1969 and Vanoni, 1975)

The total load can also be divided into 'bed sediment load' and 'wash load', which are defined as being, respectively, of particle sizes found in appreciable quantities and in very small quantities in the shifting portions of the bed (Vanoni, 1975). However, some writers separate as wash load, that part of the suspended load which, although consisting of solid particles, is so fine-grained that its settling velocity is very small or nil. (Chorley, 1969 and Hall, 1984) This portion is carried in colloidal suspension. Solution load is by definition transported in the dissolved state.

Solution loads and bed loads were not considered in this study. From the outset it was assumed that, in causing siltation of the Tamar River, solution loads would have a minor effect in comparison with suspended sediment (Rivers and Water Supply Commission, 1983). Also, this variable was already being monitored by the Water Research Laboratory.

The bed loads do not reach the Tamar River, since there is at least one dam or weir on each of the lower reaches of the main tributaries, which prevents movement of bed load. There are no records to indicate pre-weir (pre 1950s) bed load transport rates, however visual observations made by the author show little or no build-up of bed material behind these weirs, hence it may be assumed that bed load transported by the tributaries, to the Tamar River, prior to the construction of the weir, was negligible. If the bed loads remain in the system, they would be continually broken down, by chemical and physical processes, into particles which are small enough to be eventually flushed out as suspended sediments. (Foster *et al.,* 1986)

B. MEASUREMENTS OF SUSPENDED SEDIMENT LOADS

The measurement of suspended sediment load is important for many reasons. Sediment data and an understanding of the processes of erosion and sediment transport are necessary in a variety of water management tasks. Knowledge of the amount and characteristics of sediment in a water source is needed if the sediment is to be removed as economically as possible before the water enters the distribution system; many industries require sediment-free water in their processes and the domestic consumer has strong objections to coloration or turbidity. Information on sediment movement and particle size distribution is needed for the design of dams, canals and irrigation works. Streams and reservoirs that are free of sediment offer advantages for recreation. Any changes of suspended sediment levels in streams and rivers could severely affect the balance of ecosystems. Recently concern has grown over the concentration and absorption of radionuclides, pesticides, herbicides and many organic materials by sediments; data on sediment movement and particle characteristics are needed to determine the extent and cause of this potential danger to health. (Gower, 1980; Walling and Webb, 1981b; Rodda, 1985; and Pigram, 1986)

Table 1 is a comparison of average annual suspended sediment transport rates of rivers in each of the continents (except Antarctica), taken from three separate studies, Strakhov (1967), Holman (1968) and Milliman and Meade (1983). Each study exhibits similar trends, with Australia and Africa having the lowest average sediment yield, and Asia the largest. On a global scale, Holman (1968) demonstrated that approximately 19×10^9 t of sediment reach the ocean per year, a quantity equivalent to a denudation rate of 75 mm per 1,000 years. However, Milliman and Meade (1983) suggest a global figure of 13.5×10^9 t of sediment per year reaches the ocean.

World data of sediment loads of rivers show that generally, the denudation rates of catchments range between 1 and 10,000 t/km^2/year. However, if the data are restricted to catchments less than 10,000 km^2 with an annual rainfall between 1,200 and 1,500 mm (i.e. similar rainfall to the North Esk basin, see Chapter 3) the world average denudation rate is 600 t/km^2/year. (Walling and Kleo, 1979)

"Disturbance of surface soil for agriculture, mining and urbanization is a major contributor towards increased sediment loads in rivers world-wide ..." (Loughran, 1984). How the activities of man affect the natural amounts and distribution of erosion and sediment transport must be determined if future changes in land use are to be carried out in such a way as to minimize increases in erosion rates. Accelerated erosion of fertile soil due to mismanagement is common, and changes in the sediment pattern resulting from man's activities can have far-reaching social and economic repercussions (Pigram, 1986).

The magnitude of soil erosion and suspended sediment transport can be changed by man's activities, through changes in land use and management, by

CONTINENT	AREA (km^2x106)	SEDIMENT YIELD (t/km^2/year)		
		Strakov	Holman	Milliman & Meade
Europe	9.7	43	35	50
Asia	44.9	166	600	380
Africa	29.8	47	27	35
North & Central America	20.4	73	96	84
South America	18.0	93	63	97
Australia	8.0	32	45	28

Table 1: Selected river suspended sediment yield data from Strakhov (1967), Holman (1968) and Milliman and Meade (1983) for several continents.

erosion control practices, by the construction of structures in the river and by channel modification schemes. (Detwyler, 1971; Gower, 1980; Rodda, 1985; and Stott, *et al.,* 1986) However, quantifying the effects of man's activities on suspended sediment load in rivers is difficult. Finlayson and Wong (1982) found that relationships obtained in small catchment studies cannot be easily extrapolated to other areas. Regardless of this, most suspended sediment studies are still conducted on small catchments, due to their manageability, e.g. Imeson and Vis (1984).

Sheet and rill erosion are much reduced by increasing the density of vegetation, as demonstrated by Wischmeier and Smith (1965) who found a 250% decrease in soil loss after planting a high quality grass cover on fallow land. Conversely the removal of forest can greatly increase erosion. Brown and Krygier (1971), O'Loughlin (1974), O'Loughlin *et. al.* (1978), Nolan and Janda (1981) and Cassells *et al.* (1982) all report an increase in sediment yield following deforestation. Management practices during logging can also greatly affect suspended sediment loads in rivers, Megahan (1972), Pearce and Griffiths (1980), Burgess *et al.* (1981), Reid *et. al.* (1981), and Megahan *et. al.* (1986). In the Eden area, N.S.W., the impact of clear-fell logging in a dry sclerophyll catchment has been examined by Rieger, *et al.* (1979) and Burgess *et al.* (1981). Increases of up to 150% in sediment loads following the construction of roads and the start of logging were reported. The suspended sediment loads apparently returned to close to pre-logging levels after twelve months. Most of the increase in sediment load was explained by poorly sited and constructed roads, and sediment loads tended to decrease as logging continued.

Kriek and O'Shaughnessy (1975) have also reported on the impact of roads and logging in forested catchments. They worked in two catchments in the Coranderrk experiment in Victoria. During the logging, 50% of the timber stand was removed. The study plots showed an initial impact due to road construction with increases in suspended sediment loads which returned to pre-construction levels in approximately twelve months. A further episode of increased sediment transport accompanied the logging, with a trend towards pre-logging loads after two years. Langford *et al.* (1982) whilst working in the same catchment, found that after logging of the Blue Jacket Creek there was no return to pre-logging suspended sediment concentrations. The difference between these findings and those of Kriek and O'Shaughnessy (1975) was interpreted as being due to differences in road drainage, with Blue Jacket Creek having longer and steeper sections of road draining towards the stream.

While studying 11 small drainage basins in the Keuper region of central Luxembourg, Imeson and Vis (1984) found that at any given specific discharge, the maximum suspended sediment concentration for cultivated catchments was at least twice that from the forested catchments.

Ketcheson *et. al.* (1973) identify two ways in which agricultural practices can effect the generation of stream sediment; (1) erosion of soil from the land surface, and (2) erosion of soil from streambank areas. Agriculture may contribute passively to the processes affecting stage 2. In stage 1, agriculture is instrumental in determining the kind of soil cover available to protect the soil surface. This protection may be vegetative as determined by the crops and cropping practices used, or non-vegetative as determined by tillage practices and surface roughness. For instance, direction of ploughing is important, as on short low-angle slopes, contour ploughing produces some 50% less sediment than ploughing uphill and downhill (Piest and Spomer, 1968). In stage 2, agriculture may be instrumental in providing more or less vegetation cover, and controlling the extent of farm animal activity on the banks of streams passing through agricultural land.

There have been many studies conducted on the sediment contribution of agricultural land, some of these are; Piest and Spomer (1968), Ketcheson *et. al.* (1973), Loughran (1977), Al-Ansari et. al. (1977), McHenry and McIntyre (1984), and McColl *et. al.* (1985). Their field sites were spread all over the world, and all concluded that better land management should decrease the contribution of agricultural activities to river sedimentation. While studying suspended sediment movement patterns of Midwestern streams, U.S.A., Wilkin and Hebel (1982) found that cropped floodplains are the most severely eroded lands in the watershed, followed by cropped lands bordering the floodplains. They concluded that the majority of cropped uplands may not be nearly as important in determining suspended sediment levels in streams as is generally thought.

Table 2 is a summary of published data on soil erosion losses from hill slope plots and small catchments in eastern Australia, compiled by Olive and Walker (1982). It contains 24 examples, two from forested plots, and the rest from agricultural land (e.g. bare, fallow, pasture and cropped areas). In general, Table 2 suggests that soil losses per unit area from small plots are greater than from large plots, and these are greater than the few values available from small catchments. This undoubtedly reflects the fact that the larger the system studied, the greater the opportunities of redeposition of eroded material within it (Finlayson and Wong, 1982).

The maximum reported soil losses (38,200 t/km^2) occurred from deeply rilled cane fields in northern Queensland during one year of observation (Matthews and Makepeace, 1981), see Table 2. Even under cane mulch, erosion losses were 9,000 t/km^2. A single storm event experienced in the Darling Downs, southern Queensland (Kamel, 1980), removed soil at the rate of 10,000 t/km^2. These values are far in excess of the soil loss tolerance levels of 500-1,200 $t/km^2/year$ which have been developed for conservative management of agricultural soils in the U.S. (Olive and Walker, 1982). Adamson (1974) and Edwards (1980), whilst studying erosion rates of pasture, found that the bulk of soil erosion losses over a long period could be attributed to a few storm events.

In their analysis of the data from Table 2, Olive and Walker (1982) conclude that erosion losses from pasture and cropland in southern Australia appear to be small except where soil surfaces are bare. Where long-term data are available, erosion losses occur during a few high intensity storm events.

LOCATION	AREA	MANAGEMENT	SOIL LOSS RATE EQUIV. (t/km^2)	LENGTH OF RECORD	DATA SOURCE
Goondi	Small field	Cane mulch	9,000	1 yr	Matthews & Makepeace (1981)
"	"	row cult.	35,300	1 yr	"
"	"	hoed	38,200	1 yr	"
Darling Downs	std. runoff plots	bare fallow	10,000	1 storm	"
"	"	crop, 0 till	<100	1 storm	Kamel (1980)
"	0.8 ha	wheat	5,000		Freebairn & Wockner (1982)
Inverell	std. runoff plots	bare	6,400	1 yr	Armstrong (1981)
Gunnedah	41.5 m plot	wheat, fallow	20,100	26 yr	Edwards (1980)
"	41.5 m plot	pasture	70	26 yr	"
"	1 ha	bare	5,700; 12,200; 18,000	storms	Marston & Perrens (1980)
"	1 ha	mulch	0;3,8000; 7,100	storms	"
Cowra	std. runoff plot	wheat,fallow	7,500	34 yr	Packer & Aveya (1981)
"	"	ley,fallow, wheat	800	34 yr	"
Ginninderra	0.01 ha plots	bare	2,600	1 storm	Kinnell (1982)
"	88 ha	pasture	24-230	6 yr	Costin (1980)
Upper Shoalhaven	2 x 3 m	forest	4-700	2 yr	Williams (1972)
"	2 x 3 m	forest	40-740	2 yr	"
Wagga Wagga	7 ha	impr. pasture (contours)	40	22 yr	Adamson (1974)
"	7 ha	unimproved past.	3,600	22 yr	"
"	40 m plots	wheat,fallow	6,300	30 yr	Edwards (1980)
"	40 m plots	pasture	100	30 yr	"

Table 2: Summary of some published data on soil erosion losses from agricultural and forested plots and catchments in eastern Australia. Compiled by Olive and Walker (1982).

Reservoir construction can create many problems as demonstrated by the silting of the San-Men reservoir on the Yellow River (Hathout, 1979). McManus and Duck (1985) found similar problems with the Glenfarg and Glenquey reservoirs in Scotland. Paskett (1982) suggests that proper land management techniques would decrease reservoir sediment accumulation. Problems can also occur downstream of a dam. Pemberton (1981) found that clearing of the reservoir area before closure of the Stateline dam, on the Smith's Fork River, U.S.A., exposed sediments that were flushed through the dam and deposited in the gravel spawning reach of the river for a distance of about 9 km downstream from the dam. Urban development is the most dramatic change of land use and the accompanying construction can greatly increase sediment yield. Walling and Gregory (1970) demonstrated that the annual sediment yield of some 200 t/km^2 from a small agricultural catchment was increased by a factor of four after urbanization. Wolman (1967) compared sediment yields from four landuse types. He found that undisturbed forests provided the least sediment to rivers, with urban areas, grazing land and cropped land all having progressively larger sediment yields. Wolman suggests that, of the four landuse types, urban land provides the least sediment after forested land. He points out that during urban construction, these areas can provide up to 1000 times more sediment to the river systems than any other landuse type. Since Wolman's work, other studies have shown similar results (Williams, 1976; Warner, 1976; Lam, 1978; Gower, 1980; and Lootens and Lumbu, 1986).

The increasing practice of open strip mining also presents problems of increased sediment loads in rivers. Collier *et. al.* (1964) report that mining over less than 1% of a catchment increased the sediment yield by 83%. The effects of tin mining over small areas of the Ringarooma River Basin, Tasmania, between 1875 and 1979 have been investigated by Knighton (1987). He found that mine tailings had a profound effect on the supply and transport of suspended sediment within the river system.

From the above discussion it can be seen that human activities can have a profound effect on the quantity of sediment transported by rivers. The magnitude of these effects vary, although they tend to be greatest when the landuse decreases the amount (or changes the type) of vegetation cover. However, these effects are not always permanent, since a number of studies have shown that after logging, the initially high sediment loads of rivers have returned to low loads of pre-logging after a period of one to two years (Kriek and O'Shaughnessy, 1975; Rieger *et al.*, 1979; and Burgess *et al.*, 1981).

Man's activities in the North Esk Basin can be categorized into five groups, forestry, farming, recreation, urbanization and road building. Forestry activities include selective logging, clear felling and replanting, all of which necessitate road building and changes to the natural vegetation. There are two main farming activities, cropping and grazing. Cropping is mostly confined to the river flats, whilst grazing also occurs on hills which surround the river flats. Almost all grazing in the area is carried out on improved pastures, therefore both farming types involve ploughing, and often include irrigating. There are a wide range of recreational activities within the North Esk Basin. They include bushwalking, camping, caravaning, fishing, rafting, canoeing, many types of sports and snow skiing. Of these, skiing is possibly the most disruptive, since it requires the grooming of ski slopes. The population within the North Esk Basin is very scattered, with only a few very small towns. Therefore urbanization is only a small part of man's activities within the area. Lastly, all the above activities require an extensive transport network within the area, if they are to function properly. As a result of this, road building plays a major role in man's activities within the North Esk Basin.

From the above discussion of various suspended sediment studies, it is reasonable to expect that man's activities within the North Esk Basin have increased the rates of erosion, and therefore increased the amount of suspended sediment load within the North Esk River. To what degree this has occurred, or whether these changes have persisted, is not certain. Other studies also indicate that the relationship between man's activities and suspended sediment origins is complex. Consequently, this study will not attempt to directly attribute suspended sediment origins to individual landuses, rather it will investigate the existence of preferred geographical locations for suspended sediment origins.

C. AIMS

Due to the limited resources available, a detailed study was restricted to the suspended sediment load of the North Esk River Basin (Figure 1). The North Esk River was not only small and manageable, but was also considered to be representative of the Tamar River tributaries. The North Esk basin has at least one example of every type of landuse found in the Tamar catchment, as well as most rock types.

Only one previous study of suspended sediment loads has been carried out in Tasmania. Olive (1973) sampled three small catchments in southeastern Tasmania, Mountain River, Browns River and the Snug River. He measured both suspension and solution loads over a one year period. The measurements were used to estimate denudation rates for the period. The applicability of Olive's study to the present study is very limited, since the streams he measured are considerably smaller.

Mountain River has a catchment area of 40 km^2 and an average annual discharge of 27.581 Ml (mega litres). The corresponding measurements for Browns River are 12 km^2 and 4.663 Ml, and the Snug River are 19 km^2 and 5.487 Ml. The North Esk River has a catchment area of 921 km^2 which is a factor of between 23 and 77 larger than Olive's rivers. The average annual discharge of the North Esk River is 916.595 Ml, which is between 33 and 197 times larger than the rivers in Olive's study.

Meteorological differences between the two study areas are also evident. North Eastern Tasmania receives most of its rain from orographic processes, whilst frontal systems dominate the rainfall in South Eastern Tasmania. The average annual rainfall for each of the study areas also differ. Mountain River, Browns River and the Snug River have average annual rainfalls of 900, 750 and 700 mm respectively, which are smaller than the North Esk River's average annual rainfall of 1,160 mm.

The aims of this investigation are somewhat different to those of Olive's study. The first and main aim was to derive an estimate of the mean annual suspended sediment transport of the North Esk River, and the second was to investigate the geographical origins of suspended sediment within its catchment.

The study will use suspended sediment rating curves to calculate suspended sediment transport rates. However, as explained earlier, man's activities in the area have almost certainly changed the suspended sediment loads within the river system. This means that there is a high likelihood that the relationship between suspended sediment load and river discharge has also changed. Consequently, this study will restrict itself to current estimates of suspended sediment transport and will therefore not be directly concerned with historic transport rates.

Data sources from the North Esk River catchment are very limited. There are no usable records of suspended sediment concentrations available for the North Esk River. Therefore a large number of measurements were made so as to provide the suspended sediment concentration values needed for the study. To facilitate these measurements, a large amount of time was invested in the design, construction and installation of a turbidity meter, which was used to measure concentrations of suspended sediment at hourly intervals under a wide range of discharges. The data from the turbidity meter were supplemented with hand samples from the study area.

Historic discharge data are available from only two sites within the North Esk basin. These data will be used to obtain an estimate of the average annual discharge of the North Esk River, which will be used in conjunction with the suspended sediment rating curve (derived during the study) to estimate the current mean annual suspended sediment transport.

The thesis firstly discusses the various ways by which rivers transport sediment, and then presents results of some previous sediment transport studies. The first part of Chapter 2 examines suspended sediment sampling techniques: including a literature review of the various ways of estimating suspended sediment concentrations and transport in rivers; and a description of the sampling techniques used in this study, including a detailed description of the turbidity meter's design and application. The last part of Chapter 2 describes the suspended sediment transport characteristics of the North Esk River, e.g. the cross-sectional profile of the suspended sediment concentrations. The study area is described in Chapter 3. This description includes the geology, soils, climate, vegetation and landuse within the North Esk River basin.

Estimates of annual suspended sediment transport rates for the North Esk River are presented in Chapter 4. These estimates are made for the North Esk River at two locations, Corra Linn (near its mouth) and Ballroom (about half way up the river). The estimates are then extended to provide estimates for the South Esk River and the whole Tamar River basin. In this chapter an averaging technique (the RUME technique), which provides improved estimates of the annual sediment transport rates, is presented.

The geographical location of the origins of the suspended sediment being transported by the North Esk River is addressed in Chapter 5, entitled Sediment Provenance. At the beginning of this chapter, Pinkard's survey of erosion in north eastern Tasmania (1980) provides the basis for the discussion on soil erosion. This is followed by a description of some of the factors which may affect the suspended sediment concentrations within the North Esk River. This chapter concludes with the presentation of four case studies of suspended sediment provenance.Chapter 6 presents a discussion of the results describing some of the implications of the findings, and some conclusions are drawn in Chapter 7.

CHAPTER 2: METHODOLOGY

A. MEASURING SUSPENDED SEDIMENT CONCENTRATIONS

There are many techniques available to measure suspended sediment concentration in rivers (Stichling, 1968; Task Committee on Sedimentation, 1969; McCave, 1979; Graf, 1971; Loughran, 1971; Shaw, 1983; and Ward, 1984). These techniques can be placed in one of two categories; direct methods (water sampling and sediment traps), and indirect methods (radiation attenuation).

The simplest method for the determination of suspended sediment concentration is to take a known volume of water, filter it and determine the weight of material retained on the filter. In the initial stages of the development of samplers, an open container or bucket was used to dip samples from a river. However, this method was shown to cause significant errors (Ward, 1984). This instrument was followed by the bottle or closed container type, which could be opened and closed instantaneously at any selected depth. Later, instantaneous samplers of the horizontal trap type, which orientated themselves in the direction of flow, were developed. (Task Committee on Sedimentation, 1969 and Vanoni, 1975)

There are two types of water samplers in use today, instantaneous samplers and integrating samplers. The latter are moved through the depth of the water column to provide a depth integrated sample, or left in a fixed position to provide a time-integrated sample. There are many types and makes of instantaneous samplers. The two principal types are represented by the NIO bottle (from the formerly named British National Institute of Oceanography) and the Van Dorn bottle. The NIO bottle is an open PVC tube with hemispherical bungs on spring loaded arms which close each end. As the diameter of the openings is equal to the body of the bottle, it has good flushing characteristics. The Van Dorn bottle is an open tube normally made of PVC, with a rubber spring through the inside of the bottle and connected to the end stoppers. To set the bottle, these are pulled out and connected to a release mechanism. There are many minor variants of these types of samplers, and they are relatively easy to construct (e.g. Duursma, 1967).

The single stage sampler has been developed as an aid in obtaining information on flashy streams, particularly those in remote areas where observer services are not available. It is used to obtain a sample at a specific depth and on the rising stage only (Loughran, 1971). Two versions of this type of sampler are shown in Figure 2. The sampler operates on the siphon principle and therefore the velocity in the intake is not equal to the stream velocity. The vertical intake nozzle shown in Figure 2(a) eliminates plugging from surface debris but does not take a sample of acceptable accuracy when sand particles are present. In contrast, the horizontal intake nozzle shown in Figure 2(b) increases the accuracy with respect to the sand particles in the flow but also increases the danger of plugging due to surface or near surface debris. (Loughran, 1971; Vanoni, 1975; Ryan, 1981; and Ward, 1984)

With careful operation, the single stage sampler can be used to obtain supplementary information on sediment concentration at selected points in the vertical profile. Because of the limitations of the sampler, concentration data so obtained must be used with caution in the determination of the mean concentration in any stream. (Ward, 1984)

A time integrating sampler is one which collects a sample during a finite time interval. Time integrating samplers are of two types: depth integrating and point integrating. The depth integrating samplers are designed to accumulate a water sediment sample, as they are lowered to the streambed and raised to the surface, at a uniform rate. During transit, the velocity in the intake nozzle is nearly equal to the local stream velocity at all points in the vertical. Point integrating samplers are designed to accumulate a water sediment sample which is representative of the mean concentration at any selected point in a stream during a short interval of time. (Vanoni, 1975)

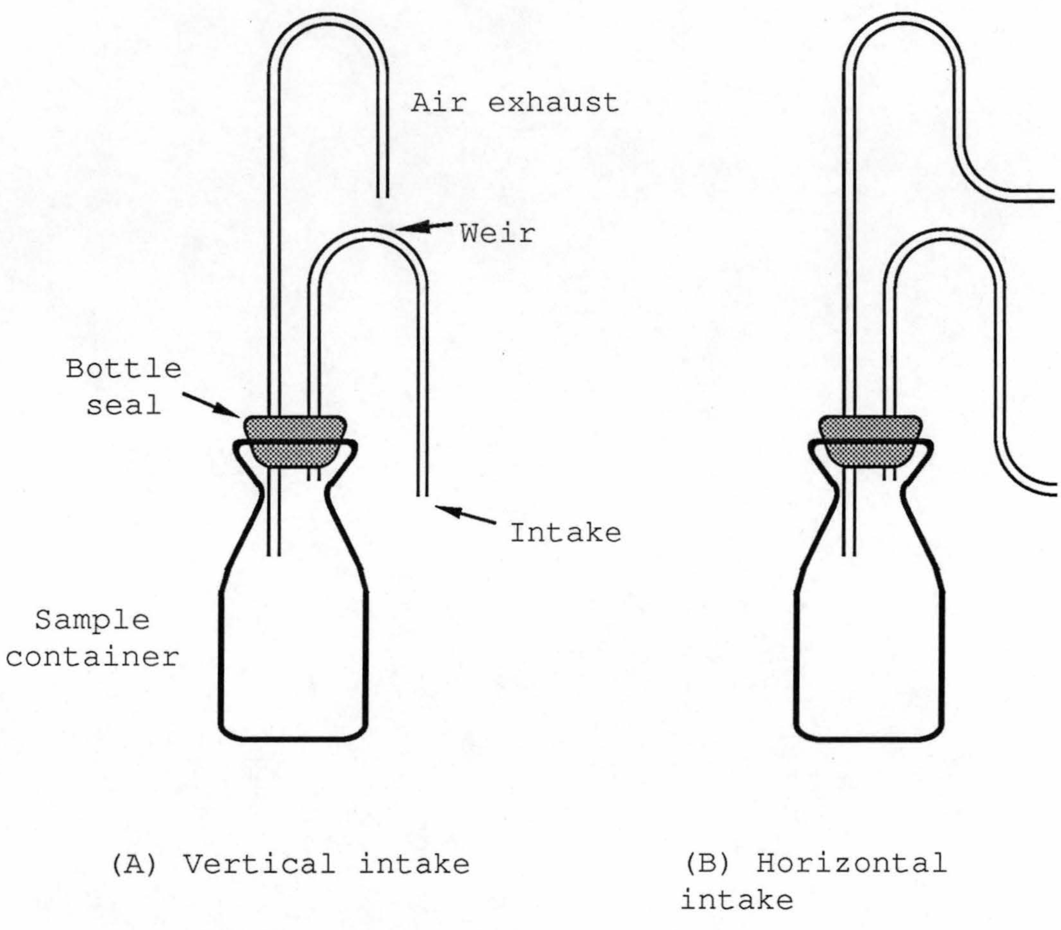


Figure 2: U.S. single stage suspended-sediment sampler

The requirements of an ideal integrating suspended sediment sampler have been summarized by Nelson and Benedict (1951) and are as follows: (i) The velocity at the entrance of the intake tube should be equal to the local stream velocity; (ii) the intake should be pointed into the approaching flow and should extend upstream from the zone of disturbance caused by the presence of the sampler; and (iii) the sample container should be removable and suitable for transportation to the laboratory without loss or spoilage of the contents. Furthermore, the sampler should: (iv) Fill smoothly without sudden inrush or gulping; (v) permit sampling close to the streambed; (vi) be streamlined and of sufficient weight to avoid excessive downstream drift; (vii) be rugged and simply constructed to minimize the need for repairs in the field; and (viii) be as inexpensive as possible, while consistent with good design and performance. Integrating hand samplers have been used by Zakaria (1979), Allen and Petersen (1981), Ryan (1981), Singhal *et al.* (1981) and Lootens and Lumbu (1986).

Pumping samplers have been used in suspended sediment studies since 1968. (Task Committee on Sedimentation, 1969) They are designed so that they can automatically obtain a continuous record of sediment concentration by sampling at a fixed point at specific time intervals. The velocity in the intake is not equal to the stream velocity, and the intake does not always meet the requirements of an ideal sampler since it often does not point into the flow. However, the pumping sampler can be rated or calibrated by comparing mean concentrations determined with it to mean values in the river cross section determined from samples collected with standard depth or point integrating sampling equipment. (Vanoni, 1975 and Ward, 1984) Many studies have used pumping samplers, e.g. Walling and Teed (1971), Ryan (1981), Finlayson and Wong (1982) and Lam (1984).

Sediment traps can also be used to sample suspended sediment in rivers. One example of a sediment trap is the Delft Bottle. This has a nozzle pointing into the flow which opens into an expansion chamber shaped like a bottle and with holes in its rear plate (Figure 3). Water entering the nozzle slows down in the expanded

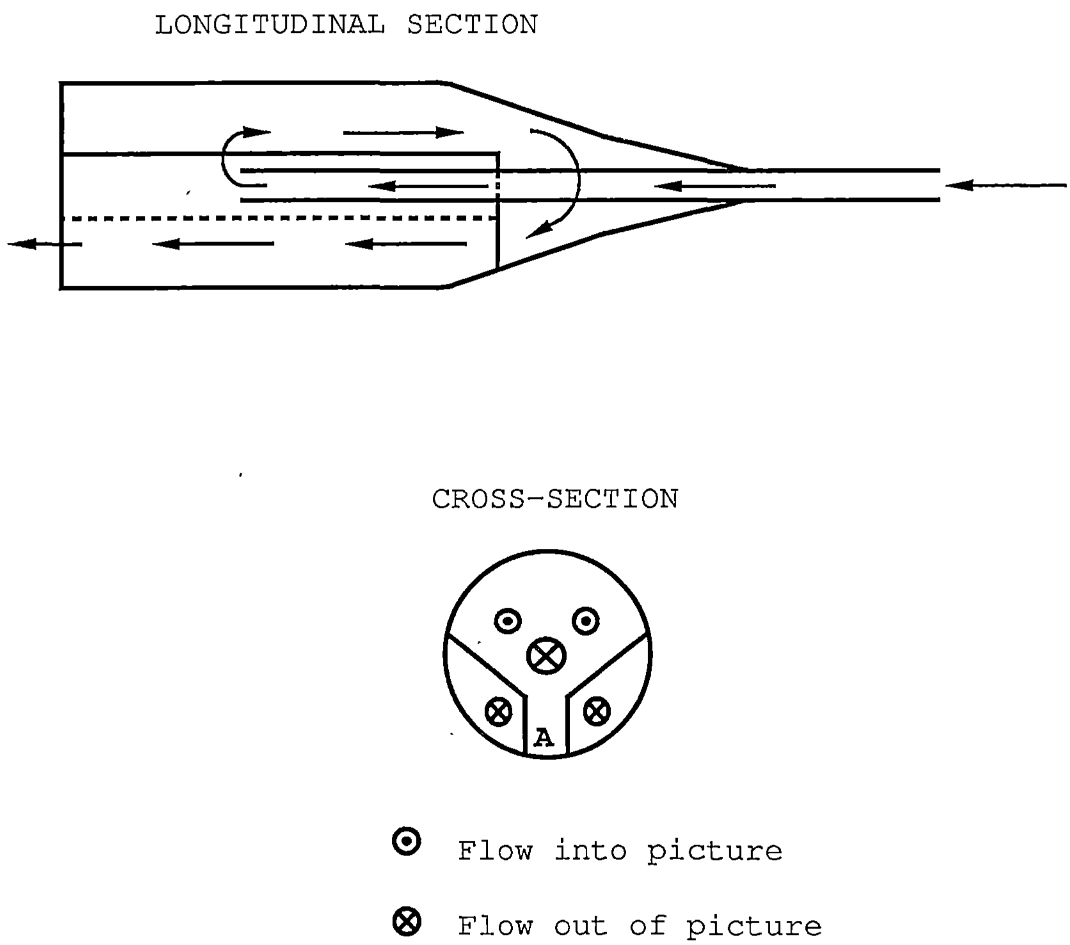


Figure 3: Delft Bottle; schematic diagram showing flow pattern. Most trapped sediment accumualtes at point **A**.

volume of the bottle, drops its load of suspended sediment in the bottle and passes out through the holes in the rear. It catches material >50 µm in diameter. In order to determine concentration, a measurement of flow speed at the nozzle height of the bottle is also required. (McCave, 1979)

There are many indirect methods for measuring suspended sediment concentrations (Austin, 1973; Gibbs, 1974; Jerlov and Nielson, 1974; McCave, 1979; Shaw, 1983; and Ward, 1984). The two most commonly used methods involve the monitoring of density and optical properties. Density monitoring uses the nuclear direct sensing technique, and has been used in studies to monitor suspended sediment load in rivers as early as 1970 (McHenry *et al.*, 1970; Welch and Allen, 1973). More recently, the technique has been used by Berke and Rakoczi (1981), Tazioli (1981) and Xianglin *et al.* (1981). In this method, gamma rays are passed through the turbid water and their attenuation is measured. This attenuation allows for the calculation of the density of the medium through which the rays pass. A simple comparison between the density of the turbid water and the density of clean water will enable the sediment load to be determined. In a discussion on sediment and dissolved loads of major world rivers, Knighton (1984) suggests that, a range of between 7% and 91% of the total sediment load is carried in solution. When using density monitoring to measure the suspended sediment load of a river, it is often necessary to independently measure the solution load, so that it may be subtracted from the water density method, leaving the suspended sediment value. For this reason, conductivity measurements are often taken in conjunction with the density technique.

For many years it has been common practice to examine the optical properties of turbid water as a guide to the amount and characteristics of the suspended sediment (Fleming, 1967; Kunkle and Comer, 1971; Truhlar, 1978; Grobler and Weaver, 1981; Brabben, 1981; Dunkerley, 1984; and Lambert and Walling, 1986). The principal optical measurements are of beam attenuation (or transmission) and scatter. In the former the light beam is aimed directly at the sensor, whereas in the latter the sensor measures the light scattered (reflected and refracted) by suspended particles. The measuring instruments are the beam transmission meter or transmissometer, the scatterometer or nephelometer, and the secchi disc. Both transmission and scatter are functions not only of the number, but also the size, refractive index and shape of the particles. Thus different suspensions of the same concentration will have different optical properties. It is therefore undesirable to calibrate optical sensors in terms of artificial turbidity standards when studies are carried out in a natural environment (Austin, 1973).

Figure 4 is a schematic diagram of a nephelometer. The principle behind a nephelometer is relatively simple. Scattered light from a collimated beam of light, passing through a column of water, is collected by a photocell which has been positioned at an angle ø from the light beam. The angle ø is the scattering angle. Turbidity is then related to the amount of scattering. Tikhonov and Goronovskii (1984) described a single beam nephelometer which was designed to automatically monitor water quality.

When monitoring suspended sediment concentrations, nephelometers have the apparent advantage that only suspended particles cause significant light scattering (Austin, 1973), so that coloured but sediment-free water will not yield spurious results. However, such water does attenuate the light beam. At high concentrations of suspended sediments the beam can be depleted to near zero, resulting in erroneous results (Dunkerley, 1984). For these reasons, light scatter is generally used in conjunction with light attenuation (e.g. Briggs, 1962; Fleming, 1967; Vanous, 1981; Dunkerley, 1984; and Gilvear and Petts, 1985).

The secchi disc is the simplest of the optical methods. It is a white disc of 20-30 cm diameter which is lowered into the water to a depth D at which it just disappears from view. The distance D is then used as an indication of attenuation and hence turbidity. Detailed discussions of secchi disc measurements and their meaning are given by Postma (1961), Otto (1966), Tyler (1968), and Williams (1970). The calibration of the disc in terms of suspended sediment concentration

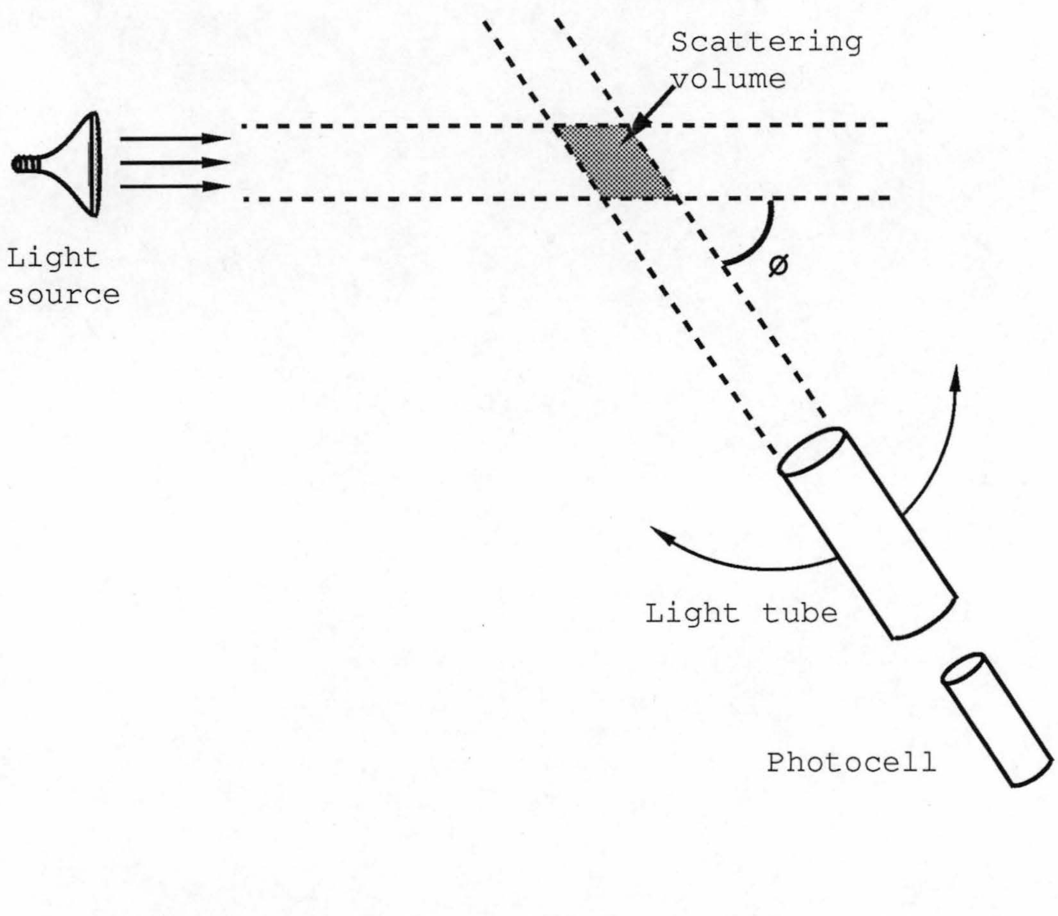


Figure 4: Schematic diagram of a nephelometer. Ø is the scattering angle. Scattered light is collected and passes through a black tube to the measuring device (photocell).

can only be done by taking simultaneous water samples for gravimetric analysis. With a rough calibration curve, the disc depth does provide a quick estimate of conditions and this is its chief value.

The transmissometer is based on the principle of light absorption. Parallel light suffers a decrease in intensity on passing through turbid water because of absorption and scattering by water and particles. Absorption by particles is highly correlated with wave length, and organic particles exhibit strong absorption in the blue (at approx. 450 nm) with another peak in the red region of the spectrum (at approx. 670 nm) (McCave, 1979).

Figure 5 is a schematic diagram of a transmissometer. A known intensity of light flux is aimed, over a fixed path length, through turbid water and onto a photocell. The resultant intensity of light is measured and compared to the initial light intensity to determine the light attenuation. This is then related to turbidity. Single beam transmissometers were successfully used by Brabben (1981) to monitor sediment loss from drainage basins supplying water to two reservoirs in East Java.

There are various types of transmissometers available on the market. Some are placed in the turbid water when in use, others remain out of the water, and have the water pumped past the sensing unit. A double-beam device is described, with a summary of the principle, by Thorn (1975), Grobler and Weaver (1981) and Ward (1984). The double-beam system eliminates the problem of fouling of the lens assuming that both lenses are equally contaminated. Burz (1970) compared two turbidity meters, the Sigrist photometer (a nephelometer) and the Askania turbidimeter (a transmissometer). This study provided no conclusive evidence that one was better than the other. Dunkerley (1984) described a low-power infrared turbidity meter which used a combination of nephelometric and transmission measurements to arrive at a turbidity value.

Most suspended sediment studies that use indirect methods rely on the use of turbidity meters. Most of these instruments are based on light attenuation, and

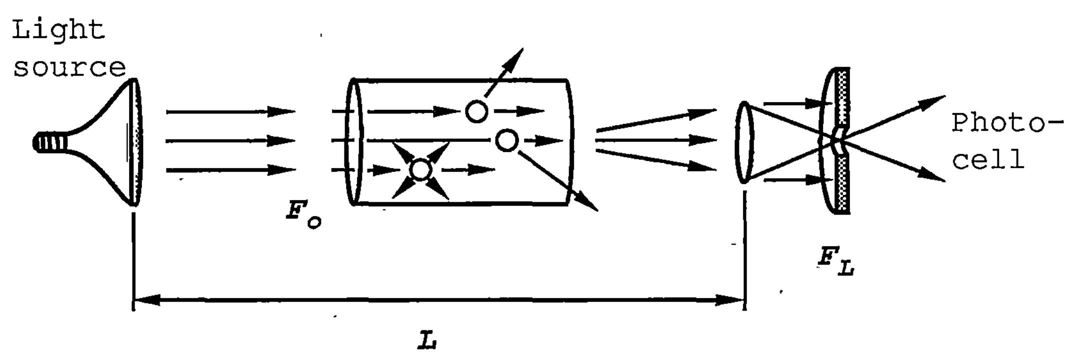


Figure 5: Schematic diagram of a transmissometer. The incident light flux F_o is scattered and absorbed so a smaller flux F_L is received at the end of the light path L.

although this method has many drawbacks, (Burz, 1970; Austin, 1973), it has often been used successfully to monitor suspended sediment concentration (Walling, 1977a; Brabben, 1981; Grobler and Weaver, 1981; Lammerts van Bueren, 1984; and Finlayson, 1985).

All of the above techniques for measuring suspended sediment concentration in rivers require calibration by direct sampling methods. Unfortunately, while the sampling methods are reasonably well standardized, the laboratory procedures for separating the sediment from the water appear to be of variable efficiency and reliability (Loughran, 1971).

The filtration technique is by far the most common method of separating particles from water samples (Dyer, 1979). Loughran (1971) has described a number of techniques based on filtration. They are rather similar, but have two significant differences. The first difference is in the technique itself. While all techniques require filtering the water sample (often with vacuum filtration apparatus) through a filterpaper, one group requires desiccating by drying the filter paper and residue (usually in an oven) and then weighing them. The weight of the filter paper is subtracted to obtain the weight of the sediment. The second group requires burning the filter paper and sediment after filtration, and the residue is weighed. A constant value for the remaining paper ash is often subtracted to obtain the weight of the sediment, although there are ashfree filter papers on the market, e.g. Whatman. (Loughran, 1971)

The second difference is in the type of filter paper used. At present, there is no international standard filter paper for use in the filtration of suspended sediment (Foster, pers. comm.). Loughran (1971) described four laboratory techniques associated with four different studies, each using a different filter paper.

The laboratory techniques used in this study are described in Appendix 1. To preserve consistency, the author followed the techniques used by the Water Research Laboratory in their study of the Tamar River. They used Whatman GF/C glassfibre filter papers, and dried rather than burnt the filtered samples.

B. ESTIMATING SUSPENDED SEDIMENT TRANSPORT

The simplest method for determining the instantaneous suspended sediment transport of a river is by using one of the direct methods. This is comparatively easy, since sediment particles move at essentially the same velocity as the flow. When measurements of sediment concentration are combined with measurements of water discharge, the transport rate of the sediment is derived. To obtain an unbiased measurement of sediment concentration, either depth integrating samplers are used or a knowledge of the cross-sectional characteristics of sediment concentration is needed. The main drawback of this technique is that it is time consuming as well as providing only an instantaneous, rather than a representative value.

There are two fundamental ways to estimate the suspended sediment transport of rivers. They are theoretical methods and empirical methods.

Many attempts have been made to relate sediment transport rates to the flow conditions in rivers, since it is relatively easy to obtain measurements of the flow parameters. A great deal has been accomplished, in this regard, in developing theories of suspended sediment transportation through consideration of the mechanics of turbulent flow of liquids. Some of the more notable examples of these theoretical models are Einstein (1950), Laursen (1958), Blench (1966), Ackers and White (1980), Celik (1982) and van Rijn (1984).

Celik (1982) presented a method for predicting the suspended sediment concentration of a river, which was based on the k-ε turbulence model, used by Nakagawa *et al.* (1975) and Ueda *et al.* (1976). Celik's method was one of the first attempts to use the velocity and eddy-viscosity distributions with a second order turbulence-closure model in calculating suspended sediment concentration distributions.

This method allows the suspended sediment concentration distributions to be predicted in a fully developed open channel flow with a fixed, rough bottom for various types of sediment material. Calculations are made using the k-e turbulence model and relating the mass transfer coefficient to the turbulent eddy viscosity distribution which is also calculated as a part of the solution.

Van Rijn (1984) uses a different approach. His method computes the suspended sediment load through the depth-integration of the product of the local concentration and flow velocity. The method is based on the computation of the reference sediment concentration from his bed-load transport model. The method is calibrated with measurements of concentration profiles. A verification analysis, using about 800 suspended sediment measurements, demonstrates that about 76% of the predicted sediment concentrations are within 0.5 and 2 times of the measured values.

Empirical methods involve the estimation of sediment transport from continuous discharge data using relatively infrequent sampling of sediment concentrations. Two standard ways of doing this are to multiply mean concentration by mean discharge (the averaging technique), and to use a rating curve to predict unmeasured concentrations.

The averaging method, as described by Walling and Webb (1981a), involves the estimator:

$$La = \sum_{j=1}^{T/\Delta t} CjQj \, \Delta t$$

where La = sediment transport

C = concentration

Q = discharge

T = total sampling time

Δt = sampling interval for each sample

This is Walling and Webb's interpolation procedure 2 and is the approved method for estimating pollutant loads in the UK Harmonized Monitoring Program.

By far the most popular empirical method for estimating the suspended sediment transport of a river is the sediment rating curve. The sediment rating curve has two basic forms, the concentration / river discharge curve and the suspended sediment transport / river discharge curve. The former curve is derived by correlating simultaneous instantaneous measurements of suspended sediment concentration and river discharge. The latter curve correlates the product of suspended sediment concentration and river discharge (rate of suspended sediment transport) with river discharge. Both forms are power curves (Dunne and Leopold, 1978; Knighton, 1984; Ferguson, 1985), and enable the prediction of suspended sediment transportation from the record of river discharge. This technique involves average discharge values which are applied to a sediment rating curve to determine the corresponding transportation rate. Since the form of the rating curve is a power function, which is usually derived from instantaneous values, the use of average discharge values will provide underestimates of the true transportation rates (see Appendix 2). The size of these errors are generally in proportion to the temporal size of the average used. For instance, Walling (1977a) suggests that yearly totals of sediment transport calculated with the use of hourly discharge averages underestimate the true value by approximately 10 percent, whereas a similar calculation with the use of daily discharge averages can underestimate the true value by as much as 50 percent.

This problem has been known since 1956 when Colby stated that ".... an instantaneous sediment rating curve is theoretically not applicable to the direct computation of daily sediment discharges from daily water discharges ....". Despite this warning, many researchers still insist on applying daily discharge data to rating curves which have been derived from instantaneous samples (e.g. Hall, 1967; Imeson, 1969; Nilsson, 1971; Temple and Sundborg, 1972; Douglas, 1973; and Al-Ansari *et al* 1977).

The sediment rating curve which is calculated with sediment transport vs discharge data has two main problems. Firstly, the use of mean daily flows produce underestimates (explained above) and secondly, the conversion of sediment concentration to transport negates the validity of the regression as both variables are a function of discharge. (Olive and Rieger, 1984)

To overcome the second problem some authors have based the regression model on sediment concentration rather than instantaneous load, (Loughran 1976 and 1977; Geary, 1981; Walling and Webb, 1981a; and Lootens and Lumbu, 1986). This technique also has two main problems. The first problem is the same averaging problem as the other technique (described above). The second problem was described by Loughran (1976) as: "... the wide scatter of points on sediment concentration vs discharge plots can make this an inferior technique for the calculation of transport rates ...", however, he goes on to say that regardless of this problem, this is still a useful technique.

Although it may be argued that sediment transport (sed. conc. x disch.) vs discharge regressions produce spurious correlations, since discharge is a part of both variables (Kenney, 1982), sediment transport is a real variable (regardless of how the data are derived), and consequently the relationship is still valid. Some authors continue to use 'sediment transport vs discharge' rating curves rather than 'concentration vs discharge' rating curves, even though the improvement in correlation is spurious (Nolan and Janda, 1981; Mimikou, 1982; Akrasi and Ayibotele, 1984; Makhoalibe, 1984; and Foster *et al.,* 1986).

Leitch (1982) calculated loads using the flow duration series rather than the discharge records. Further refinements of the regression model involved the separation of rising and falling stage data and the determination of two rating curves (Loughran, 1976 and 1977; Walling, 1978; and Geary, 1981).

In recent years considerable doubt has been thrown on the validity and accuracy of the sediment rating curve as a predictive model. Campbell (1977) recognized that a significant problem existed when he wrote "... suspended sediment and stream discharge data, as related to surface erosion measurements and regional erosion rates, show that typical rating curves significantly underestimate the occurrence of high sediment concentrations and that in most years the sediment concentrations greatly exceed those computed by rating curves." Kellerhals *et al.* (1974) came to similar conclusions. They found that rating curves for the Red Deer River Basin, Alberta, Canada, significantly underestimated the occurrence of peak sediment concentrations.

Campbell (1977) calculated that yearly total suspended sediment transport may be underestimated by as much as 40%. Geary (1981) and Olive *et al.* (1980), working on separate rivers in Australia, found that the sediment rating curve underestimated the actual sediment transport rate by 72% and 83% respectively. Olive *et al.* found that there was little improvement in the prediction using hourly (instead of daily) flows.

"Obviously serious difficulties are apparent in the sediment rating curve model." (Olive and Rieger, 1984) The major sources of error are related to the basis of a single simple relationship between sediment and discharge. Olive and Rieger (1984, 1985 and 1986) have recognized hysteresis effects in the relationship, by looking at sediment vs discharge through time.

Ferguson (1987) compared the two common empirical methods of estimating suspended sediment transport in rivers (described above). He found that both the averaging method (described by Walling and Webb, 1981a), and the sediment rating curve technique, underestimate the actual sediment transport.

C. SEDIMENT TRANSPORT CHARACTERISTICS

The accuracy of sediment discharge determinations is dependent not only upon the reliability of field methods and equipment utilized in the collection of data, but also upon knowledge of the distribution of the sediment in the flow. Particularly valuable is an understanding of the vertical and horizontal distribution of the sediment in a stream cross section.

In alluvial streams, the concentration of coarse material transported in suspension depends mainly upon velocity, concentration of fine sediment, bed configuration, and the shape of the measuring section (Graf, 1971; Bogardi, 1974; Vanoni, 1975; Garde and Ranga Raju, 1978; Celik, 1983; and Van Rijn, 1984). Therefore, the concentration of the coarse material in suspension may increase or decrease from section to section, even though the water and total sediment discharge remain uniform.

The suspended sediment concentration generally is at a minimum at the water surface, and at a maximum near the stream bed. The coarsest fractions of the suspended sediment, which are usually sand, exhibit the greatest variation in concentration from the stream bed to the water surface. The fine fractions, i.e., the silt and clay, are usually uniformly distributed over the depth of the stream, or nearly so (Vanoni, 1975; Celik, 1983; and Van Rijn, 1984).

Momentary or instantaneous fluctuations in suspended sediment concentrations are related to scale and intensity of stream turbulence and particle size of sediment in the bed of the stream. Maximum deviations from mean concentration values are to be found in streams where the suspended sediment consists largely of sand. In contrast, minimum deviations from mean concentration values occur in streams where the suspended sediment consists largely of silt and clay. Thus, the amount of the momentary fluctuation in concentration of the suspended sediment at any depth varies with the ratio of the concentration of the sand fraction to the total concentration. The amount of fluctuation also is affected by the bed configuration. (Celik, 1983)

The lateral distribution of suspended sediment at a stream cross section varies with velocity and depth, channel slope and alignment, bed form, particle size of sediment in transport, and inflow from immediate upstream tributaries (Vanoni, 1975; Garde and Ranga Raju 1978; Celik, 1983; and Van Rijn, 1984).

Natural streams seldom have symmetrical cross sections or straight channels. In medium to deep streams with well developed meanders, the velocity and concentration usually increases from the inside to the outside of the bend. Secondary circulation undoubtedly plays an important part in lateral distribution for both straight and curved channels, but at present little is known of this phenomenon (Vanoni, 1975).

Before a regular sampling program could be devised for this study, it was necessary to determine the nature of the cross-sectional profile of suspended sediment concentration at various points within the North Esk River system. For this reason, thirteen cross-sectional profiles were measured. All measurements were taken by hand with a Van Dorn type sampler (see 'Section D' in this chapter for a description of the hand sampling technique used in this study).

Twelve cross-sections were measured whilst wading and one from a flying fox. The wading samples were taken upstream of the wader, so that the wader did not affect the flow and hence the sample. Also care was taken not to include the saltation load in the samples. The samples were taken at 1/5, 1/2 and 4/5 of the river depth. If the depth was not sufficient for three independent vertical samples then either two samples, taken at 1/5 and 4/5 of the river depth, or one sample, taken at 1/2 of the river depth, were taken. Each cross-section took an average of approximately half an hour to complete.

Eight cross-sections were measured at the junction of two rivers. These were all taken upstream of the junction. The sites for these cross-sections were carefully chosen so that they were far enough upstream not to be influenced by back-water effects from the junction.

Figure 6 presents five individual cross sections of suspended sediment concentration for the North Esk River at Ballroom (Figure 7). The average velocities of the river associated with these cross sections ranges from 0.3 m/s to 2.7 m/s. Nearly all concentration values in each of the five cross sections of Figure 6 are within ±1 mg/l of the mean concentration for the respective cross section, which is the approximate accuracy of the sampling technique (Foster, pers. comm.). However, there are two exceptions, the cross section which was

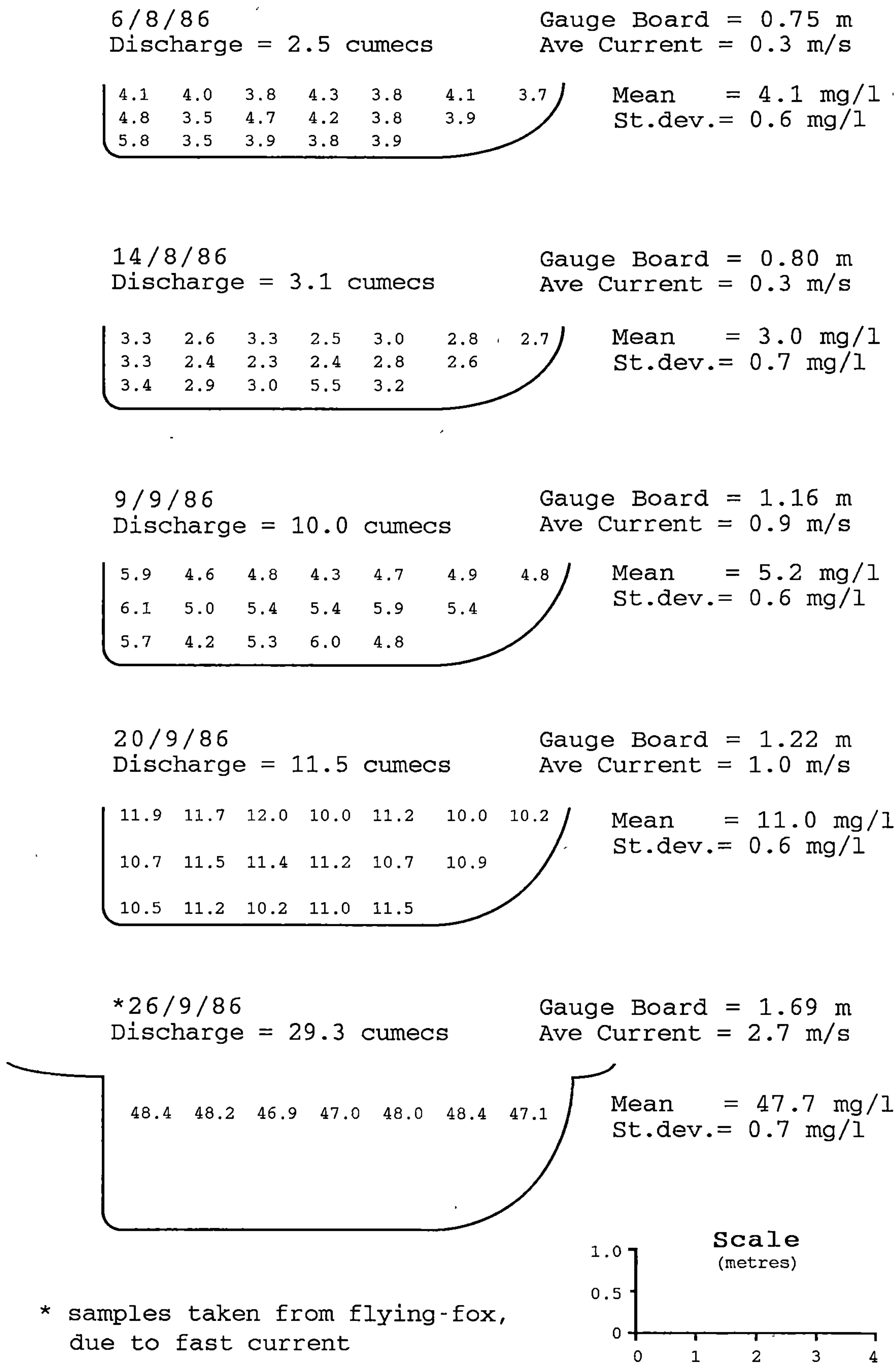
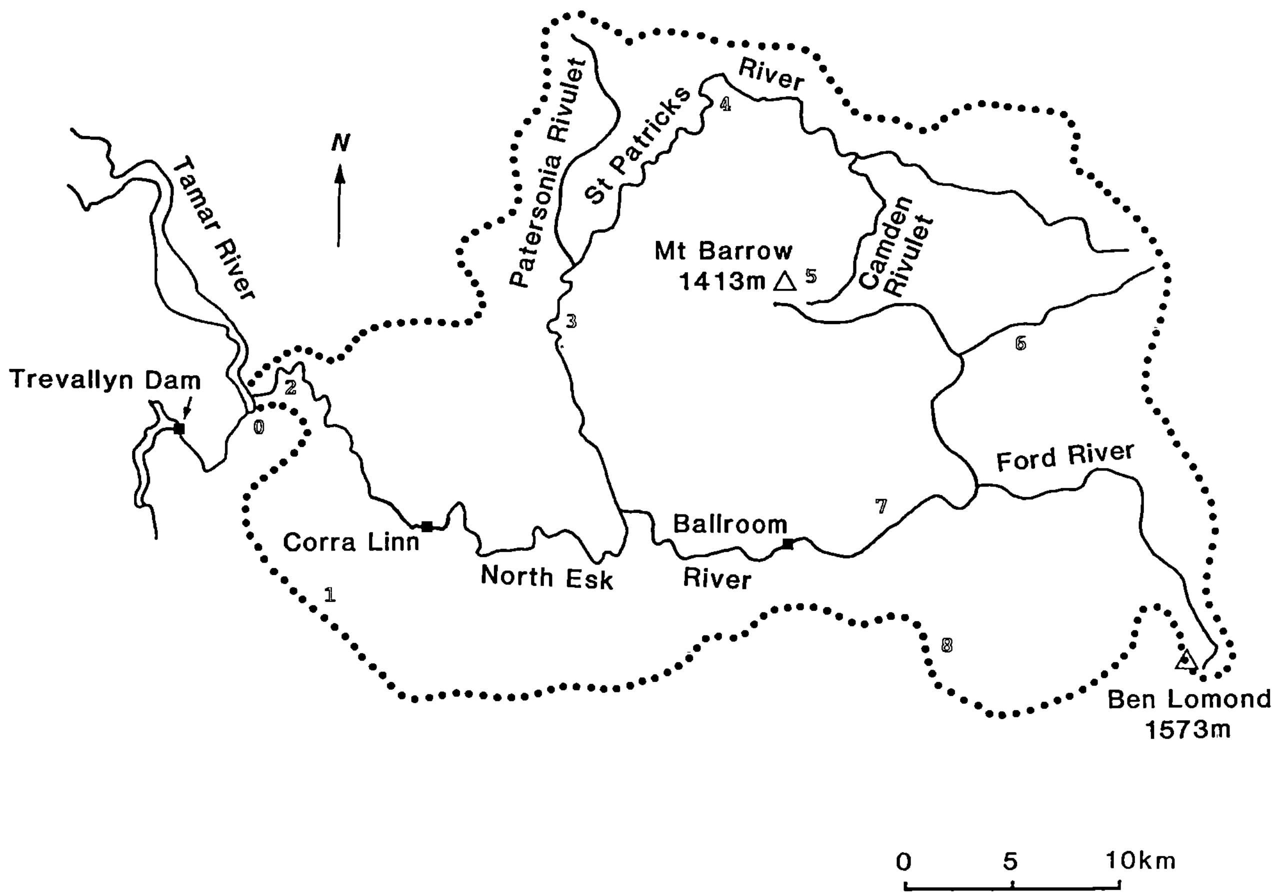


Figure 6: Cross sections of suspended sediment concentration for the North Esk River at Ballroom. All measurements in milligrams per litre. Samples taken at 1/5, 1/2, and 4/5 of the river height.



Rainfall Recording Stations

Station No.	Station Name
1	Launceston Airport
2	Launceston Pumping Station
3	St Patricks River
4	Myrtle Bank
5	Mount Barrow
6	Upper Blessington
7	Musselboro
8	Burns Creek

Figure 7: The North Esk River drainage basin. Including the locations of the rainfall recording stations, operated by the Commonwealth Bureau of Meteorology. (Tasmanian Lands Department, 1984)

measured on the 6/8/86 has a value of 5.8 mg/l in the bottom left of the cross section, which is 1.7 mg/l greater than the mean for that cross section. Also, the cross section measured on the 14/8/86 has an anomaly situated in the centre close to the bottom. This concentration of 5.5 mg/l is 2.5 mg/l larger than the mean for this cross section. Both of these anomalies occur in samples which were taken close to the river bed. They may contain some sediment from the saltation load as well as suspended load. Since there are only two samples of this type, it may be assumed that the saltation load is not significant during low flows at these cross sections (Figure 6). However, it is unrealistic to assume that the saltation load is going to remain inactive at higher flows, when the currents are much stronger. Due to the sampling techniques applied in this study (i.e. single point measurements rather than depth integrating samples), only suspended sediment has been monitored. The saltation load, along with the bed load, has not been monitored. This is a realistic approach, since the study is directed towards estimating the contribution of the North Esk to the accumulation of sediment in the Tamar estuary. Weirs on the lower reaches of the North and South Esk Rivers prevent the saltation load and the bed load from reaching the estuary, as explained previously (Chapter 1).

The data in Figure 6 are only representative of the cross sectional profiles of suspended sediment concentrations for velocities of less than 2.7 m/s. Chorley (1969) and Celik (1983) maintain that at velocities of ≥1 m/s the transport of sand is approximately uniform through all parts of the cross section. Hence, for the purposes of this study, it will be assumed that the cross sectional profile of suspended sediment concentration within the North Esk River at Ballroom is consistently homogeneous.

It can be seen from Figure 8A and 8B that homogeneous cross sectional suspended sediment concentration is not restricted to the North Esk River at Ballroom, but is a characteristic of other sampled cross sections in the North Esk catchment.

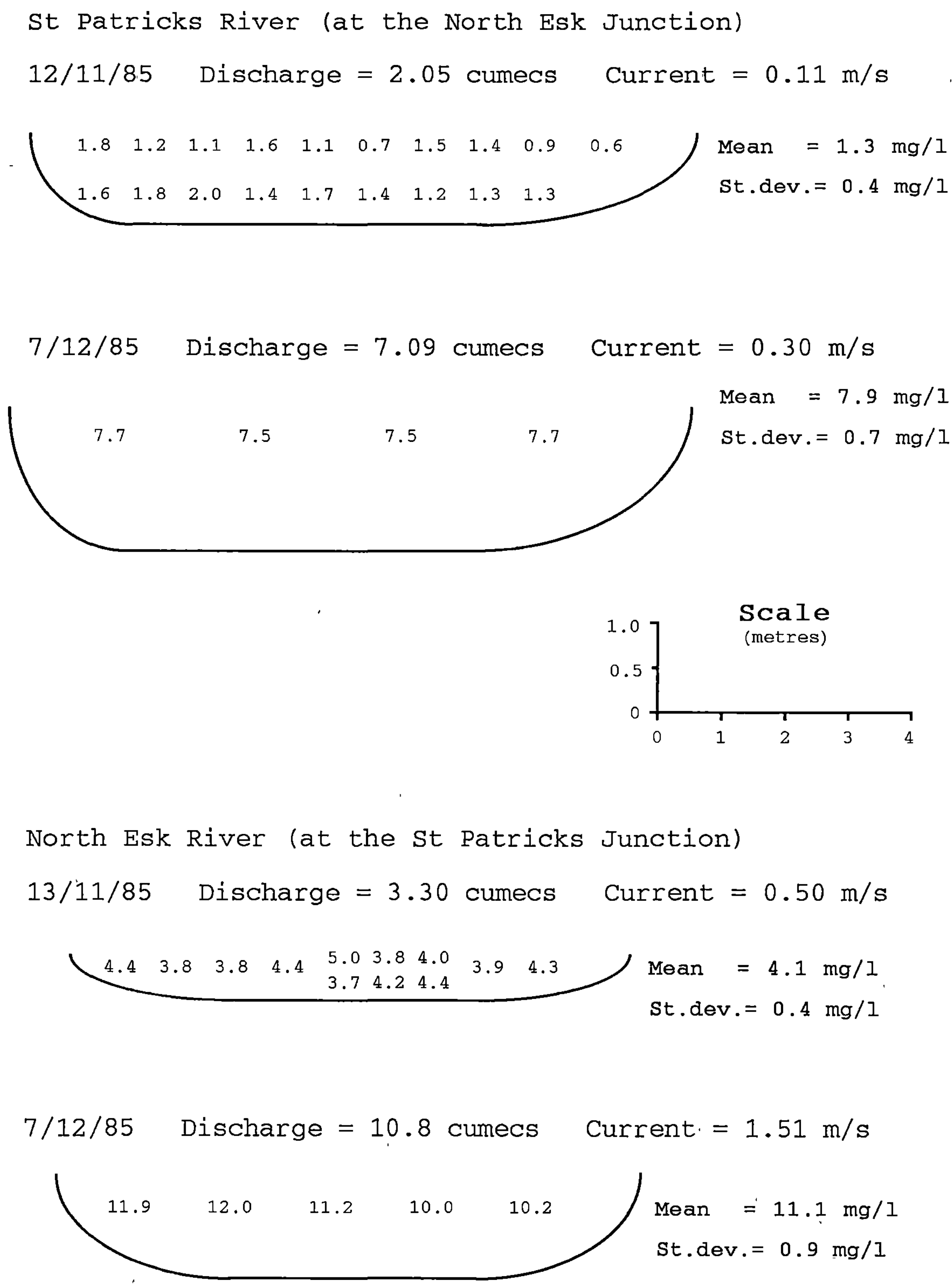
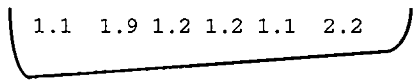


Figure 8A: Cross sections of suspended sediment concentration from various points within the North Esk basin. All measurements in milligrams per litre. Samples taken at 1/5, 1/2, and 4/5 of the river height.

St Patricks River (at the Camden Rivulet Junction)

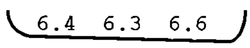
29/11/85 Discharge = 2.21 cumecs Current = 0.50 m/s



Mean = 1.5 mg/l
St.dev.= 0.5 mg/l

Camden Rivulet (at the St Patricks River Junction)

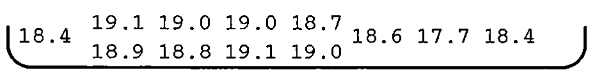
29/11/85 Discharge = 0.54 cumecs Current = 0.63 m/s



Mean = 6.43 mg/l
St.dev.= 0.15 mg/l

North Esk River (at the Ford River Junction)

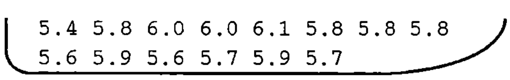
30/11/85 Discharge = 1.95 cumecs Current = 0.59 m/s



Mean = 18.8 mg/l
St.dev.= 0.2 mg/l

Ford River (at the North Esk River Junction)

30/11/85 Discharge = 1.37 cumecs Current = 0.40 m/s



Mean = 5.8 mg/l
St.dev.= 0.2 mg/l

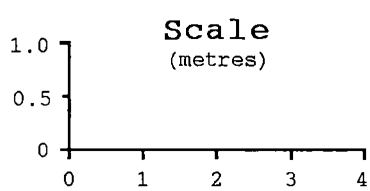


Figure 8B: Cross sections of suspended sediment concentration from various points within the North Esk basin. All measurements in milligrams per litre. Samples taken at 1/5, 1/2, and 4/5 of the river height.

D. TECHNIQUES APPLIED IN THIS STUDY

The sediment concentration data used in this study were obtained with a combination of hand samples and turbidity measurements.

a. Hand Samples

Hand samples were taken with the use of a Van Dorn type sampler. This sampler was made at the Water Research Laboratories of the University of New South Wales. It consisted of a perspex tube 9 cm in diameter and 35 cm long. This tube was attached to a pole 250 cm long, and had two rubber stoppers which were attached to each other, through the tube, via a thick rubber band. To set the sampler, the rubber band was stretched sufficiently to allow the stoppers to be attached to each other outside the tube by a "U"-bolt. In this state the water was able to freely flow through the tube. To trigger the sampler the "U"-bolt was removed quickly which allowed the rubber band to pull the stoppers into place at each end of the tube, hence trapping a water sample of approximately one litre. This sample was then tipped into a clean sample bottle for storage until analysis a few hours later. An inspection of the sampler at this stage usually revealed that all sediment had been transferred to the bottle, if this was not the case, a known quantity of sediment free water was used to rinse the sediment into the bottle.

The samples were analysed using Whatman GF/C Glass Microfibre filters in a standard filtration method, for a detailed description of this method see Appendix 1. The resultant sediment concentration was expressed in milligrams per litre. Foster (pers. comm.) suggests that this technique yields accuracies of ±0.5 to ±1 mg/l.

b. Turbidity Measurements

The turbidity measurements were taken with the use of a turbidity meter which was designed and constructed as part of this study. The turbidity meter was designed to incorporate three main features. They are: the ability to withstand large floods (including strong currents as well as rocks and logs); to measure turbidity without appreciably disturbing the flow of water; and most importantly, to be cheap and easy to maintain. Figure 9 is a circuit diagram of the electronics. A detailed description of the function of these electronics can be found in Appendix 3. The meter has two principal components, the light source and the sensor unit. The light source consists of a 2.5 v Eveready globe mounted with a light dependent resistor (LDR) in a blackened Eddystone aluminium box (Figure 10). The output of the globe is kept constant by a feedback circuit through the LDR. The globe voltage is adjusted to approximately 2 v, which is 0.5 v lower than its rating. This increases the life of the globe as well as producing a yellow light, the best colour for assessing turbidity. This is because it is least affected by transmission through water, since reds are absorbed by water, while blues and greens are scattered.

The light produced by the globe is directed via a collimating lens to the output sensor, which is situated on the opposite side of a clear perspex tube, through which the water flows (Figure 10). This beam is 10 mm wide and has a path length of 48 mm, 32 mm of which is through water. The output sensor produces a voltage that is inversely proportional to the incident light, and hence proportional to the turbidity of the water passing through the perspex tube.

The tube is a dual construction, consisting of a clear perspex tube, surrounded by a galvanized iron pipe for protection. They were attached at both ends with Selley's roof and gutter silicon sealant. This pipe was welded to a galvanized iron box used to house the light source and electronics (Figure 10).

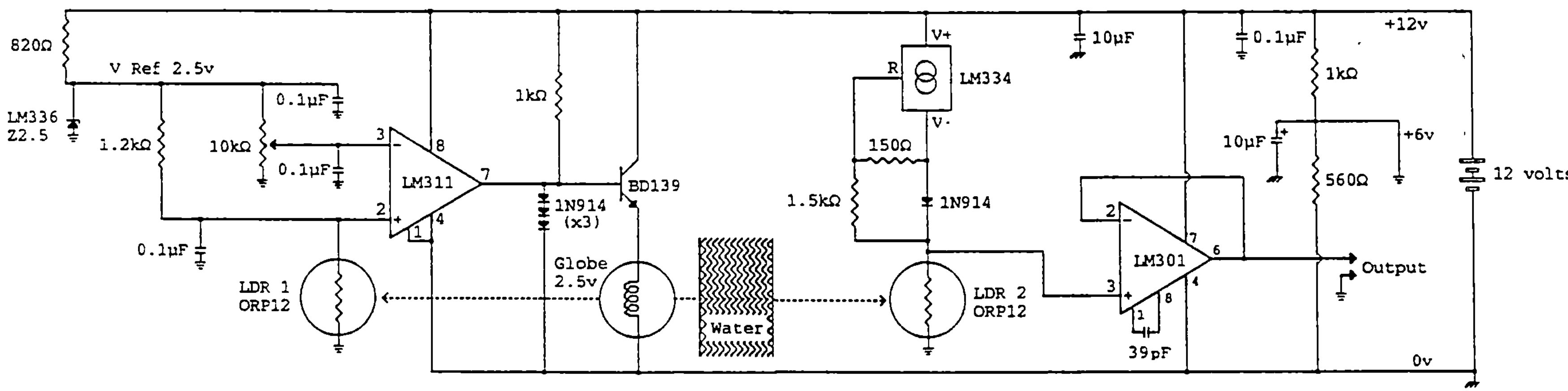
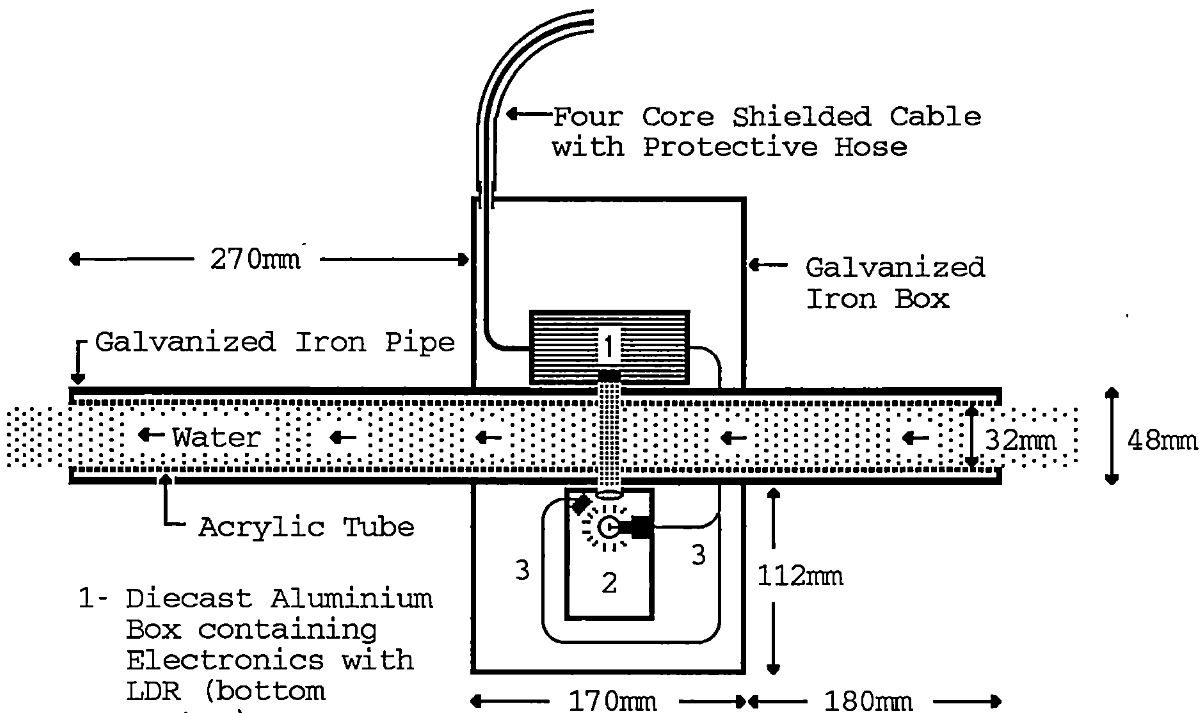


Figure 9: Circuit Diagram of the Turbidity Meter's Electronics.



1- Diecast Aluminium Box containing Electronics with LDR (bottom centre)

2- Light Source: Diecast Aluminium Box containing Lightglobe, LDR (top left), and Collimating Lens (top centre)

3- Wires connecting the Light Source with the Electronics

Figure 10: Turbidity meter section

During tests, it was found that some outside ambient light was reaching the sensor as a result of multiple reflection within the perspex tube. This problem was rectified by blackening 150 mm of each end of the tube with matt-black paint.

The power supply to the turbidity meter consisted of a 12 v car battery that was trickle charged by a solar panel. The power to the turbidity meter was controlled by a Campbell Scientific CR21 Micrologger (Plate 1), that also monitored the output of the meter. The CR21 was programmed to switch the meter on for two minutes every hour. During this time the output of the meter was sampled every ten seconds and stored as a sum, at the end of each period.

The output of the turbidity meter was calibrated for temperature drift with the use of a Sanyo MIR 251 incubator. This test was conducted over a temperature range of 0 °C to 20 °C. The resultant calibration was:

$Y = 0.30 - 0.03T$, $R^2 = 96.90\%$, and the Standard Error = 0.03 v.

Y is the offset (volts) of the turbidity meter's output at 10 °C.

T is the temperature (°C) of the river.

The results were normalized to 10 °C for convenience.

The turbidity meter was mounted on a stake in the middle of the North Esk River at Ballroom. The meter's intake was one metre above the river bed, putting it no less than 0.5 m below the water surface of the river at times of low flow. During the period of the meter's use, the largest flood reached a height of 2 m above the instrument. This meant that the fixed intake of the turbidity meter was sampling different parts of the water depth. However, this did not pose a problem, since the cross sectional profile of the suspended sediment concentration was virtually homogeneous, as explained earlier, see Figure 6.

The stake was a 1.5 m long piece of 76 mm channel iron. This was driven and cemented into the river bed. At the top of the stake was bolted a plate, with a

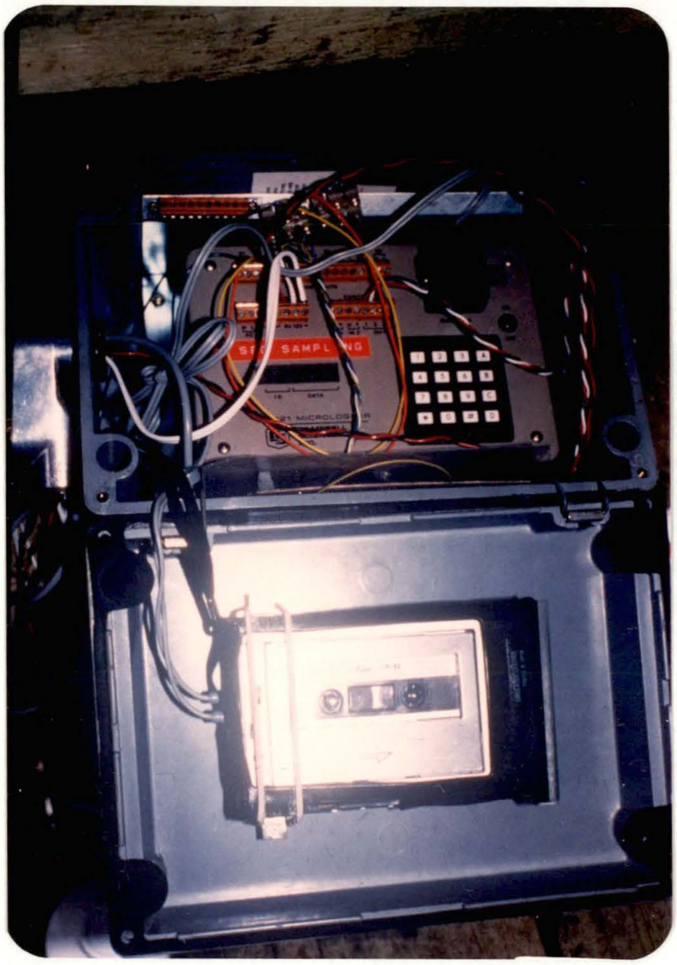


Plate 1: Campbell CR21 Micrologger with cassette tape recorder for data storage.

'mate' attached to the turbidity meter. The two plates were held together with lynch pins (Figure 11). This system proved to be a very quick and easy method of mounting the turbidity meter. An example of this mounting is shown in Plate 2, which is a photograph of a prototype turbidity meter mounted in a smaller stream.

Cleaning of the meter was carried out by scuba diving or snorkeling, however this was only necessary during extensive periods of low flows, since the meter proved to be self cleaning during moderate to high flows. If the meter were to be used extensively on a 2 minutes per hour basis, as was done in this study, the globe would last for approximately one year. The meter needed to be removed when replacing the globe, a task which required little skill, but took approximately 3 hours due to the elaborate sealing system.

The turbidity meter was installed at Ballroom on the 26th of June 1986 and taken out at the completion of the study on the 17th of October 1986. During this period 53 hand samples were taken, using a Van Dorn bottle, and analysed. The range of suspended sediment concentrations was 2.81 to 51.30 mg/l. The results were plotted against the corresponding temperature corrected turbidity meter outputs (Figure 12). The top cluster of points (together with some of the lower cluster) represent a single flood. The gap, in the middle of the data, is a result of a lack of hand sampling because the author was attending other observation sites.. A least squares regression was fitted and produced the following results:

$$Y = -184.2 + 15.9X + 0.5T$$

$R^2 = 99.1\%$, and the standard error = 1.2 mg/l.

where Y is the suspended sediment concentration (mg/l)

X is the output of the turbidity meter (volts)

and T is the water temperature (^oC).

This regression indicates that the turbidity meter can measure suspended sediment concentrations to an accuracy of ±2.4 mg/l at the 95% confidence limits.

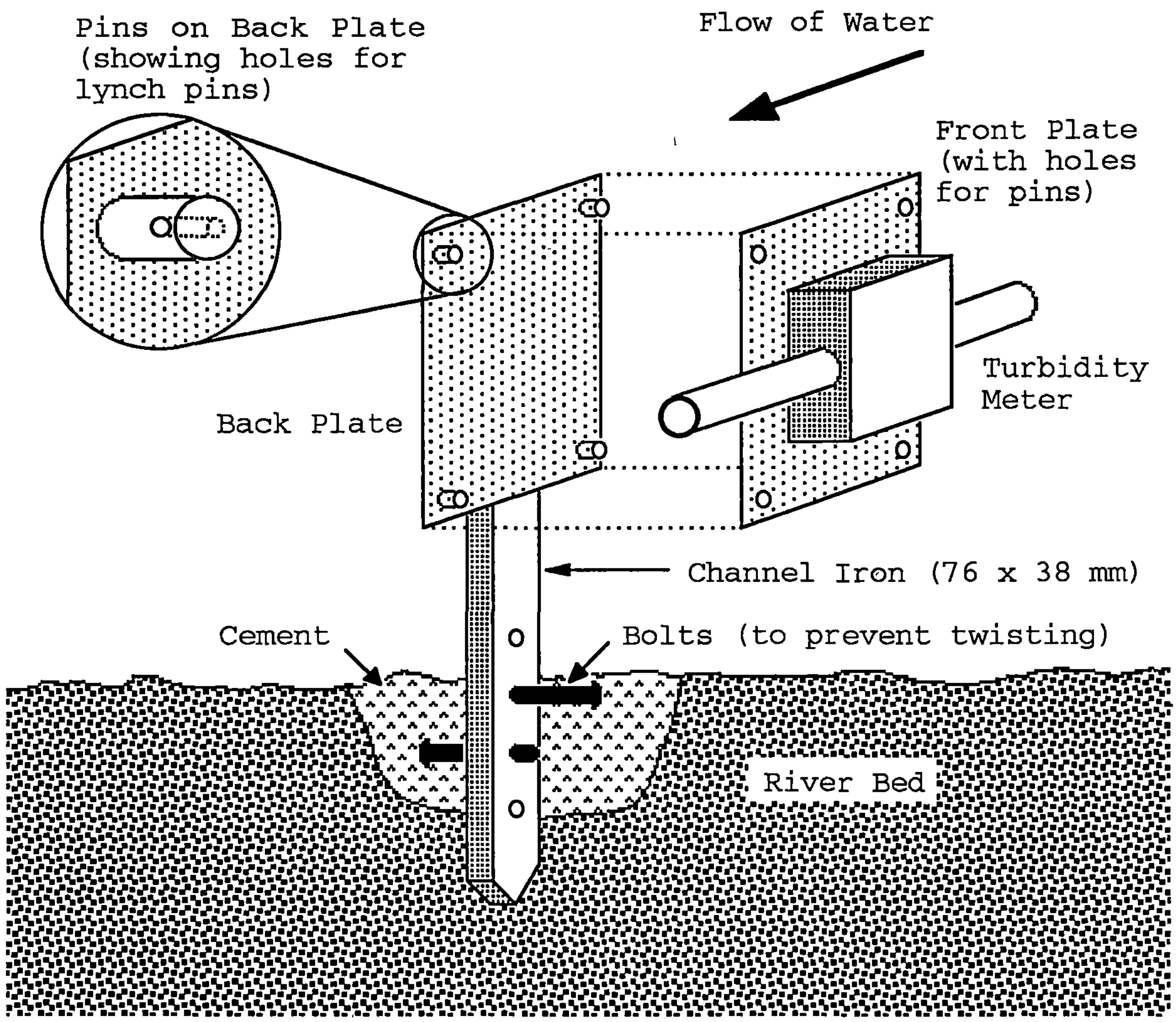


Figure 11: Turbidity meter mounting

Plate 2: Prototype turbidity meter, mounted in a small stream.

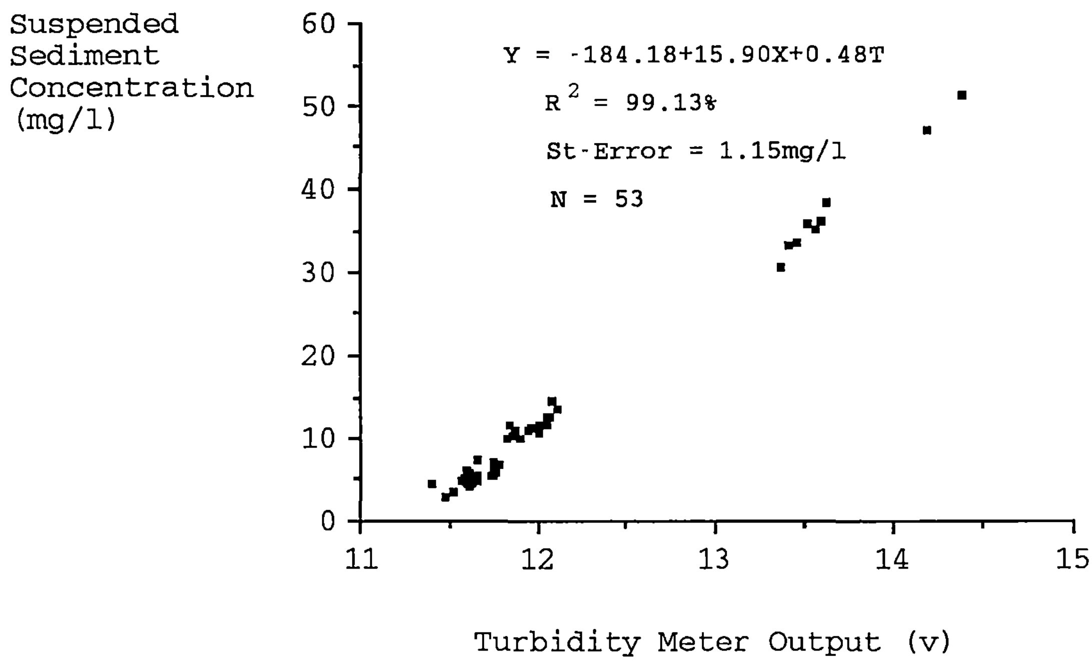


Figure 12: Turbidity meter calibration, where T is the water temperature (°C).

CHAPTER 3: THE STUDY AREA

The North Esk River Basin is situated in the north east of Tasmania (Figure 1). It has two main sections, comprising the catchments of the North Esk and the St. Patricks Rivers (Figure 7). The drainage basin is approximately 1050 sq. km in area and the high ground is dominated by Mount Barrow around which the North Esk and St. Patricks Rivers flow (Figure 13).

A. GEOLOGY AND SOILS

The geology of the basin consists mainly of three rock types, namely Palaeozoic sediments, Palaeozoic granodiorites, and Jurassic dolerites. The latter rock type dominates the lower reaches of the catchment, while the former two dominate the source areas of the North Esk and St. Patricks Rivers respectively (Figure 14).

Figure 15 illustrates the dominance of podzolic soils which cover almost 90% of the catchment. The remaining 10% is predominantly alpine humus soils which occupy the higher altitude regions (>1000 m). (Davies, 1965)

B. CLIMATE

Tasmania, on account of its relatively small size and being surrounded by sea, possesses in the main a mild maritime climate, with comparatively small seasonal ranges of average temperature and rainfall. Tasmania's rainfall is dominated by the Westerlies and, due to rain shadow effects, the area around the North Esk River is relatively dry when compared with most of Tasmania. An indication of the variability of the climate of this region can be obtained by examining the data for Launceston (Table 3), which is situated at the mouth of the North Esk River, where it flows into the Tamar River.

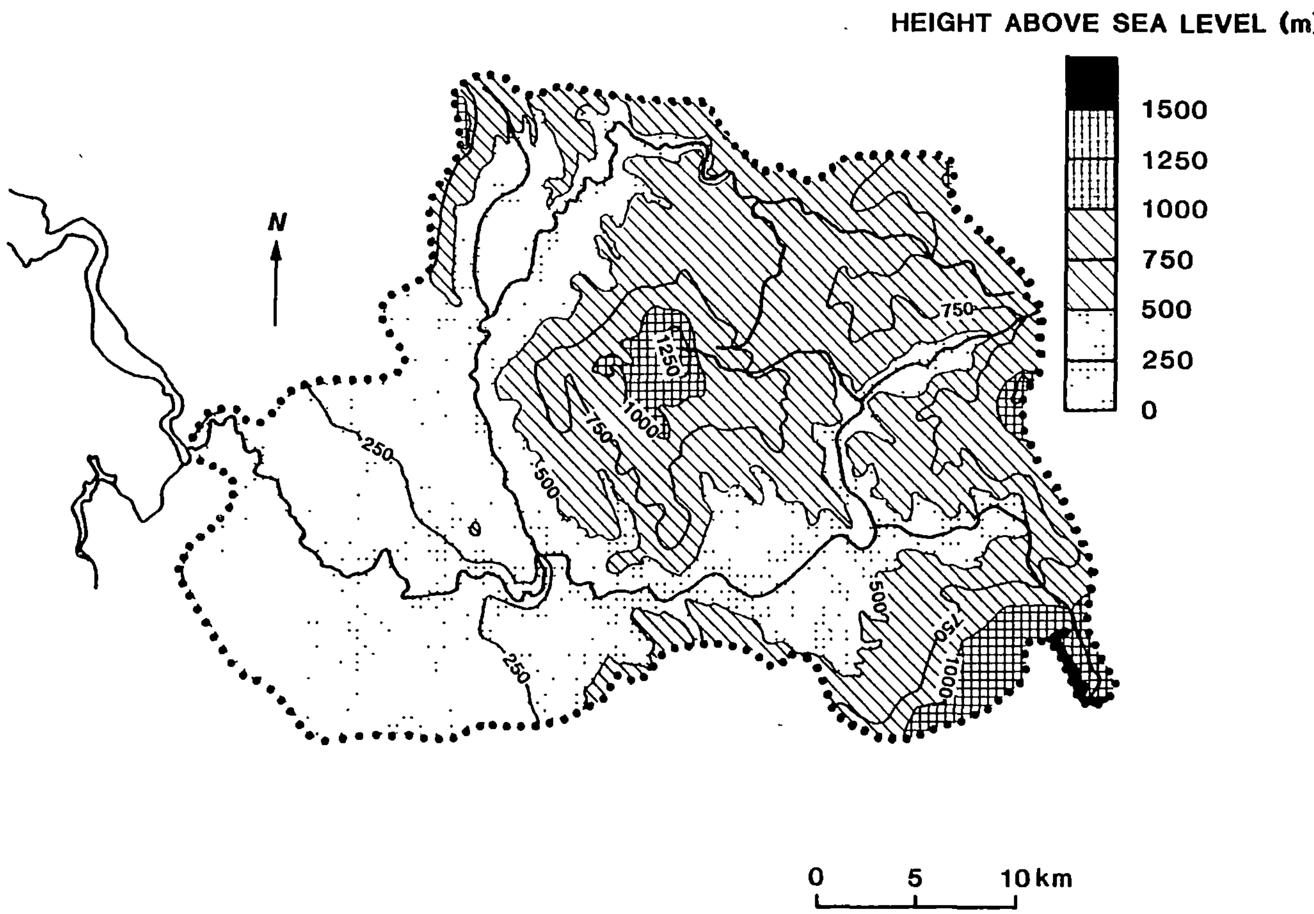


Figure 13: Relief of the North Esk River basin. (Tasmanian Lands Department, 1984)

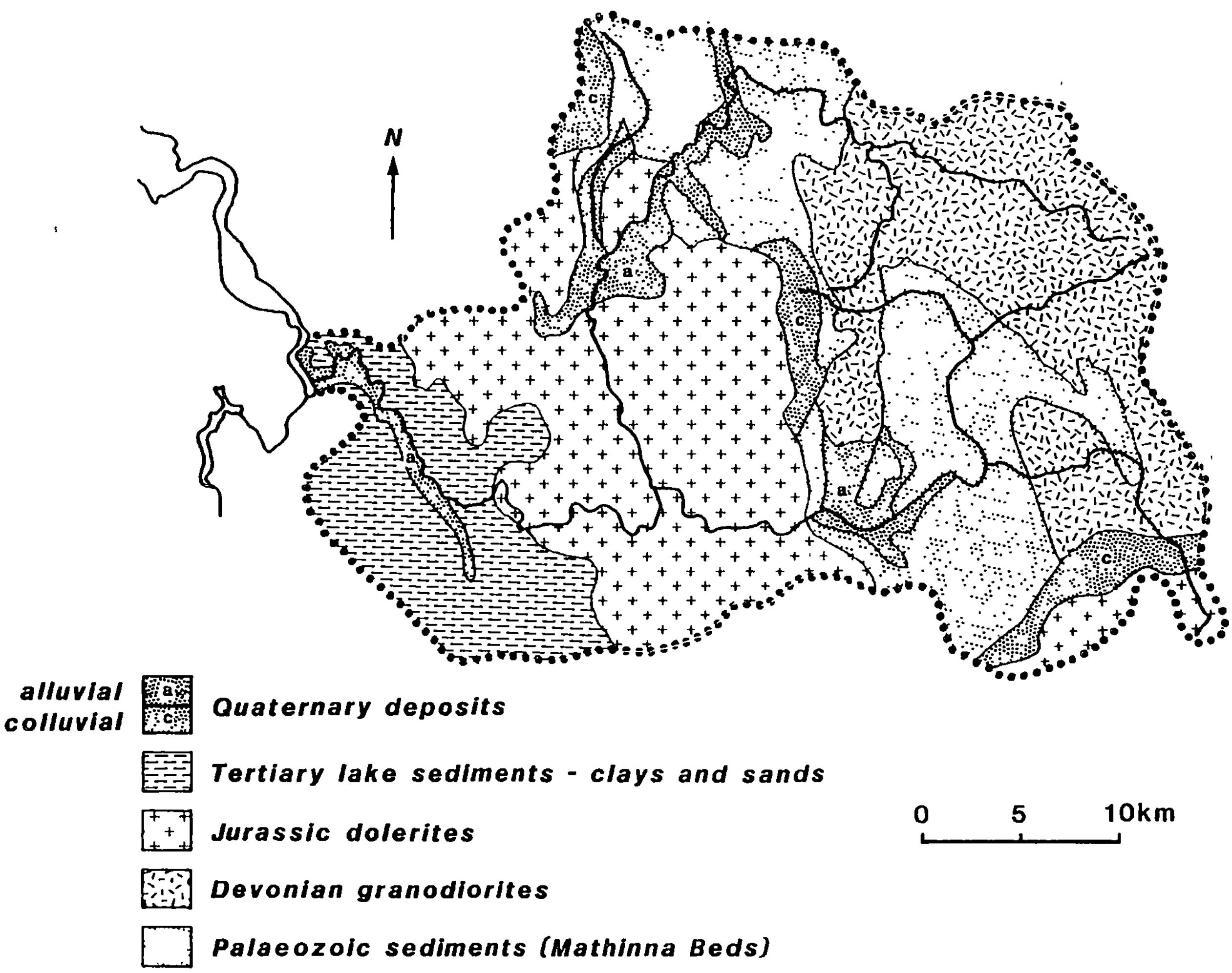


Figure 14: Geology of the North Esk River basin. (Tasmanian Forestry Commission, 1984)

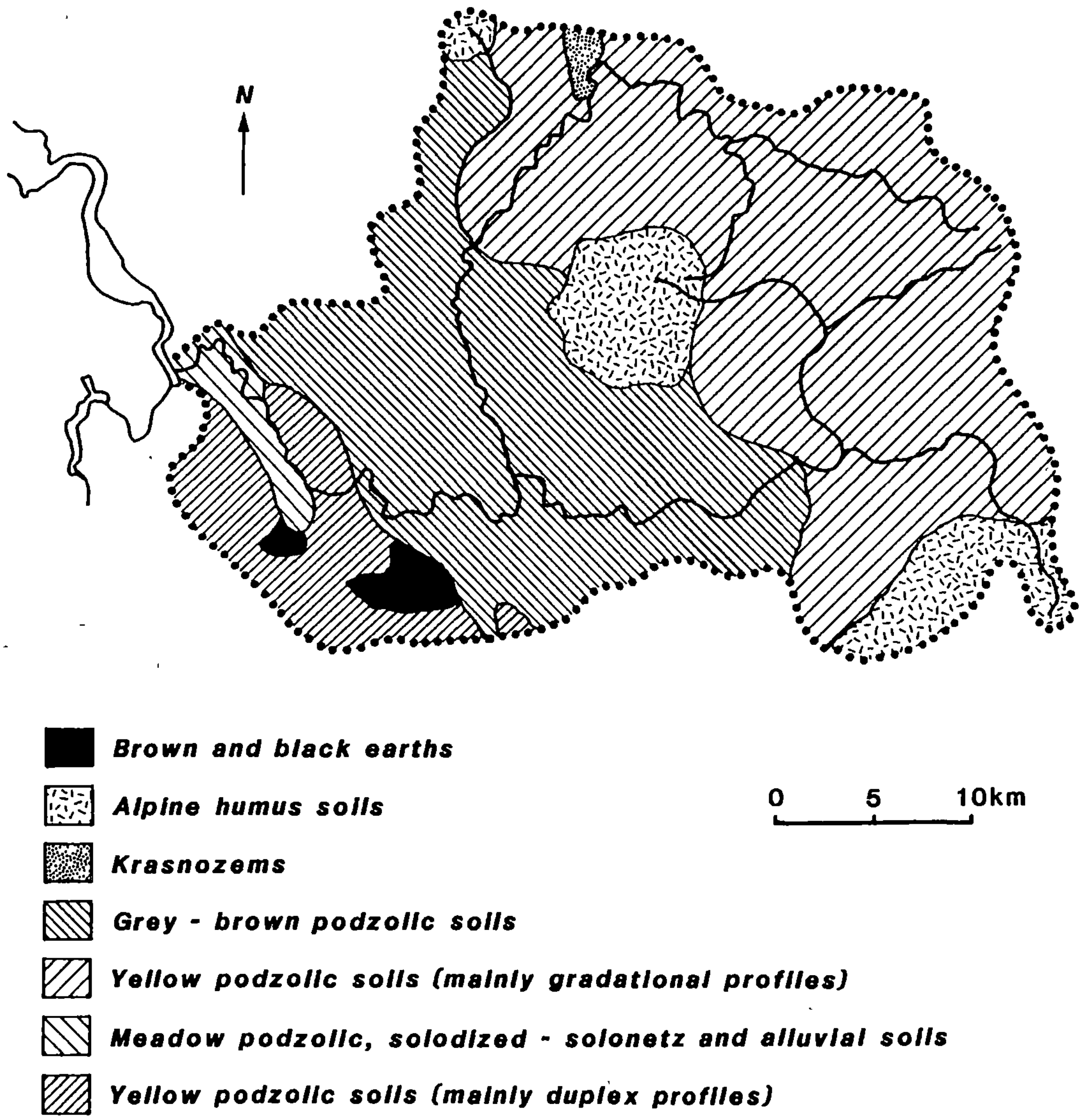


Figure 15: Soils of the North Esk River basin. (Davies, 1965)

Month	Average Maximum Temperature (°C)	Average Minimum Temperature (°C)	Average Rainfall (mm)
January	24.4	11.2	39
February	24.7	11.5	38
March	22.0	9.9	43
April	18.5	7.4	61
May	15.3	5.1	69
June	12.5	3.5	79
July	12.1	2.7	79
August	13.5	3.6	79
September	15.9	5.5	71
October	17.8	6.7	68
November	20.7	8.4	46
December	22.8	10.2	54
Year	18.4	7.1	726

Table 3: Launceston Climatological Data; Averages over the period 1908 to 1987 (Commonwealth Bureau of Meteorology, 1988)

The temperature ranges are small, both on a diurnal and seasonal basis. Using monthly averages, the diurnal variation ranges from 2.7 - 12.1 °C in July to 11.5 - 24.7 °C in February. This range is of a similar magnitude to the seasonal variation from July to February (2.7 - 11.5 °C for average minimum temperatures, and 12.1 - 24.7 °C for average maximum temperatures). (The Commonwealth Bureau of Meteorology, 1988) Unfortunately, there are no other stations (except the Launceston Airport, which is close to Launceston) which have recorded temperatures on a regular basis, over a sufficiently long period so that their averaged data are meaningful.

There is a reasonably extensive system of rainfall recorders from which historical data has been obtained. However the data, with the exception of Launceston and the Launceston Airport, are only available as either daily or monthly totals. Table 4 is a summary of this data.

Figure 16 is an isoline map depicting the average annual rainfall for the North Esk drainage basin. The pattern depicted in this map is supported by Tables 3 and 4. The average annual rainfall within the region varies between approximately 750 mm and 1500 mm. Figure 16 illustrates Mount Barrow's dominant influence on the rainfall distribution pattern. A large proportion of this precipitation, including most heavy falls, is due to orographic processes. Moist airflow with a large northerly component, usually a result of cut-off lows travelling through Bass Strait (which lies only 60 km north of Mount Barrow), is forced to rise over the mountains in the area, in particular Mount Barrow, causing widespread rainfall which is usually much more intense on or near mountains than at lower elevation. This is evident when patterns of rainfall and elevation are compared (Figures 13 and 16).

Areas of lower elevation receive most of their rain from frontal systems. Cold fronts, which usually have a westerly origin, often bring widespread rains of low intensity.

Month	Average Rainfall (mm)							
	1	2	3	4	5	6	7	8
January	40	43	59	62	68	61	47	39
February	42	38	62	76	96	41	54	33
March	42	40	69	70	87	78	52	67
April	58	58	107	112	132	82	78	68
May	63	69	135	156	155	97	92	87
June	61	76	150	174	142	93	97	81
July	81	83	180	207	160	109	141	106
August	78	76	173	196	189	123	124	94
September	64	69	135	141	153	96	102	95
October	63	69	116	116	107	74	90	70
November	51	48	88	100	103	72	63	61
December	53	50	83	84	117	87	63	77
Year	696	719	1357	1494	1509	1013	1003	878

Station No.	Station Name	Period of Record
1	Launceston Airport	1931-1987
2	Launceston Pumping Station	1883-1963
3	St Patricks River	1905-1987
4	Myrtle Bank	1931-1971
5	Mount Barrow	1963-1973
6	Upper Blessington	1969-1986
7	Musselboro	1926-1966
8	Burns Creek	1972-1987

Table 4: Average Monthly Rainfall Data for Eight Stations within the North Esk River Catchment Area (Commonwealth Bureau of Meteorology, 1988) See Figure 7 for the location of the rainfall stations.

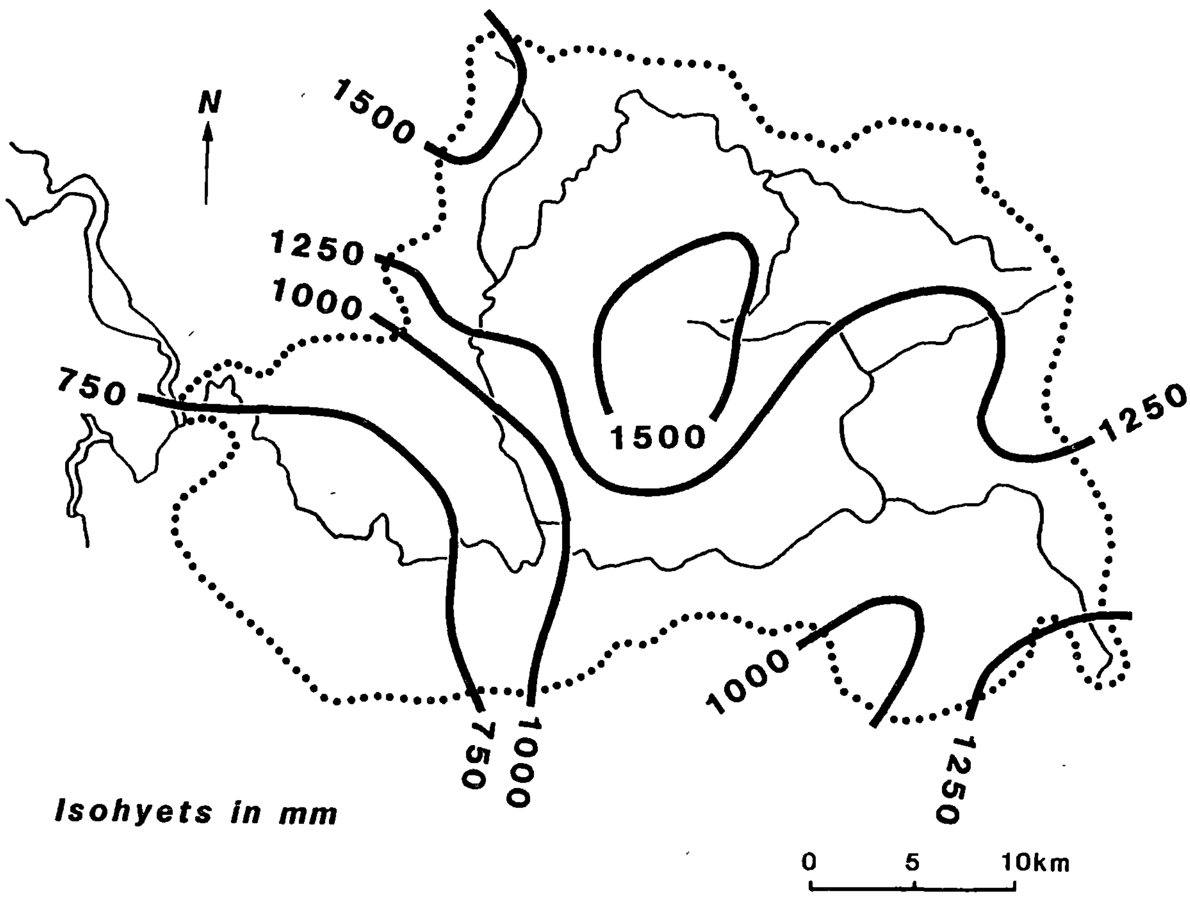


Figure 16: Average annual rainfall for the North Esk River basin. (Commonwealth Bureau of Meteorology, 1984)

Launceston's rainfall is evenly spread throughout the year, with the maximum monthly average of 79.2 mm occurring in August and the minimum of 37.8 mm occurring in February (Table 3). Although the rainfall tends towards a winter maximum, the yearly distribution is such that a flood is likely to occur at any time throughout the year. Launceston's yearly average rainfall is 725 mm (Table 3).

Tables 3 and 4 show that Launceston is one of the driest stations (726 mm/year), with the Mount Barrow station having the highest average rainfall (1509 mm/year). All stations exhibit similar seasonal trends, with the maximum rain falling during the winter months and the minimum during the summer months, although significant falls are recorded in all seasons.

It is interesting to compare the Myrtle Bank and Mount Barrow data (Table 4). While the Mount Barrow station records the highest average annual rainfall, Myrtle Bank has higher average monthly rainfalls for May to August, i.e. through the winter. This is the period during which rainfall from cut-off lows is more prevalent. Consequently, an increased proportion of rainfall in the area would be derived from orographic processes within a northerly airstream. In this situation, the rain would most likely be heaviest slightly north of the Mount Barrow station, which is the approximate location of the Myrtle Bank station.

C. VEGETATION AND LAND USE

The North Esk Basin is predominantly covered with eucalypt forests (Plate 3), with the exception of relatively small areas of farmland, including cropping and grazing (Plate 4), and even smaller regions of alpine vegetation (Figure 17). Active logging is currently being carried out on the eastern slopes of Mount Barrow, an area drained by the sources of the St. Patricks and North Esk Rivers (Plate 5). This region is also a high rainfall area (Figure 16).

Plate 3: Eucalypt forest, upper North Esk River.

Plate 4: Grazing pasture with eucalypt forest in the background, North Esk River at Ballroom.

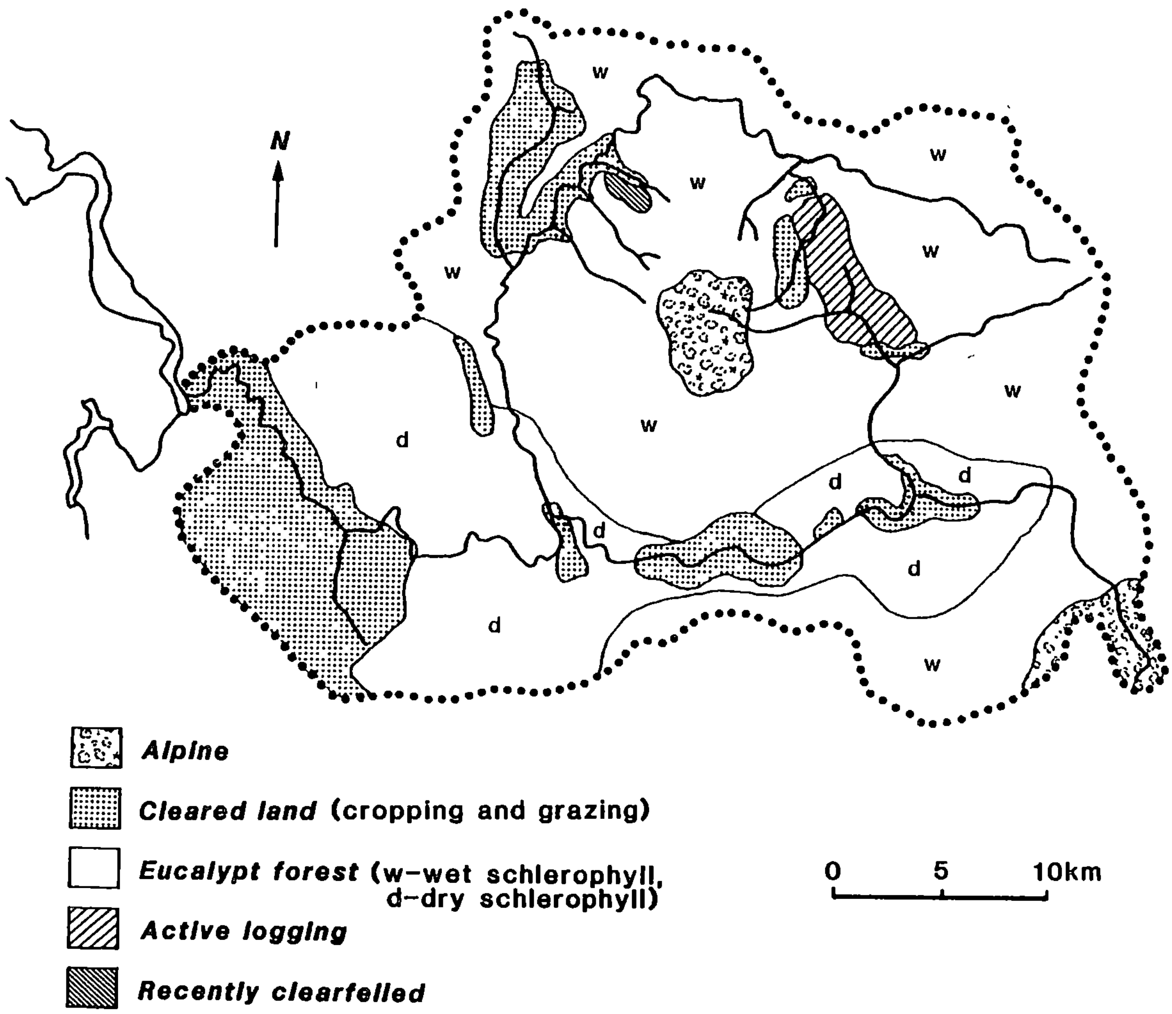


Figure 17: Vegetation and Landuse witbin the North Esk River basin. (derived from aerial photography which was supplied by the Tasmanian Lands Department)

Plate 5: Active logging, upper St Patricks River.

Most farming takes place on the floodplains and adjacent hills. The main cash crops of the area are barley and wheat, grown mostly on the river flats (Plate 6). During the preparation for planting (approximately two to four weeks per crop), these areas are at great risk to erosion due to an absence of any protection from vegetation during and for a short period after ploughing and planting (Plate 7). Grazing areas for beef and dairy cattle, and sheep, however, are less susceptible to erosion because of the infrequent ploughing (annually to once every five years) that is inherent in this type of farming.

Plate 6: Cropping on the river flats (barley) with grazing in the foreground, North Esk River at Ballroom.

Plate 7: Ploughing on the river flats, lower St Patricks River.

CHAPTER 4: ESTIMATES OF SUSPENDED SEDIMENT TRANSPORT

The main aim of this study is to estimate the quantity of suspended sediment being transported by the North Esk River. A logical way to express this quantity is as an average yearly total, in order to take into account inter-annual variations. Due to the annual variability of river discharge, it is necessary to use long-term hydrographic records to obtain an accurate estimate of the yearly average discharge, and hence suspended sediment transport. It must be stressed that the long term hydrographic records are not being used to reconstruct past sediment transport rates. This is not possible in any case, since one cannot assume that the discharge/sediment concentration relationship has remained constant over time. The aim is simply to apply the present relationship over a sufficiently long time period to obtain a meaningful estimate of the mean annual suspended sediment transport under present day conditions.

Hydrographic records exist for two sites in the North Esk Basin. The Hydro Electric Commission of Tasmania (HEC) operated a Bristol pressure recorder at Corra Linn (Plate 8) for the period 6th February, 1959, to 1st May, 1974. However, only three years of this record (1961 to 1963) have been accurately digitised, the remaining data are either missing or in such a format, that it is impossible to obtain accurate digitisation. This casts some doubt on the accuracy of the three years that are digitised. However, in the absence of other data, it will be assumed that these digitised data are sufficiently accurate.

The Tasmanian Rivers and Water Supply Commission (RWSC) have been operating a Stevens continuous water-level recorder, type A35b, on the North Esk River at Ballroom (Plates 9 and 10). For a more detailed description of this float-activated water-stage recorder, see Linsley *et. al.* (1949). This instrument has provided accurate daily average discharge records for the 39 year period between 1950 and the present, however the data for the period between 1979 and the present

Plate 8: The North Esk River at Corra Linn.

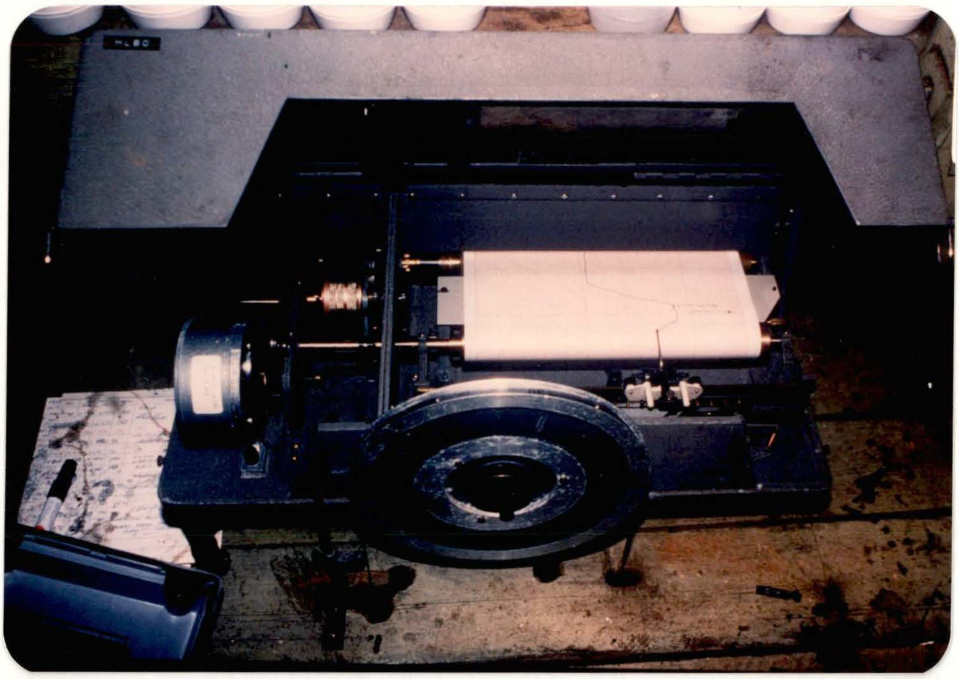


Plate 9: Hydrographic recorder, North Esk River at Ballroom.

Plate 10: Hydrographic recording site for the North Esk River at Ballroom. Note the flying fox in the foreground (for sampling at high flows), and the housing for the hydrographic recorder (left).

has been misplaced by the RWSC. Also, instantaneous minimum and maximum flows for the North Esk River have been recorded at Ballroom for over 60 years. Before 1950, the RWSC achieved this by employing someone to check water marks on gauge boards at regular intervals (usually daily). Due to the availability of the above data, Corra Linn and Ballroom were chosen as the sites for suspended sediment transport estimates.

A. SEDIMENT TRANSPORT AT BALLROOM

The North Esk River at Ballroom drains an area of 373 km^2. Over a 60 year period, the maximum instantaneous flow recorded at Ballroom was 220 cumecs, and the minimum flow was 0.28 cumecs (Rivers and Water Supply Commission of Tasmania, 1983).

Before long-term hydrographic records can be used to estimate an average yearly total of suspended sediment transport for the North Esk River at Ballroom (Figure 7), a sediment rating curve had to be constructed. This was achieved with simultaneous measurements of suspended sediment concentration and river discharge.

The turbidity meter, as described earlier, was used to monitor suspended sediment concentration at this site. After some teething problems with the turbidity meter, a continuous record of 1000 hours (41 days, 16 hours) was obtained between 5 pm on the 7th of September and 9 pm on the 17th of October 1986. During this period the maximum flow was 38.1 cumecs and the minimum was 7.5 cumecs.

The meter was designed to record a two minute average sediment concentration at hourly intervals. With the use of computer facilities at the HEC, instantaneous discharge values, corresponding to the turbidity meter data, were obtained from the Rivers and Water Supply Commission's data.

To obtain suspended sediment transport rates from this data set, the respective pairs of suspended sediment concentration and discharge were multiplied. Figure 18 is a plot of discharge vs time with suspended sediment transport vs time superimposed upon it. During the data collection period , there was only one significant logging episode. This was carried out on a steep hillside adjacent to the North Esk River, approximately three kilometres upstream of its junction with the Ford River. The logging started on the 1st of October and continued past the end of the sampling period. During the first half of the sampling period a characteristic relationship became apparent between suspended sediment transport and river discharge. As is apparent in Figure 18 the logging episode disrupted this relationship. It is for this reason that only the first 540 hours of the data set have been used to derive a relationship between sediment transport and discharge.

Figure 19 is a plot of 540 points of hourly discharge and sediment transport values. The trends of these graphs clearly resemble one another, with the major difference being the timing of the peaks. The sediment transport peaks occur on average 11 hours before the discharge peaks. The reasons for this lag time are complex, but have to do with sediment availability, both from the channel and the catchment slopes, the timing of the peak turbulence and hence the maximum shearing, and also the characteristics of the previous flood (Graf, 1971; Bogardi, 1974; Vanoni, 1975; and Garde and Range Raju, 1978). Another important aspect of the relationship between sediment transport and discharge is that, although the peaks occur at different times, the rise from the base levels and the subsequent return to the respective base levels occur at relatively similar times (Figure 19).

Figure 20 is a plot of suspended sediment transport against discharge. This is not a good approximation to a power curve, however a log-log plot does approximate to a linear relationship between the two variables (Figure 21). Some previous authors have attempted to improve this relationship by subdividing the

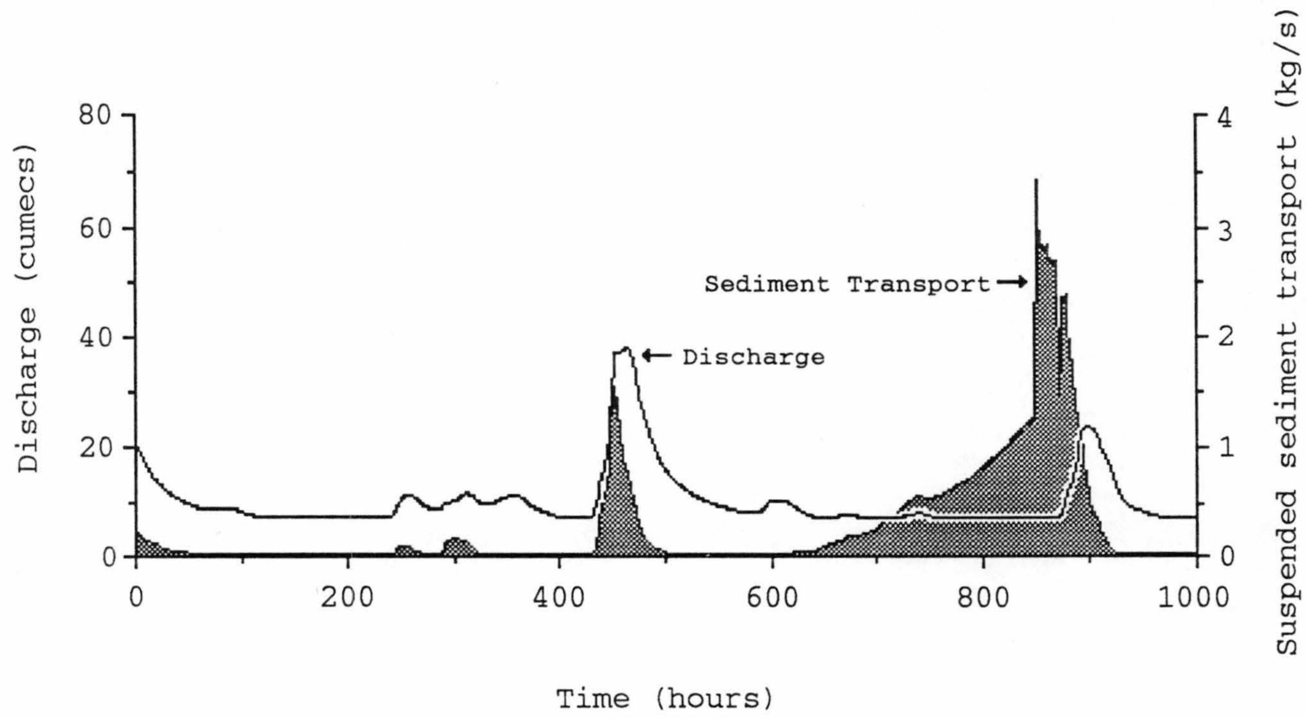


Figure 18: Discharge and Suspended Sediment Transport Data for the North Esk River at Ballroom (5pm, 7th September, 1986 to 9pm, 17th October, 1986).

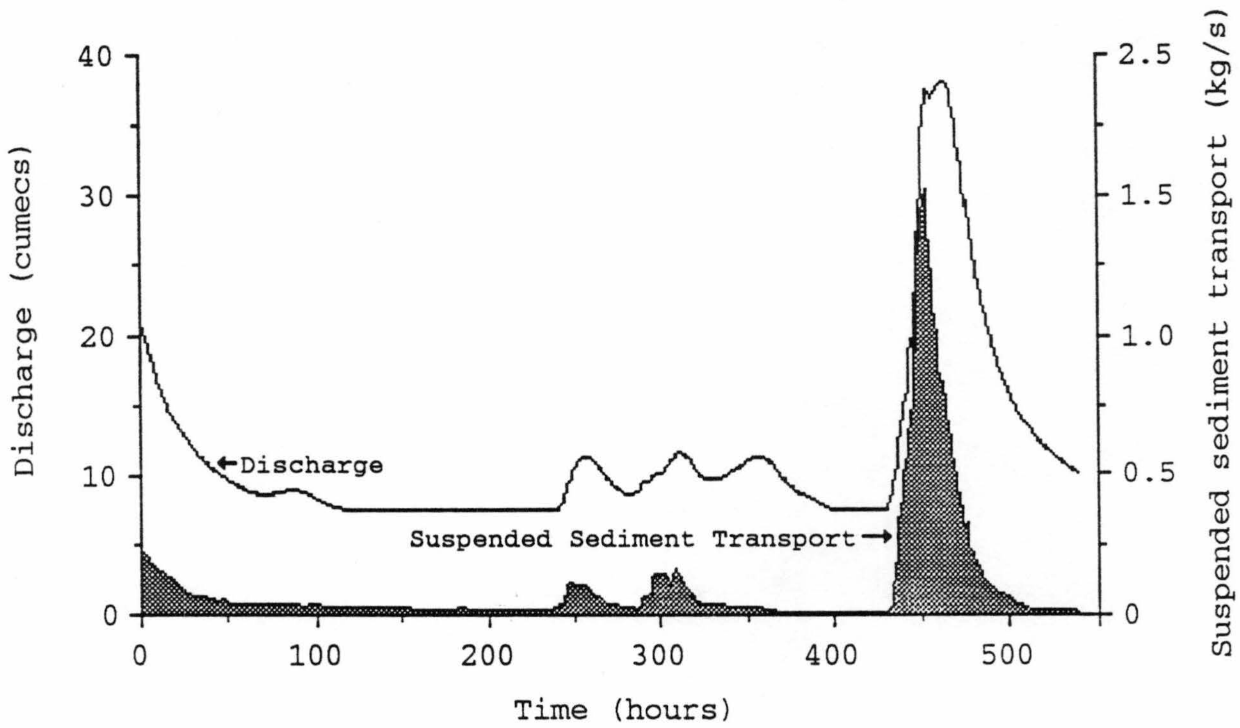


Figure 19: Discharge and Suspended Sediment Transport for the North Esk River at Ballroom (The first 540 points of Figure 18).

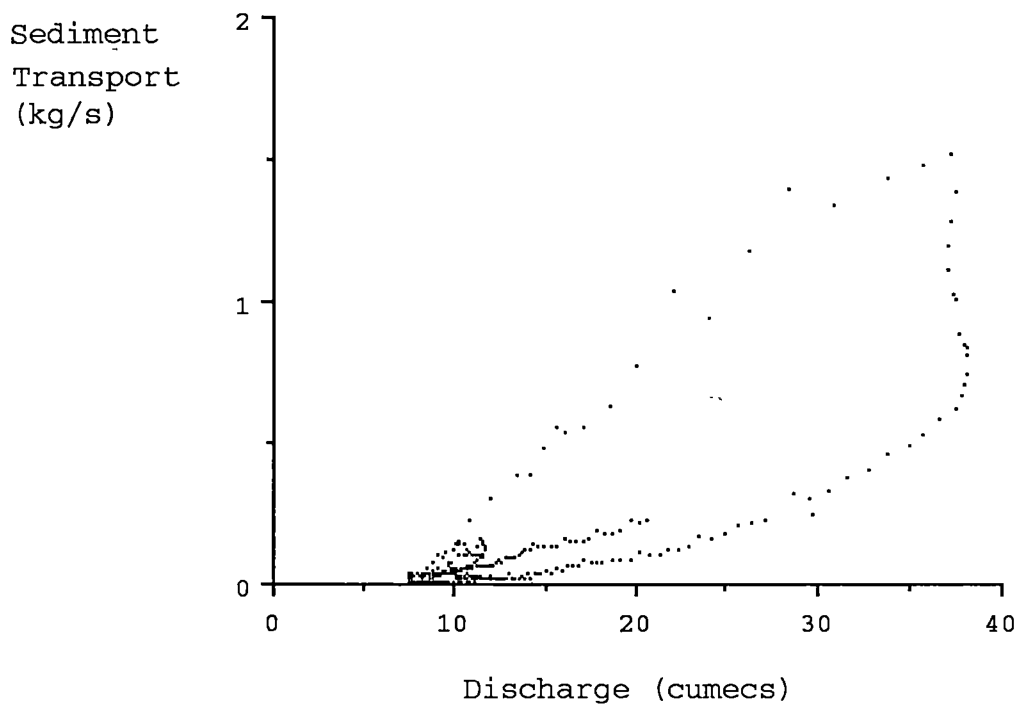


Figure 20: Suspended sediment transport vs discharge for the North Esk River at Ballroom (7th to 30th September, 1986).

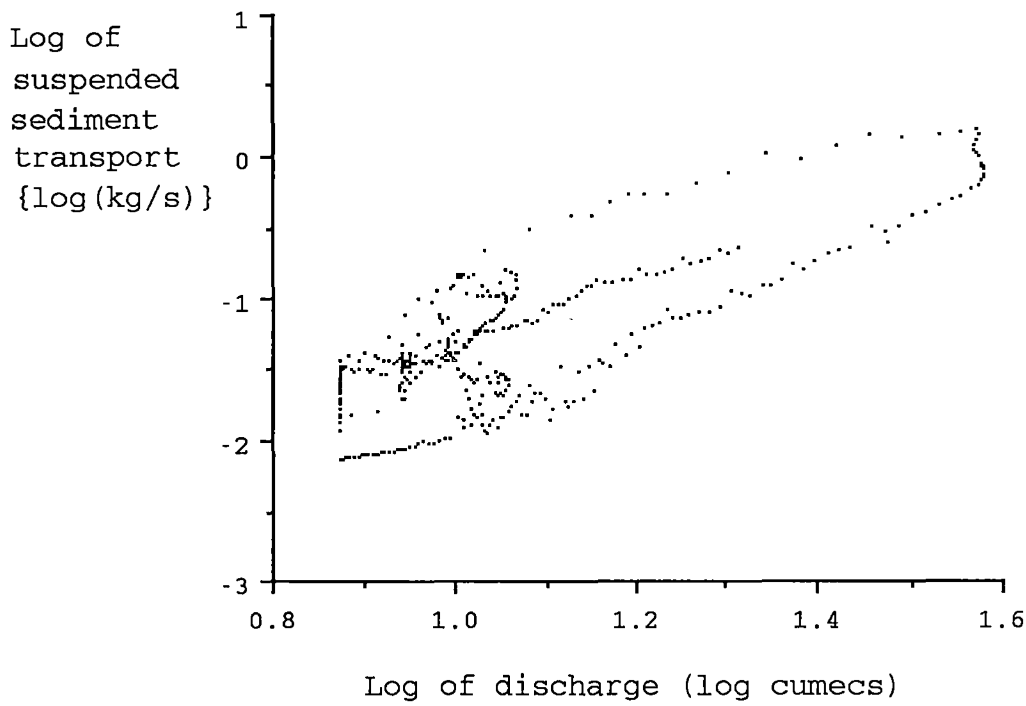


Figure 21: Log-log plot of suspended sediment transport vs discharge for the North Esk River at Ballroom (7th to 30th September, 1986).

data set into the rising or falling stage of the flood hydrograph (Walling, 1978; Geary, 1981).

Figure 22 is a plot of sediment transport vs discharge for the rising stages of the discharge data. This figure helps to explain the two separate curves which are evident on the plot of suspended sediment transport against discharge in Figure 20 where the upper curve is related to rising stages, whilst the lower curve is related to falling stages. Olive and Rieger (1985 and 1986) showed that this relationship is associated with rivers that experience exhaustion of 'sediment availability' during moderate to large flood events. Clearly, it is an observation of this type that prompted others to separate these two curves when deriving their rating curves. Figure 22 clearly shows the lag time between the sediment transport peak and the discharge peak. Over most of the discharge range, while discharge is increasing so is sediment transport. However, since sediment transport peaks before discharge, the last few values of increasing discharge are associated with sharply decreasing values of sediment transport (Figure 22). Clearly it is difficult to accurately fit a curve to such data. Hence, it was decided to use the standard rating curve technique. A linear regression (Figure 23) yielded the following equation:

$$Y = 0.2138 + 2.3486\,X$$

with $R^2 = 66.3\%$

and the Standard error of estimate = 0.29

where Y is the predicted Log of the suspended sediment transport [log(kg/s)],

and X is the log of the river discharge (log cumecs)

Before proceeding, this is an appropriate time to discuss the accuracy of sediment transport prediction achieved by the equation. The regression line explains 66.3% of the variance, with a standard error of 0.29 [log(kg/s)], which

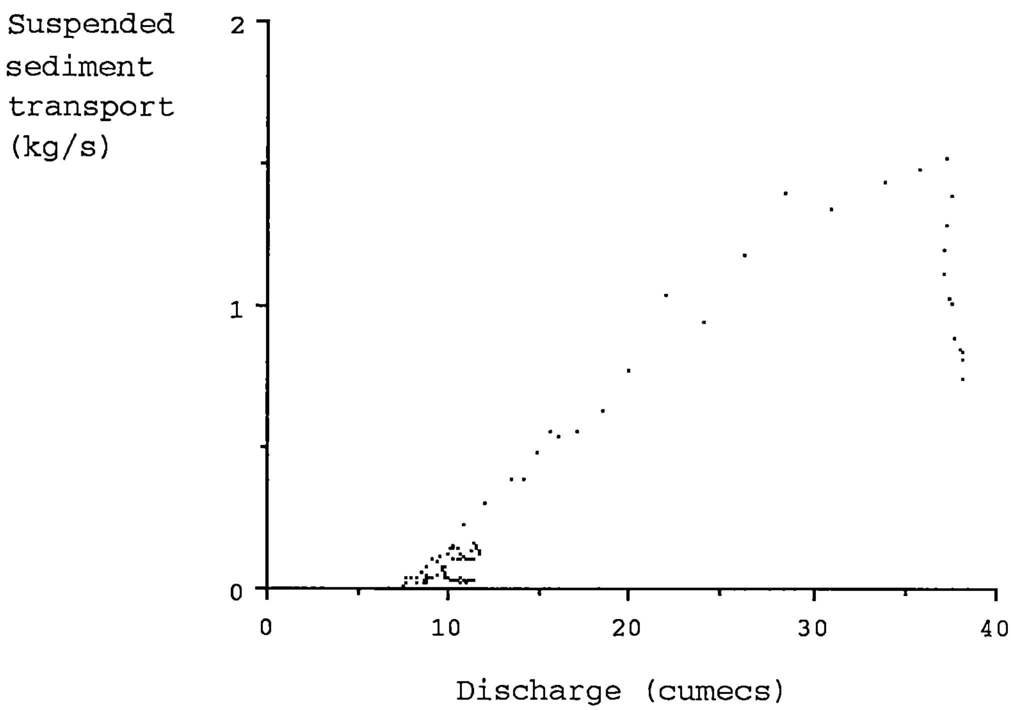


Figure 22: Suspended sediment transport vs the rising stage of discharge for the North Esk River at Ballroom (7th to 30th September, 1986).

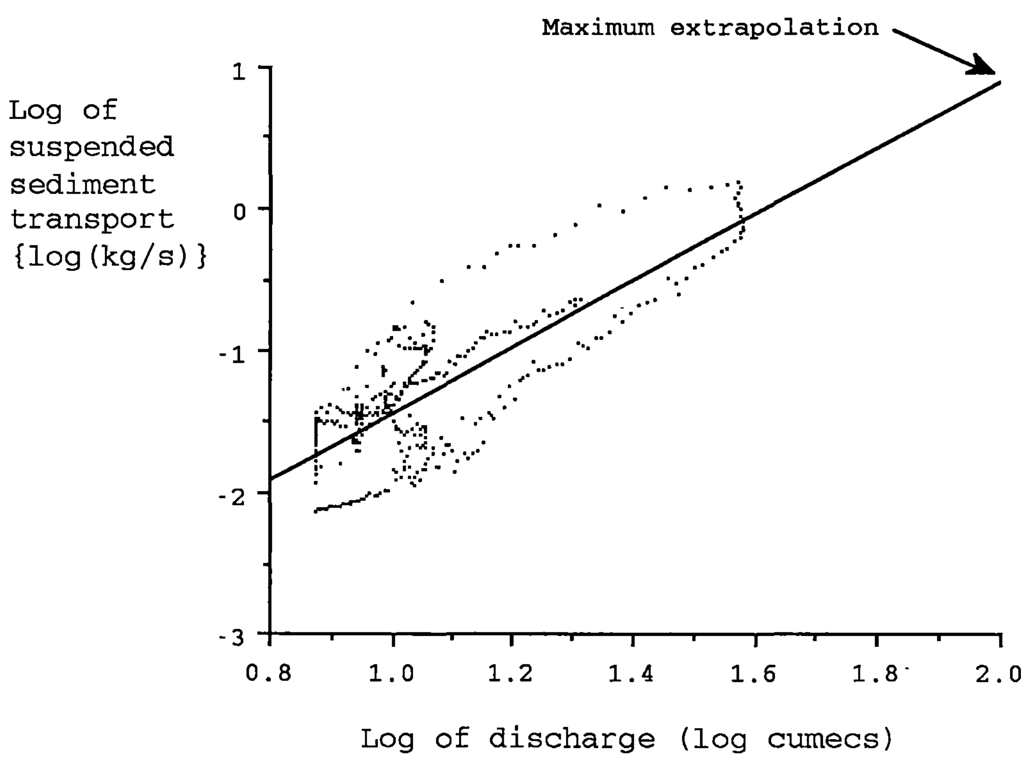


Figure 23: Suspended sediment rating curve for the North Esk River at Ballroom.

converts into 2 kg/s. This means that the average error of a predicted value would be ±4 kg/s at the 95% confidence limit (i.e. ±2 standard errors). Campbell (1977) recognized that a significant problem existed with this technique when he wrote "... suspended sediment and stream discharge data, as related to surface erosion measurements and regional erosion rates, show that typical rating curves significantly underestimate the occurrence of high sediment concentrations and that in most years the sediment concentrations greatly exceed those computed by rating curves." Kellerhals *et al.* (1974) came to similar conclusions. They found that rating curves for the Red Deer River Basin, Alberta, Canada, significantly underestimated the occurrence of peak sediment concentrations.

Campbell (1977) calculated that these underestimates account for as much as 40% of the total yearly suspended sediment transport. Geary (1981) and Olive *et al.* (1980) found that the sediment rating curve underestimated the actual sediment transport rate by 72% and 83% respectively. To overcome this problem, Campbell suggested that an approach, other than the rating curve technique, was needed, i.e. a physical model. In this study, such an approach was not feasible, since the data set used to derive the rating curve did not include enough significant flood events. Also, the period of data collection (7th September to 17th October, 1986) did not cover all seasons, hence seasonal variations could not be accounted for. For the purpose of this study there was no feasible alternative to the rating curve approach.

In addition to these problems, the extent to which the rating curve can be extrapolated is of concern. During the time that the turbidity meter was operating, the largest instantaneous flow for the North Esk River at Ballroom was only 38 cumecs (i.e. 1.58 log cumecs in Figure 23). Therefore, this was the largest value available for use in the sediment rating curve. The largest discharge value in the 29 year data set (intended for use with this rating curve) was 98 cumecs (i.e. 1.99 log cumecs in Figure 23). The rating curve therefore had to be extrapolated approximately 26% beyond the largest measured discharge value of 1.58 log cumecs. Figure 23 shows that an extrapolation of this extent may result in a less reliable suspended sediment transport estimate. Unfortunately, this is a problem that could not be overcome with the present data set.

The only way of improving this situation is to continue to monitor suspended sediment concentrations of the North Esk River at Ballroom, until the rating curve has been extended beyond the desired discharge value (98 cumecs or 1.99 log cumecs). Since this is not feasible for this study, the rating curve will be used in its present form, and any large suspended sediment transport rates which result from this rating curve extrapolation should be treated with caution.

The historic river discharge data available for the North Esk River at Ballroom are a combination of those held by the Rivers and Water Supply Commission and the HEC. They were compiled by the HEC. As described earlier, these data consist of daily average discharge records for the 29 year period between 1950 and 1978.

Since the sediment rating curve for Ballroom is a power curve, and is based on instantaneous sampling, as explained earlier, the use of average discharge data will provide underestimates of the true suspended sediment transport (Appendix 2). This problem can be overcome by using an averaging algorithm.

This technique involves the application of progressively larger discharge averages to the sediment rating curve. This produces progressively worse estimates of the yearly suspended sediment transportation (Walling, 1977a). If these are then plotted on a graph, of yearly sediment transport against the average period, it will always produce a polynomial which is shaped like a negative exponential. For a mathematical proof of this, see Appendix 4. If this curve is used to extrapolate backwards to an instantaneous averaging period (i.e. an average of zero days), the resultant value for yearly suspended sediment transport should be an accurate estimate of the true value. This technique is best explained by applying it to the Ballroom data. The discharge data for 1967 was chosen for this example because, although it appears to be a typical year, it provides the most striking example from the 29 year record of discharge data.

Consider the daily average discharge values for the North Esk River at Ballroom for 1967 (Figure 24). The first point on the 'averaging graph' is obtained by applying each individual daily average discharge to the sediment rating curve and summing the results to give 819.5 t/year. The second point is obtained via the same process, however this time the 365 discharge values that are applied to the rating curve are made up of running means of two days. Note that 365 running means are needed so the 365th mean is made up of the 365th and 1st daily average discharge value for 1967, i.e. a wrap-around technique is used to obtain 365 values; this produces a slightly smaller estimate of 689.4 t/year. The running means together with the wrap-around technique eliminate any bias towards or away from the end points (being at the beginning and end of each day as well as the year). The third value employs running means of 3 days, the fourth uses running means of 4 days, and so on until the last mean is 365 days long.

Figure 25 is a plot of yearly sediment transport against the size of the running means, for the North Esk River at Ballroom during 1967. This graph clearly illustrates that as the period over which the discharge averages are taken increases, the yearly sediment transport estimates become smaller. If a curve was to be fitted to the entire data set of Figure 25, in an attempt to estimate the Y-intercept, then the values furthest from this intercept would influence its value. Hence, to ensure a more accurate value for the Y-intercept it is more appropriate to use only those points which are closest to the Y-axis.

Figure 26 is a plot of the first ten values from Figure 25. The best fit to these points was found to be a sixth order polynomial:

$$Y = 1,068.567 - 344.002\,X + 116.844\,X^2 - 25.291\,X^3 + 3.077\,X^4 - 0.194\,X^5 + 0.005\,X^6$$

$R^2 = 100.0\%$

Standard error = 0.080 t

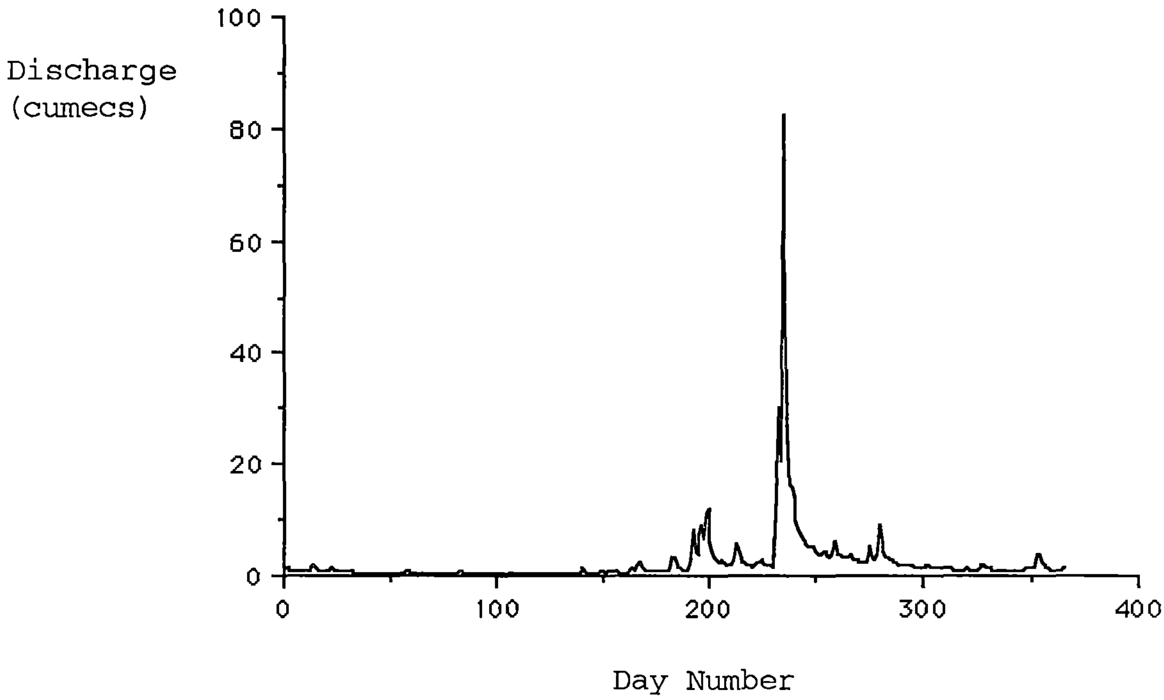


Figure 24: Daily average discharge for the North Esk River at Ballroom during 1967.

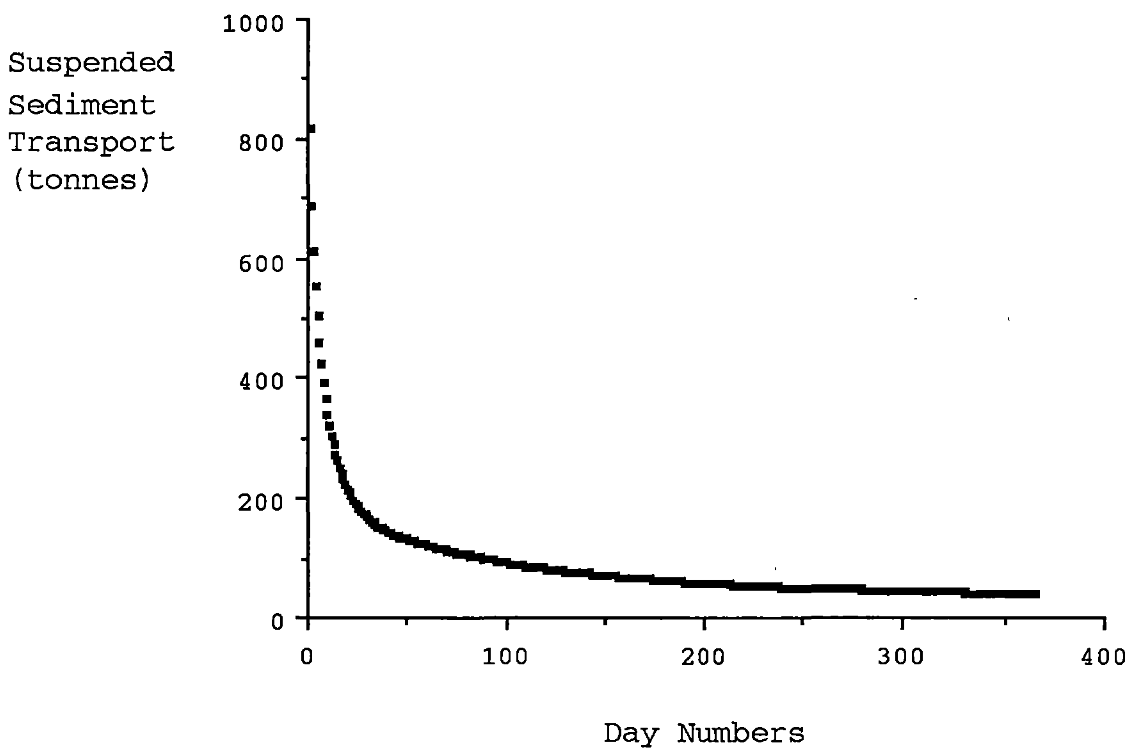


Figure 25: Total suspended sediment transport estimates of the North Esk River at Ballroom for 1967. Each estimate uses a progressively larger time interval over which to average discharge.

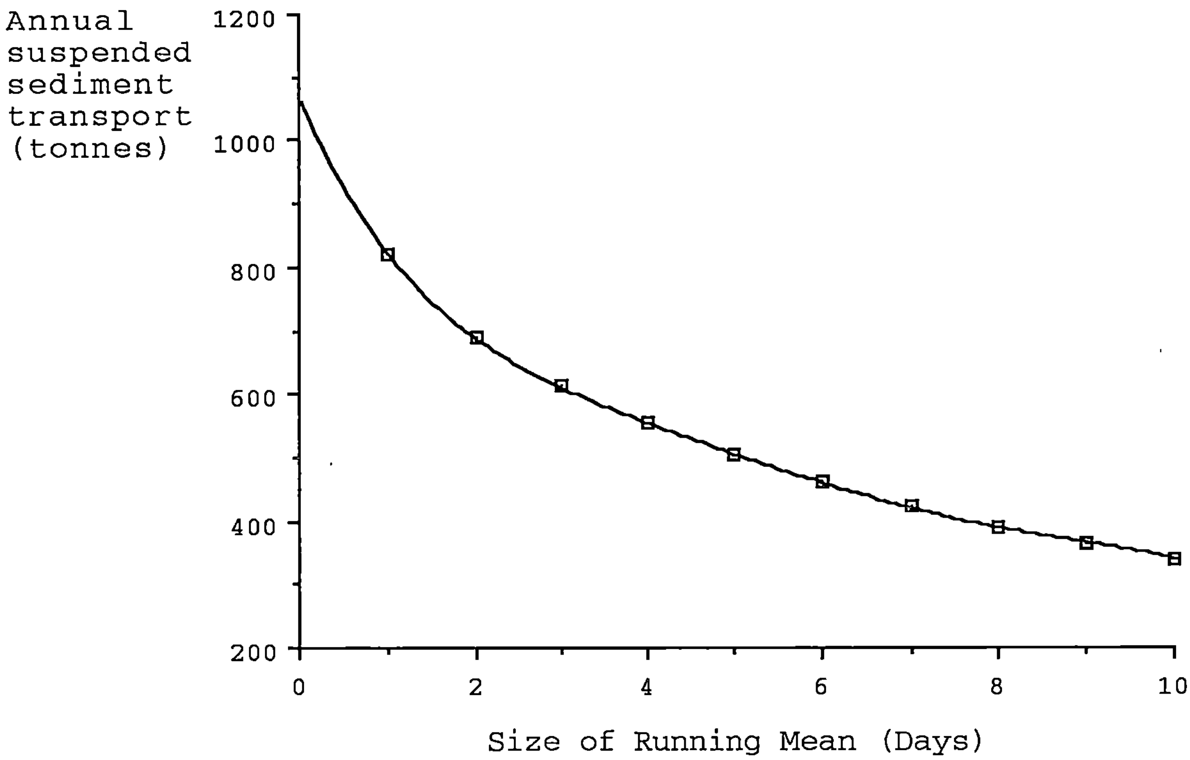


Figure 26: Total suspended sediment transport estimates of the North Esk River at Ballroom for 1967 (the first 10 values from Figure 25). Each estimate uses a progressively larger time interval over which to average discharge.

This regression accounts for 100.0% (rounded to one decimal place) of the variance, and as such could be considered to be an excellent predictor. Hence, the Y-intercept of 1,069 t can be regarded as a highly accurate estimate of the total suspended sediment transported during 1967, by the North Esk River at Ballroom. The standard error of 0.080 t represents an accuracy of ±0.16 t (i.e. 0.015%) at the 95% confidence interval. It can be considered insignificant compared with the range of experimental errors that are involved in the collection of the data. Clearly the new technique provides a dramatic improvement on previous methods of estimating annual suspended sediment transport of rivers, as reported by Walling (1977a). The new estimate of 1,069 t compares with a previous best estimate of 819 t, derived with the use of daily discharge averages. The new estimate is 250 t (i.e. 30.4%) larger than the original estimate of 819 t. For the remainder of this thesis, the above technique will be referred to as the RUME technique which stands for the 'running mean extrapolation technique'

The rating curve of Figure 23, was used with the RUME technique to convert the HEC data into 29 estimates of annual totals of suspended sediment transport for the North Esk River at Ballroom. The total of these 29 estimates of annual suspended sediment transport is 42,688 t, which is 4,238 t more than the estimate calculated without the use of the RUME technique. The RUME technique was used to estimate annual suspended sediment transport individually for each of the 29 annual discharge periods and compared with the values obtained with the traditional technique of daily discharge averages. The traditional technique was found to underestimate annual suspended sediment transport by between 5.2% and 30.4% with an average of 10.7%. The RUME technique has clearly eliminated a very substantial source of underestimation.

When the RUME technique was applied to the 29 sets of discharge records, the minimum annual suspended sediment transport was 211 t and the maximum was 3,985 t. The average annual suspended sediment transport was 1,472 t with a standard deviation of 1,072 t and a standard error of 199 t. A histogram of annual sediment transport is shown in Figure 27. This demonstrates the extreme variability of the amount of suspended sediment transport in the North Esk River. It also illustrates the need to use long term hydrographic records to obtain a meaningful estimate of mean annual suspended sediment transport.

B. SEDIMENT TRANSPORT AT CORRA LINN

Due to the absence of present day continuous discharge measurements, a turbidity meter was not installed at Corra Linn. Instead, hand samples were used to determine suspended sediment concentrations. These were combined with simultaneous measurements of river discharge to produce a suspended sediment rating curve. The discharge was estimated by reading the instantaneous stage from the in situ gauge board and using a stage-discharge rating curve (Figure 28), derived by the HEC and checked in 1986 by the Water Research Laboratory. The suspended sediment concentrations were then multiplied by their respective discharges to obtain an estimate of suspended sediment transport at the time of sampling and plotted against the relevant instantaneous discharge.

Corra Linn, on the North Esk River (Figure 7), was the meeting point of the area covered by this study and the Water Research Laboratory's study area. For this reason it was possible to combine data from both studies to derive a suspended sediment rating curve for the North Esk River at Corra Linn. Figure 29 is a plot of the data collected at Corra Linn by the author and Mr Walker. Since data from the two sources were consistent, probably due to the use of similar sampling methods, a regression was fitted to the combined data.

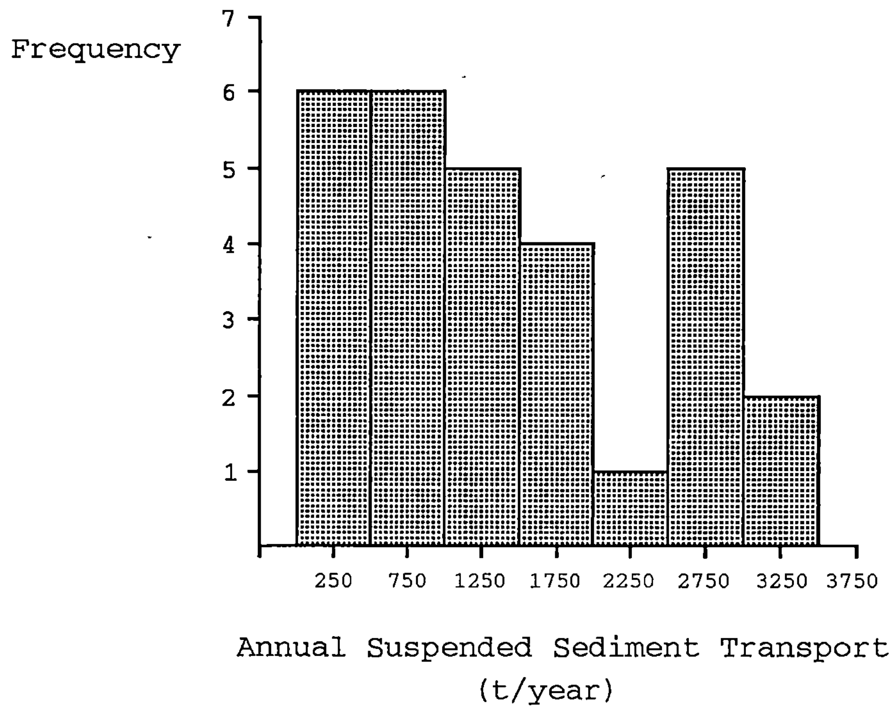


Figure 27: Histogram of estimates of annual suspended sediment transport for the North Esk River at Ballroom, (derived from 29 years of discharge data, 1950 to 1978).

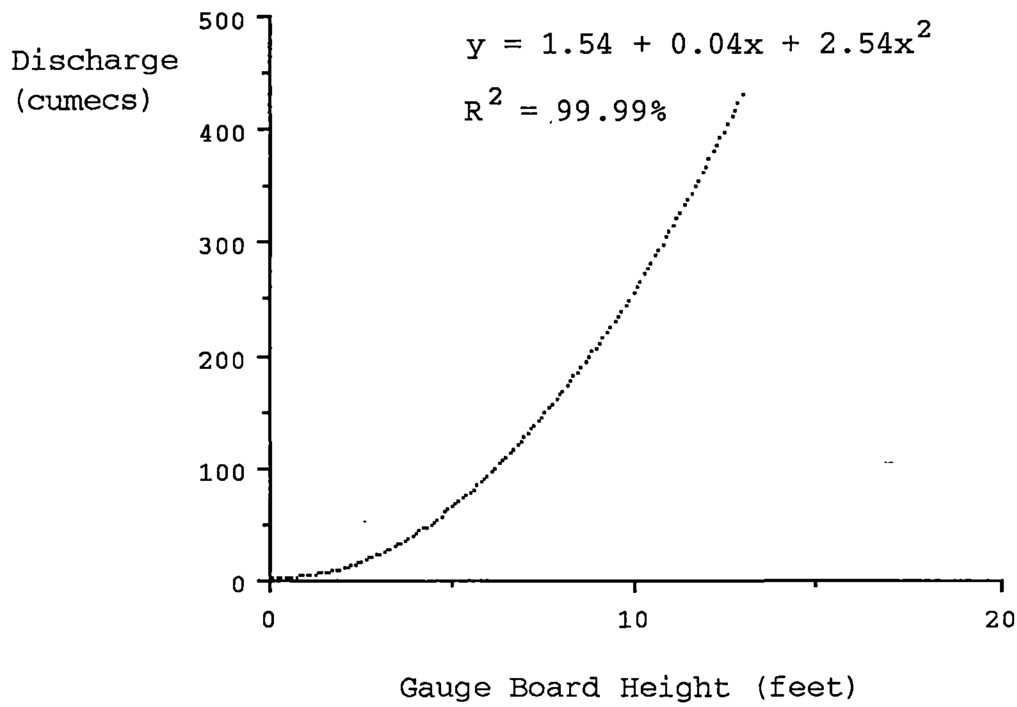


Figure 28: Stage-discharge rating curve for the North Esk River at Corra Linn. Compiled by the Hydro-Electric Commission, Hydrology section, Hobart (using data collected between 6th February, 1959 and 1st May, 1974)

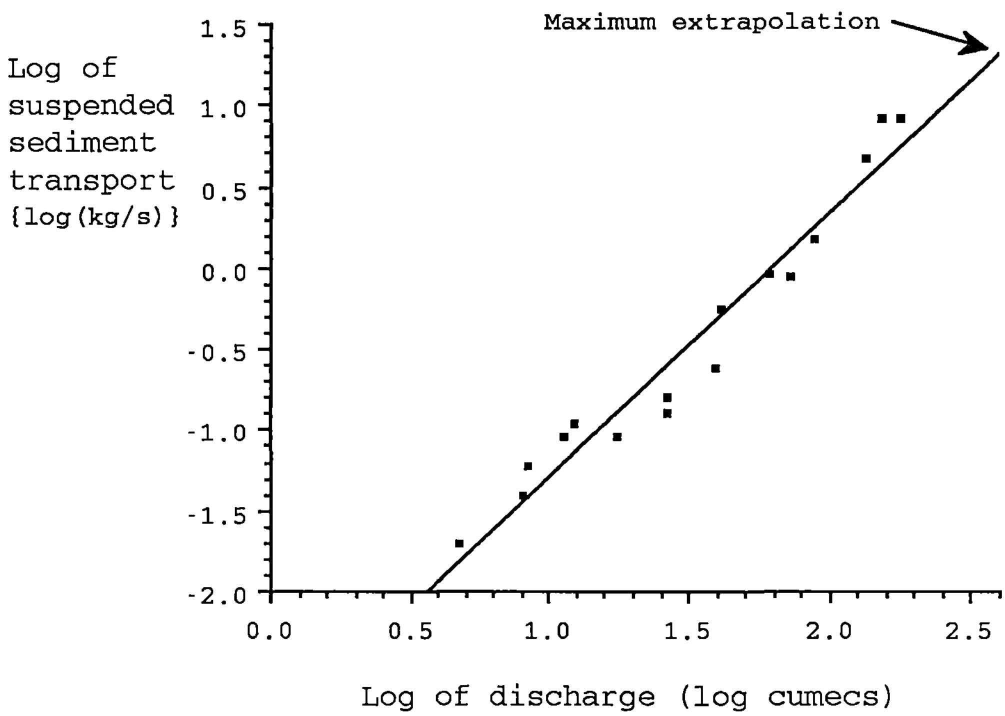


Figure 29: Suspended sediment rating curve for the North Esk River at Corra Linn.

The best fit between suspended sediment transport (y) and discharge (x), was found to be:

$$Y = -2.9 + 1.7\,X$$

where Y is the Log of suspended sediment transport [log(kg/s)]

and X is the log of river discharge (log cumecs)

The regression accounts for 95% of the variance, and has a standard error of 0.19 log(kg/s) or 1.5 kg/s. This enables discharge to be used as a reliable predictor of suspended sediment transport, provided that the relationship between the two variables has not changed over the period for which sediment transport is to be predicted.

The largest discharge value used to construct the sediment rating curve is 178 cumecs (i.e. 2.25 log cumecs in Figure 29), however, the largest discharge value in the 29 year data set, intended for use with this rating curve, is 392 cumecs (i.e. 2.59 log cumecs in Figure 29). The rating curve will therefore have to be extrapolated approximately 15% beyond its largest discharge value of 2.25 log cumecs. For the purpose of this study, the use of the rating curve to a discharge value of 2.59 log cumecs is considered to be a reasonable extrapolation, and any suspended sediment transport estimates which are made with discharge values less than 2.59 log cumecs are considered to be reasonably accurate.

It is not the aim of this study to estimate historic sediment transport rates. Instead, the purpose is to obtain a meaningful average annual suspended sediment transport rate in order to assess the longer term rate of sediment supply to the Tamar estuary. To calculate such an average, it is necessary to obtain an estimate of the average discharge. Due to the extreme variability of discharge from year to year, it is necessary to use discharge values over a long period of time. When doing so the assumption has to be made that there has been no change in the rainfall/runoff relationship or the suspended sediment rating curve in the time period involved.

The discharge record at Corra Linn is only three years long (1961-63). This record needs to be much longer if it is to be used to estimate an average suspended sediment transport rate for the North Esk River at Corra Linn. It was therefore decided to compare the discharge record with that of Ballroom for the same period to see if the much longer Ballroom record can be used to synthesize a longer discharge record at Corra Linn. Figure 30 is a log/log plot of daily average discharge of Corra Linn against Ballroom for 1961-63 and 17 days during 1985-86 (collected by the Water Research Laboratory and the author). Both sets of data (the 60s and 80s) exhibit very similar relationships, which suggests that there has been no change in the rainfall/runoff relationship between 1961 and 1986 for either of the two stations, i.e. any discharge changes that have occurred apply equally to both.

If a linear regression is fitted to the data in Figure 30, the result is:

$$Y = 0.253 + 1.175\,X$$

where Y is the log of discharge at Corra Linn (log cumecs)

and X is the log of discharge at Ballroom (log cumecs)

This regression explains 93% of the variance, and has a standard error of 0.135 (log cumecs) or 1.4 cumecs, which indicates that discharge at Ballroom is a good predictor of discharge at Corra Linn. This technique provides the mechanism by which the 3 year discharge record at Corra Linn is extended to a 29 year record (i.e. 1950-78).

The largest Ballroom discharge value used to construct this regression line is 63 cumecs (i.e. 1.80 log cumecs in Figure 30), however, the largest Ballroom discharge value in the 29 year data set, intended for use with this regression line is 98 cumecs (i.e. 1.99 log cumecs in Figure 30). Therefore, the regression line will

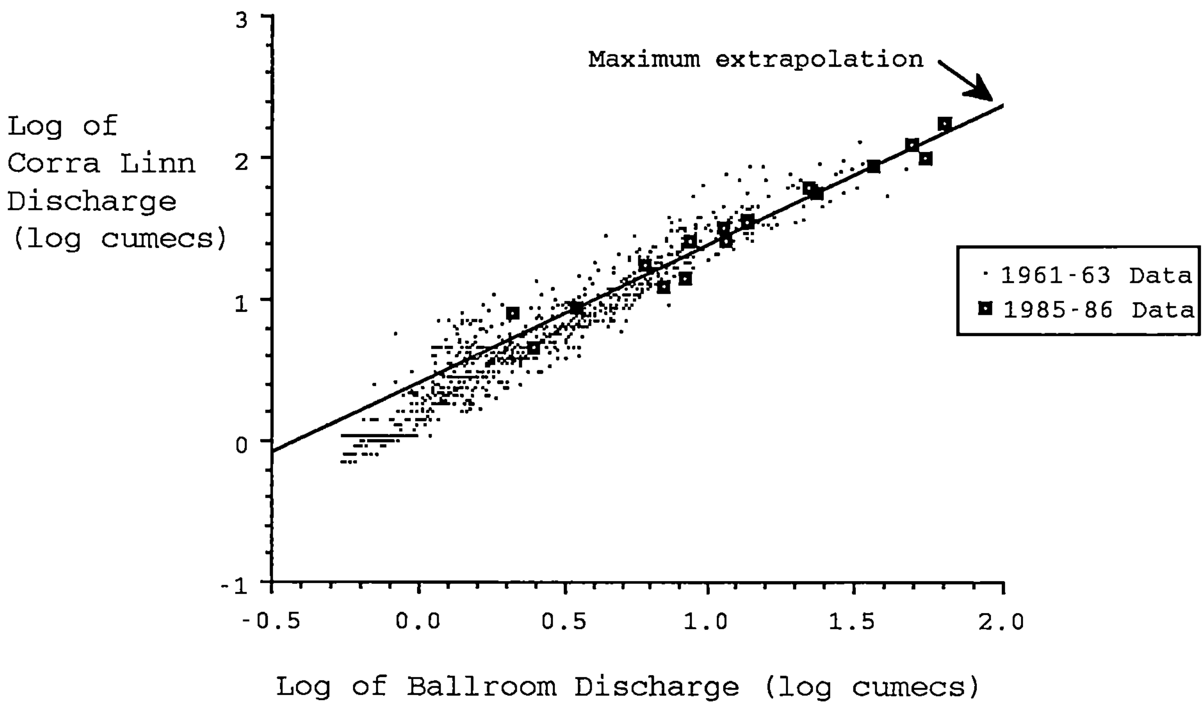


Figure 30: Log-log plot of daily average discharge for the North Esk River at Corra Linn against the discharge at Ballroom for 1961-63 and 17 days during 1985-86.

have to be extrapolated 10% beyond the largest Ballroom discharge value of 1.80 log cumecs. As can be seen in Figure 30, this is a reasonable extrapolation, which should produce results of acceptable accuracy on which to base a long term estimate of the average annual suspended sediment transport rate of the North Esk River at Corra Linn.

The synthesized discharge record (derived above) for the North Esk River at Corra Linn was converted into suspended sediment transport using the sediment rating curve for Corra Linn (Figure 29) and the RUME technique. These 29 values of annual suspended sediment transport are presented as a histogram in Figure 31. Of the 29 estimates of annual suspended sediment transport for the North Esk River at Corra Linn, the minimum is 1534 t and the maximum is 16,449 t. The estimated average annual suspended sediment transport is 7225 t with a standard deviation of 4584 t and a standard error of 851 t.

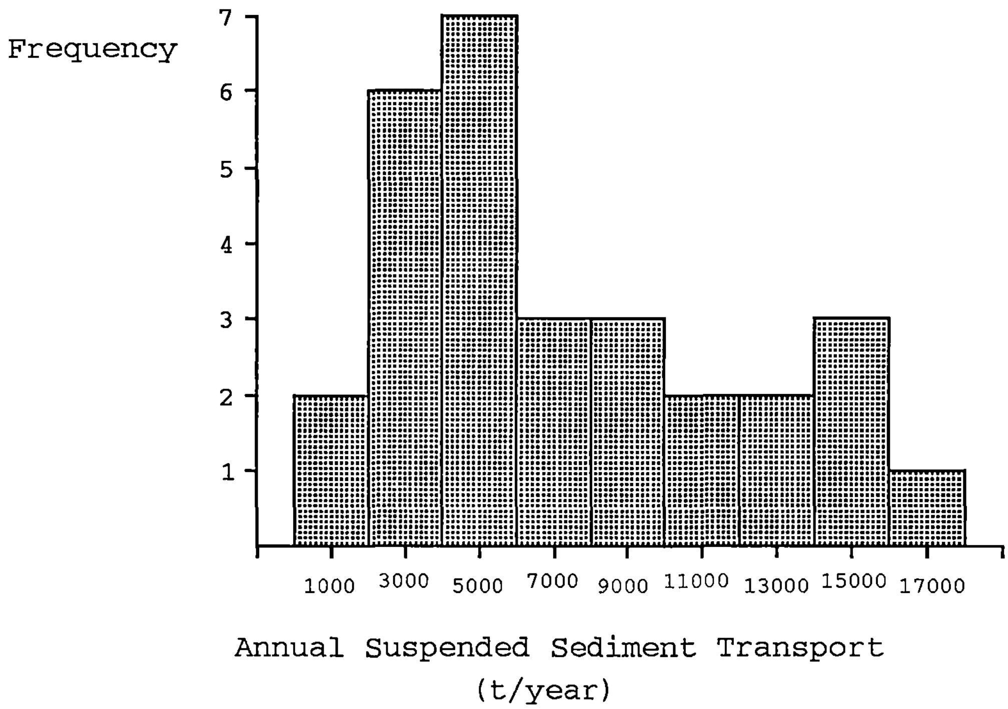


Figure 31: Histogram of estimates of annual suspended sediment transport for the North Esk River at Corra Linn, (derived from 29 years of discharge data, 1950 to 1978).

CHAPTER 5: SEDIMENT PROVENANCE

This study was conducted with a limited budget. Most of the time in the field was spent measuring river flows and associated sediments. There was no time available to make a detailed study of sediment provenance. A study which included an investigation of the various types and rates of soil erosion, surveying of slope length and gradient, and investigating the factors which affect suspended sediment concentrations within the North Esk River basin would be extremely valuable, but was considered to be outside the scope of this thesis. However, to provide background information, a limited discussion of sediment origins forms the subject of this chapter.

Field measurements at a limited number of strategically selected sample sites were simple, but very time consuming. Since there are only two gauge boards (rated for discharge), within the North Esk basin, at other sites discharge had to be measured by current meter. Initially, seven sites were chosen for the installation of gauge boards. At each site, cross-sections of sediment concentration and river flow were taken. It was intended that these data would provide the necessary information to construct rating curves for each of the sites. However, this exercise proved to be so time consuming, that it soon became apparent that the rating curves for each site could not be adequately calibrated within the time period available for fieldwork. It also proved to be dangerous to make discharge measurements during high flows.

Due to the problems of obtaining detailed measurements at seven sites, it was decided to change to a system with less detailed measurements from a larger number of sites. Hence, only sediment concentrations were determined from each of twenty-one sites, during three flood events. This was possible with only one sample at each cross-section, since the previous cross-sectional measurements of sediment concentration, taken from the original seven sites, showed that the cross-sections were mostly homogeneous (Figures 6, 8A and 8B).

A. SOIL EROSION

Sediment in rivers is predominantly a result of soil erosion within the catchment area. Some of the factors which control this erosion are precipitation, its intensity, duration and its distribution in time and the resulting overland flow. Conditions that can affect the rate of erosion are the properties of the soil, the nature of the relief and vegetation, the type of soil management, and erosion control measures (Hunt, 1972; Faniran and Areola, 1978; and Zachar, 1982).

Potential sources of river sediment in the North Esk basin are erosion of the soil from slopes by raindrop impact and surface run-off, leading to sheet, gully and rill erosion; riverbank erosion; scour of floodplains during a flood event and mass movement (Pinkard, 1980). Unfortunately, there have not been any extensive studies on soil erosion within the North Esk River basin. However, Pinkard (1980) conducted a regional survey of existing soil erosion for the Department of Agriculture, Tasmania. Most of the following soil erosion information has been taken from this survey, with a small amount of additional information from the author's personal observations. Since the author's fieldwork time was concentrated on suspended load measurement, Pinkard's survey was not checked in any detail.

Sheet erosion is by far the most widespread form of erosion in the region, as much of the country has steep or long slopes and/or relatively unstable soils. Potentially it may be active throughout the whole of the North Esk Basin. Evidence of sheet erosion, slight or severe, can be found in all parts of the basin. It is most severe in areas of maximum overland flow, i.e. on the lower slopes of hills and mountains in the higher rainfall areas. Soils on dolerite, granite, granodiorite, sandstone and Tertiary sediments are particularly susceptible to sheet erosion. Massive sheet erosion may occur as a result of increased run-off due to activities such as mining, gravel quarrying, farming and forestry operations. Sheet erosion is an insidious process and usually progresses unnoticed until more severe effects such as rilling and gullying occur. (Pinkard, 1980)

Gully erosion is common throughout the whole North Esk Basin, while rill erosion is patchy (Figures 32 and 33). Gullying can be particularly severe when associated with soils formed on Tertiary and Quaternary deposits, and soils developed on sandstones. They are most extensive on the lower slopes and swales of the low hills and plains. The soils prone to rill and gully erosion are generally unstable with sandy surface layers. Rill erosion is often present in recently cultivated areas or grazing areas where stock trails are the principal cause. It usually leads to the formation of gullies, especially where run-off is excessive and water is concentrated in a few channels. Serious rill and gully erosion has occurred in soils formed on Tertiary deposits in the western part of the basin and on the Mathinna Beds. Rill and gully erosion are also quite common on lower slopes on granite where thick colluvial mantles have accumulated and where disturbances due to mining activities, vehicle tracks, fires and forestry activities, has impaired the vegetation cover.

It is interesting to note the absence of present day gully erosion in the southwestern corner of the North Esk Basin (Figure 33). This is especially unexpected because the geology of this area is mostly Tertiary clays and sand deposits (Figure 12). Well before Pinkard's survey in 1980, the area was severely effected by gully erosion. However in the late 1960^{s} the Commonwealth Government (via the Tasmanian Department of Agriculture) funded an extensive land reclamation scheme, designed to control accelerated erosion in the region. As a result of this, virtually all gully erosion has been eliminated within the area. (Pinkard, pers. comm.)

Although the spatial extent and range of slopes is similar throughout the eastern four fifths of the North Esk catchment, most rill erosion can be found in the south-eastern sector of the catchment, occurring in areas which are not extensively used for farming or logging (Figures 17 and 32).

Due to the man-induced higher fire frequency in the past 6000 years, the vegetation in the North Esk River Basin has tended towards a dominance of fire

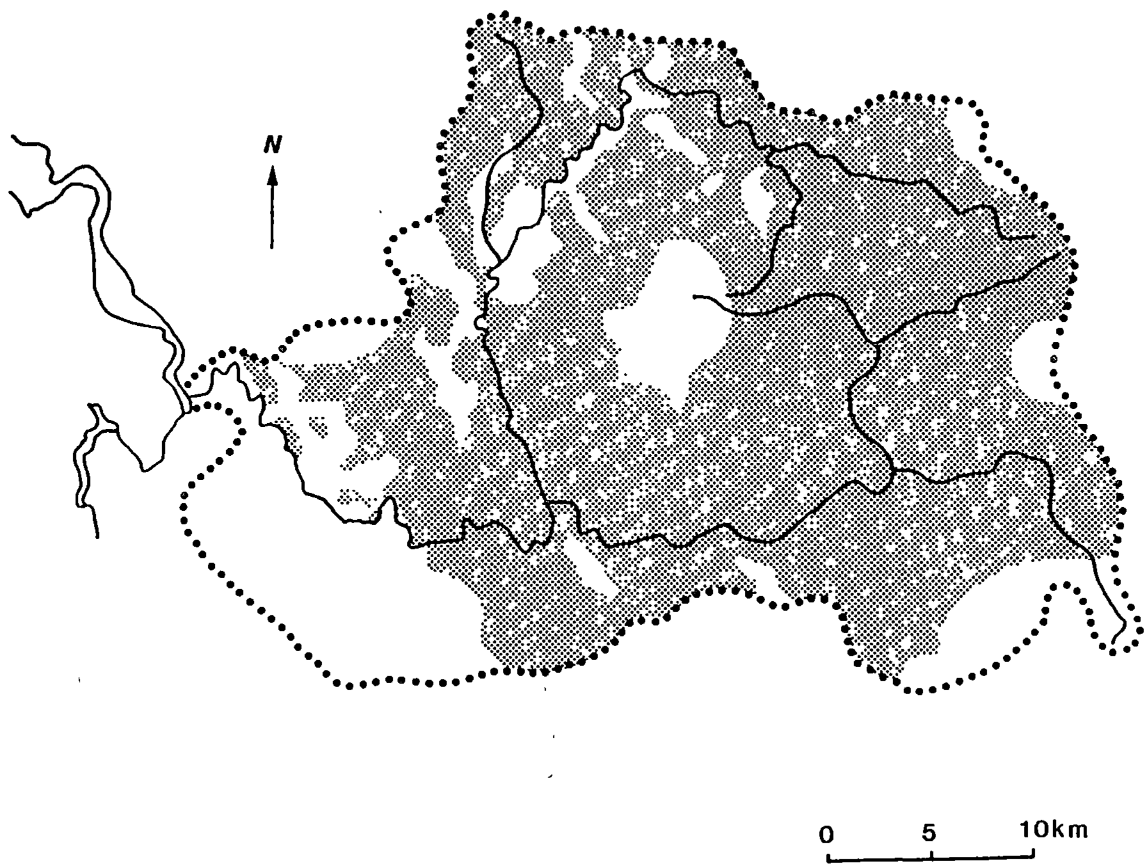


Figure 32: Areas affected by gully erosion (shaded) within the North Esk River basin. (Pinkard, 1980)

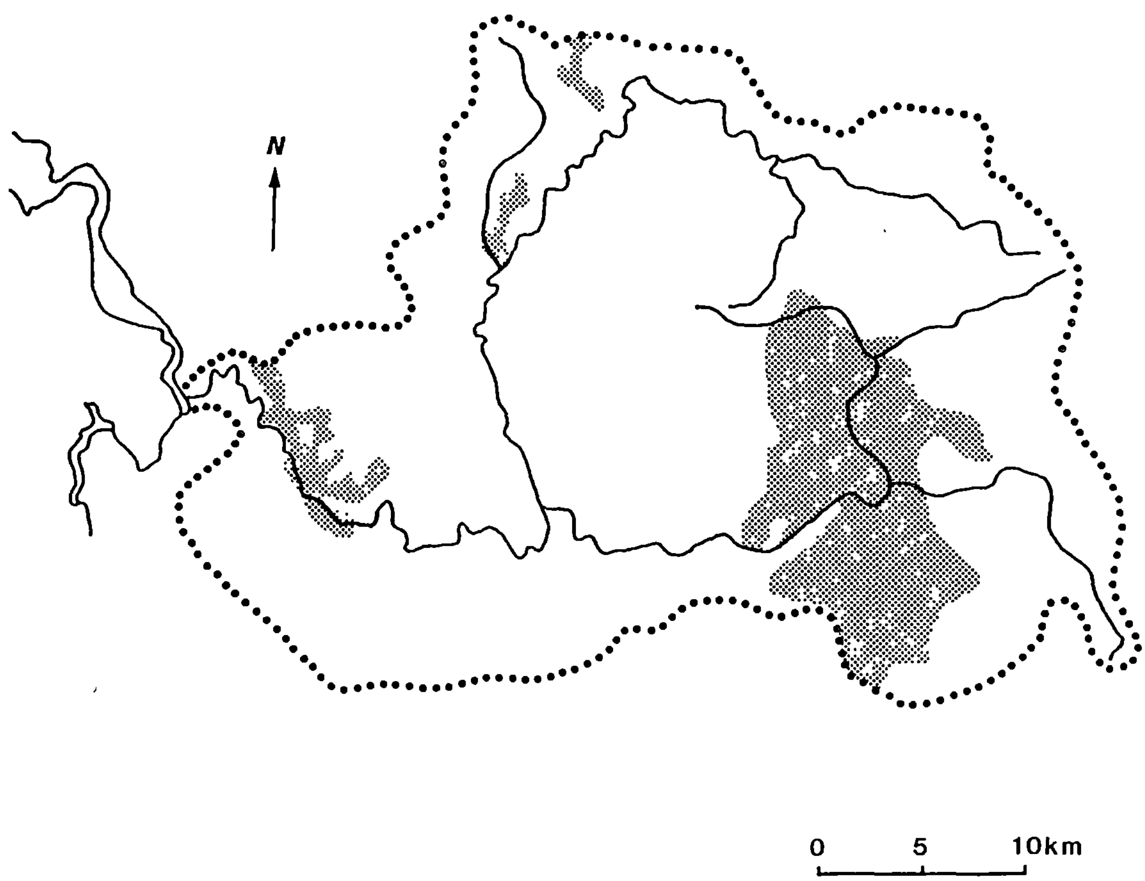


Figure 33: Areas affected by rill erosion (shaded) within the North Esk River basin. (Pinkard, 1980)

tolerant species, e.g. eucalypt forests rather than rain forests (Jackson, 1968 and Ellis, 1985). Figure 16 demonstrates that except for the south-east corner (Ben Lomond), the rainfall in the south-eastern portion of the catchment is affected by a rainshadow from Mt Barrow. The lower average rainfall has lead to a higher fire frequency. It has meant that, unlike most of the eastern four fifths of the catchment, which has maintained a cover of wet sclerophyll forest, the dryer south-eastern sector has developed a cover of dry sclerophyll forest (Kirkpatrick and Dickinson, 1984). The principal difference between these two types of forest is their understorey. Generally, the wet sclerophyll forest has a dense understorey dominated by shrubs whereas the dry sclerophyll forest has an understorey dominated by grasses.

Due to the lower average rainfall and the presence of a grassy understorey, dry sclerophyll forests tend to be more flammable than wet sclerophyll forests (Kirkpatrick, pers. comm.) This creates a 'positive feedback' situation, since a higher fire frequency prevents the regeneration on a woody understorey and helps it to remain as dry sclerophyll (Ellis, 1985). Although this area of dry sclerophyll forest is used relatively little by man (Figure 17), its higher fire frequency provides sufficient disturbance to the vegetation cover to enable the development of rill erosion (Figure 33).

Riverbank erosion is a form of erosion which is often associated with Quaternary floodplain deposits. Floodplain sediments are especially susceptible to erosion if they have little or no vegetative protection during a flood (i.e. if they are fallowed as in Plate 7). Accelerated riverbank erosion is evident along all streams and rivers where larger forms of vegetation, such as trees and shrubs, have been cleared from the banks as a result of farming or forestry activities, Plate 11 is a good example.

The term mass movement is used to describe soil erosion caused by gravity (e.g. soil creep, earth flows, landslips and slumps). Soils formed on Jurassic dolerite and Tertiary, clays and gravels are particularly prone to landslips and

Plate 11: Bank erosion, North Esk River downstream from its junction with the Ford River.

earthflows (Figures 14 and 34). Soils on steep cleared slopes on any rocktype are also prone to mass movement, (Pinkard, 1980). In contradiction to the situation shown on Pinkard's map of mass movement, evidence for it was observed throughout the southwestern corner of the North Esk Basin, an area of cleared land used for cropping and grazing (Figure 17).

B. FACTORS AFFECTING SUSPENDED SEDIMENT CONCENTRATION

"Detailed studies of variations in sediment concentration during runoff events in Australian basins confirmed the complexities of catchment transport systems demonstrated elsewhere." (Loughran, 1984) In common with the North Esk River, as will be shown later, Loughran (1974 & 1975) on Congewai Creek, N.S.W.; Lam (1984) on Upper Sandy Creek, N.S.W.; and Lootens and Lumbu (1986) on Lubwe River, Zaire; all found that concentrations of suspended sediment peaked before the discharge peak. Geary (1981) and Loughran *et al.* (1981) found the reverse for Deep Creek and Maluna Creek (N.S.W.) respectively. Belperio (1979) found that the two peaks coincided in the Burdekin River, Queensland. However, the relationship between the peaks of suspended sediment and discharge is not necessarily consistent for any one river. Finlayson and Wong (1982) found that out of three floods in the Myrtle No. 1 catchment in Victoria, the two peaks coincided during two of the floods, but in the third flood the suspended sediment concentration peaked before discharge. While monitoring the Esk River at Thorverton, England, Lambert and Walling (1986) found that the suspended sediment concentration peaked before discharge if the floods originated primarily in the upper half of the catchment. However, for floods originating primarily in the lower half of the catchment, the opposite was true, i.e. the suspended sediment concentration peak occurred after the discharge peak.

The relative timing of the sediment concentration and discharge peaks in the North Esk River (and any other river) is governed by the interaction of many

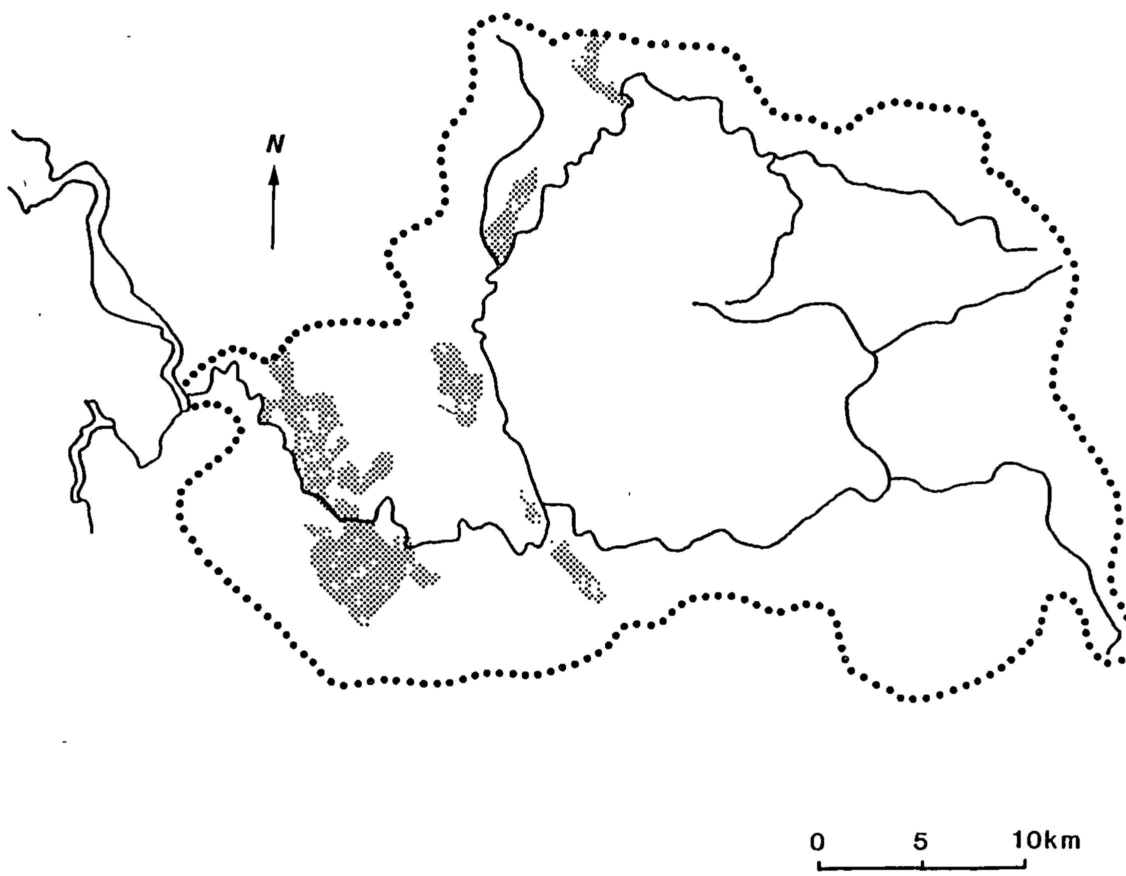


Figure 34: Areas affected by mass movement (shaded) within the North Esk River basin. (Pinkard, 1980)

factors that effect the relationship between suspended sediment load and discharge (Campbell, 1977; Olive *et al.,* 1980; Olive and Rieger, 1984, 1985 and 1986).

The magnitude of a flood event may have a large bearing on the post-flood slumping of riverbanks, which provides a significant sediment source for subsequent floods. Also the spatial distribution of rainfall during any flood is likely to modify sediment transport in subsequent floods. For instance, if the rain was confined to some of the headwater areas, runoff and hence significant discharge and sediment transport would only occur in those headwater regions of the catchment. Flow in the lower regions of the catchment would not be sufficient to maintain the high sediment transport rates of the flood affected headwater tributaries. A large proportion of the sediment would remain in the headwater tributaries of the river system until a future flood, due to widespread heavy rain, was able to flush it out.

The spatial distribution of heavy rainfall not only determines the origins of sediment (and hence the quantities of sediment available) but also whether the flood is widespread or confined to one part of the catchment.

There are two basic areas of erosion within the river system, channel erosion and extra-channel erosion. Temporal variation in the intensity of rainfall will determine the amount of extra-channel erosion. If maximum rainfall intensity occurs after soil field capacity is reached a much greater amount of surface run-off will occur. This will have a big impact on the relationship between the maximum discharge and the maximum suspended sediment transport. Saturated conditions will also encourage mass movement with an additional increase in sediment yield.

A change of vegetation cover in any area will alter the potential erosion from such land affecting the relationship between suspended sediment concentrations and discharge. Most of man's activities tend to increase the rate of erosion.

C. CASE STUDIES OF SEDIMENT PROVENANCE

a. A Case Study of Three Flood Events

Two of the most fundamental factors controlling soil erosion are rainfall and slope gradient, (Chorley, 1969; Cook and Doornkamp, 1974). As mentioned before, rainfall within the North Esk Basin, due to its orographic nature, is concentrated in the area of Mount Barrow, which is also a region of steep slopes. It follows that the most erosion sensitive areas within the North Esk Basin are likely to be found around Mount Barrow. This tends to be confirmed by field measurements of suspended sediment concentrations during three flood events.

Figure 35 is a landuse map with sampling sites indicated. Most sites were associated with river junctions. Care was taken to make sure that samples were taken far enough upstream or downstream (i.e. 200-400 m) from junctions so that it would not affect the suspended sediment concentrations being measured (for instance, changes due to back-water effects). Table 5 presents the suspended sediment concentrations which correspond to the sites on Figure 35 for the three flood events. Each of the sediment concentration values represent the largest concentration from three to five samples which were taken at one to two hour intervals at the time of the peak discharge at the site. In most instances, each concentration value in Table 5 had smaller concentrations taken before and after it. Hence, each value in Table 5 represents a 'near' maximum suspended sediment concentration value for each individual site during each flood event. This technique is questionable since much depends on the timing of samples and the varying concentrations with discharge (Olive and Rieger, 1985). However, it should provide sufficient data for general conclusions to be drawn about the geographical location of sediment sources within the catchment.

Each of the floods occurred during a characteristic synoptic meteorological situation which is usually associated with flooding on the North Esk River. A low

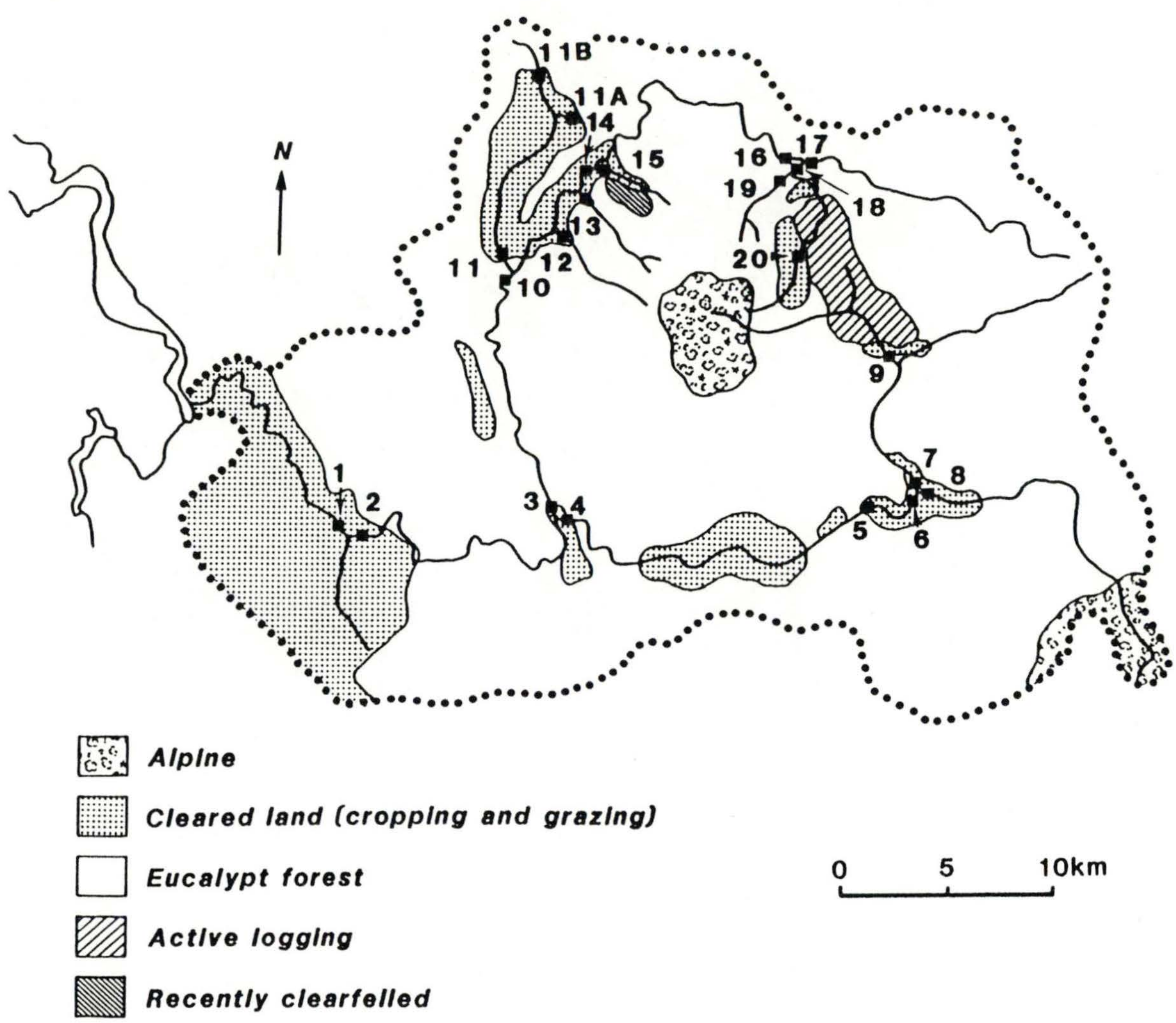


Figure 35: Vegetation and landuse, including the water sampling sites, within the North Esk River basin. Suspended sediment concentration values for the sampling sites are presented in Table 5.

Site Number (see Figure 19)	Suspended Sediment Concentrations (mg/l)		
	Flood A 5/12/85	Flood B 22/9/86	Flood C 27/9/86
1	8	7	11
2	9	6	11
3	9	6	10
4	12	5	10
5	42	5	8
6	59	6	12
7	109	8	9
8	44	5	14
9	123	6	9
10	26	6	10
11	25	91	8
11A	5	1	2
11B	6	2	3
12	6	1	1
13	5	1	2
14	66	4	7
15	64	3	6
16	24	3	4
17	19	3	3
18	65	9	7
19	4	1	2
20	31	5	8

Table 5: Peak suspended sediment concentrations for 22 sites within the North Esk Basin during three separate floods. See Figure 35 for the location of the sampling sites.

pressure system, situated in Bass Strait, directs a warm moist northerly airstream over the area. This brings light rain, with the occasional heavy shower, to most of the region with persistently heavy falls on and around the mountains, i.e. Mount Barrow and Ben Lomond. The resultant floods are generally confined to the headwater regions of the catchment. Due to an absence of discharge data (except at Ballroom) it is impossible to describe the spatial hydrographic characteristics of a 'typical' flood in the North Esk River basin. However, since only three substantial floods occurred during the fieldwork period, they were all monitored and the data are presented in order to help explain the provenance of the suspended sediment within the North Esk basin.

At the time of flood A (around the 5/12/85) there were five rainfall stations in operation that recorded daily average rainfall data. They were Burns Creek, Musselboro, the Launceston Airport, the Saint Patricks River station, and Upper Blessington (see Figure 7 for their locations). Unfortunately the Rivers and Water Supply Commission could not provide hydrographic data, from the Ballroom station, of this flood, because the data had been misplaced.

The daily rainfall data for flood A is presented in Table 6. This table indicates that between 28/11/85 and 6/12/85 the rainfall in the area was patchy with only two substantial falls, 26.2 mm at the St Patricks River station on the 30/11/85 and 31.6 mm at Upper Blessington on the 5/12/85. Both stations are in areas which receive orographic rainfall from an airstream with a large northerly component. The station at Musselboro however, is in Mt Barrow's rain-shadow, which explains why it did not record any rain during the period of flood A. The largest amount of rain during this period probably fell on the mountains (i.e. areas above 1500 m), and were therefore not recorded at the stations in Table 6 (the Mt Barrow station closed in 1973), since they are all at relatively low elevations.

The concentration measurements were taken late on the 5/12/85. Table 6 indicates that significant falls were recorded on the same day. This rain occurred in the early morning and was probably the main reason for the peak discharge later

Date	Rainfall (mm)				
	Burns Creek	Musselboro	Launceston Airport	St Patricks River	Upper Blessington
1985					
28/11	-	-	-	-	3.6
29/11	10.2	-	-	-	-
30/11	-	-	1.2	26.2	12.0
1/12	-	-	-	-	-
2/12	-	-	-	-	-
3/12	-	-	-	-	-
4/12	-	-	-	-	-
5/12	14.4	-	14.0	-	31.6
6/12	-	-	0.4	4.4	1.2
1986					
8/9	-	-	-	-	N/A
9/9	-	5.2	3.4	11.0	N/A
10/9	7.6	18.6	6.6	12.0	N/A
11/9	-	8.8	1.6	4.0	N/A
12/9	10.4	-	<0.1	-	N/A
13/9	-	6.2	5.0	4.8	N/A
14/9	14.4	-	-	-	N/A
15/9	-	-	-	-	N/A
16/9	-	-	3.6	3.2	N/A
17/9	-	-	0.2	0.2	N/A
18/9	-	-	-	-	N/A
19/9	10.4	3.0	0.6	0.4	N/A
20/9	-	-	-	-	N/A
21/9	5.0	-	-	-	N/A
22/9	2.2	10.0	3.6	15.8	N/A
23/9	-	-	-	-	N/A
24/9	6.4	-	-	-	N/A
25/9	-	-	-	-	N/A
26/9	7.6	-	-	-	N/A
27/9	-	-	-	-	N/A
28/9	-	-	<0.1	-	N/A
29/9	-	-	-	-	N/A
30/9	-	-	-	-	N/A
1/10	-	-	-	-	N/A

Table 6: Rainfall for floods A (28/11/85 to 6/12/85) and B and C (8/9/86 to 1/9/86). Refer to Figure 7 for the location of the rainfall stations. All data are totals for a 24 hour period. N.B. data from the Upper Blessington station was not available during floods B and C due to equipment failure.

that day, since the runoff would have combined with the through-flow from previous rainfall.

A cold front prior to flood B brought widespread rain to the North Esk basin (Table 6, 9/9/86 to 14/9/86). This was the first substantial widespread rain in the area for 1986, and it provided initial soil saturation prior to floods B and C.

Flood B occurred between 17/9/86 and 23/9/86 during which time there were no substantial rainfalls recorded (Table 6). The North Esk River's hydrograph at Ballroom for this period is shown in Figure 36. This depicts a small flood with a series of three consecutive peaks. However, upstream of Ballroom, the flood was relatively larger (e.g. the floodplain around the junction of the Ford and North Esk Rivers was substantially inundated). These conditions suggest that this flood was as a result of localized rain on the mountains. The concentration measurements were taken in conjunction with the third peak. Although this corresponded to a period of restricted sediment supply (Figure 18, time ≈ 350 hours) the suspended sediment data proved to have similar trends to flood C, which will be demonstrated in the following discussion.

Flood C occurred between 26/9/86 and 1/10/86. During this period there was no rain recorded at any of the four operating stations in the area, except 7.6 mm at Burns Creek on 26/9/86 and less than 1 mm at the Launceston Airport on 28/9/86. However, residents reported very heavy falls on Mount Barrow and presumably similar amounts of rain fell on other highland areas within the region. Figure 36 shows a hydrograph of flood C at Ballroom, on the North Esk River. This graph depicts a substantial flood with a clearly defined peak.

Floods A and C had respective peak discharges of 55 and 38 cumecs at Ballroom, however flood B had a peak of only 12 cumecs. Therefore, comparisons of suspended sediment measurements between floods A and C may have some validity, but any differences found between floods B and either of the other floods may not be significant due to their different discharges.

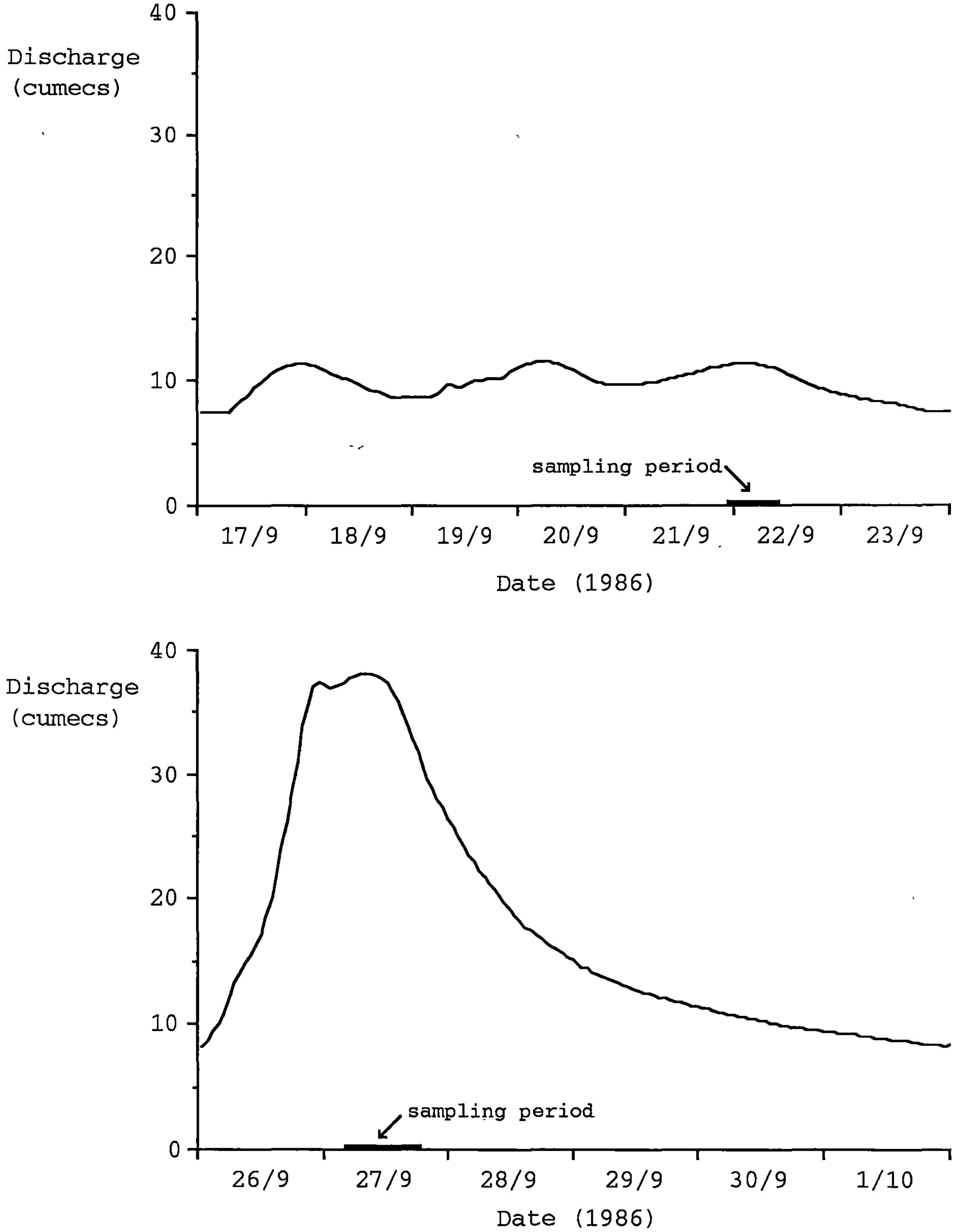


Figure 36: North Esk River hydrographs from Ballroom for floods B (top) and C (bottom)

During the course of the following discussion, comparisons will be made between pairs of suspended sediment measurements from two rivers just upstream of their junction (see Figure 35 for the location of the sampling sites). For these comparisons to be valid it must be assumed that they have similar suspended sediment rating curves. This may be an acceptable assumption, since Foster *et al.* (1986) found that all major rivers in the Tamar basin had similar suspended sediment rating curves. Therefore it is reasonable to expect that a similar situation exists with the smaller rivers in one part of the Tamar basin, i.e. the North Esk basin.

Prior to, and during the period of flood A, active logging was being conducted in the area, shaded by diagonal lines and shown, on Figure 35. Only a few months after flood A, active logging ceased until just after flood C, when a number of fresh coupes were opened on the North Esk River, above the junction of the Ford River, and on Seven Time Creek. Hence, floods B and C occurred during a period when there was no logging taking place within the catchment, with the exception of the occasional one or two trees cut for the purpose of fire wood or fence posts. The significance of logging activities will be discussed in more detail later.

In the following discussion of data shown in Table 5, only those sediment concentrations that are of particular interest will be discussed. The full significance of the sediment concentrations can be assessed by making a comparison with the sediment concentrations at low flows. Prior to these floods, sediment concentrations were measured during a period of relatively low river levels and were found to be considerably less than 5 mg/l. These measurements included sites 1,2,3,4,7,8,17, and 18 (Figure 35). However during the floods these sediment concentrations increased dramatically.

During flood A, the samples which provided the sediment concentrations at site 7 on the North Esk River and site 8 on the Ford River were taken within 10 min. of one another. Since the discharges of each river were of the same magnitude (a visual observation based on previous experience with discharge measurements of both rivers), the sediment concentrations (109 mg/l at site 7 and 44 mg/l at site 8) indicate that possibly twice as much sediment was being transported past site 7 than past site 8. This, together with a sediment concentration of 123 mg/l at site 9 indicates that a large proportion of the sediment being transported past site 6 has its origin upstream from site 9. This area is mostly forest, with a large proportion subject to active logging at the time (Figure 35). This pattern did not repeat itself during floods B and C. Table 5 indicates that for these two floods the sediment concentrations measured at site 7 were 8 and 9 mg/l respectively, while at site 8 they were 5 and 14 mg/l. Although these concentrations showed a difference between sites 7 and 8, these differences were not sufficiently great to allow conclusions to be drawn about a localized source of sediment supply. This is especially true with respect to the recently logged area, as measured at site 9. The concentrations for sites 9 and 7 were, 6 and 8 mg/l for flood B, and both were 9 mg/l for flood C. This indicates that this area was not acting as a major sediment source as it was during flood A. A reason for this could be that during flood A, as well as for some months before, there was active logging in the area, but during floods B and C, there was no active logging taking place. This result is surprising when one considers that during floods B and C there were large areas of vegetation-free clear felled land, left from previous logging activities, exposed to potential erosion agents. However, it is difficult to assign definite causes due to the many uncertainties accompanying this data. For instance, to be able to draw more definite conclusions, more detailed information would be needed about the nature of individual flood events, the amount of gully and rill erosion upstream from the sampling sites, and the nature of the suspended sediment concentration/discharge relationship (Olive and Walker, 1982; Olive and Rieger, 1984).

The North Esk River meanders through cleared farmland for approximately 1 km between sites 5 and 6. This farmland is predominantly used for grazing and the river banks have mostly been cleared of trees. The removal of protective vegetation along the river's banks has inevitably led to bank erosion (Plate 11). Since no tributaries enter the river between sites 5 and 6, it was expected that suspended sediment transport between sites 5 and 6 would increase due to the bank erosion. However, the sediment concentrations decreased from 59 mg/l at site 6 to 42 mg/l at site 5, for flood A; 6 to 5 mg/l, for flood B; and 12 to 8 mg/l, for flood C (Table 5). During each flood, at the time when the samples were taken, the river between sites 5 and 6 had broken its banks along approximately half its length and had inundated the surrounding floodplain. The unexpected drop in sediment concentrations between sites 6 and 5 may be explained by postulating that some of the sediment load has been deposited on the floodplain due to the inability of slow moving overbank flow to carry high concentrations of suspended load. This made it difficult to gauge the contribution of bank erosion to the river's suspended sediment load.

It is questionable whether measurements from three floods, between two sites 1 km apart, is sufficient evidence to make any generalized comments about bank erosion and floodplain deposition within the North Esk catchment. However, Lambert and Walling (1987) reported that conveyance losses within the lower reaches of the River Clum (Devon, U.K.) indicate that floodplain deposition is of considerable significance in the sediment budget, amounting to approximately 28% of the suspended sediment load entering the reach. This is consistent with the results obtained from a number of other studies, including Costa (1975), Trimble (1976), Magilligan (1985), and Walling *et al.* (1986).

The Camden Rivulet flows through an area of active logging (Figures 7 and 35). During flood A, upstream from this area the sediment concentration was 31 mg/l (site 20), mainly as a result of farming activities. However, flowing through the logging area, and even after having been diluted by relatively clear water (4 mg/l at site 19, see Figure 35), the rivulet registered a sediment concentration of 65 mg/l at site 18. This indicated that a significant proportion of the suspended sediment load of the river probably originated within an area of active logging.

Once again, the situation described above was not repeated during floods B and C. During these floods, site 20, above the logged area, registered 5 mg/l for flood B and 8 mg/l for flood C. The clear water at site 19 registered 1 and 2 mg/l, and the rivulet after the logged area, at site 18, registered 9 mg/l for flood B, and 7 mg/l for flood C. Clearly there had been no substantial contribution of sediment to the rivulet from the logged area during these floods. This was the same situation that occurred on the head waters of the North Esk River, above its junction with the Ford River.

The impact of clear felling on erosion rates of steep slopes can be seen by comparing sediment concentrations at sites 12, 13 and 15 located respectively on the lower reaches of the Coquet, Trout and Seven Time Creeks. These creeks have approximately similar catchment areas and aspect, drain neighbouring areas, and have comparable vegetation cover, except that Seven Time Creek has had a large area of forest clearfelled in its headwaters. This logging took place just before flood A, during which the measured suspended sediment concentrations were 6 mg/l for site 12, 5 mg/l for site 13, and 64 mg/l for site 15. If it is assumed that the vegetated regions of these areas have similar rates of natural erosion, the clearfelled region is making a large contribution to the suspended sediment load of the river for this flood. For floods B and C, the measured suspended sediment concentrations were; both 1 mg/l for site 12, 1 and 2 mg/l for site 13, and 3 and 6 mg/l for site 15. Although these figures show that the concentrations at site 15 were slightly larger than for sites 12 and 13, once again, the absence of recent logging near the river, during floods B and C, has seemingly reduced the significance of a sediment source that was apparent during flood A.

As mentioned in the chapter describing the study area, cropping is a substantial activity among farmers of the North Esk Basin. An indication of the effects of this activity upon suspended sediment origins can be gained by comparing the sediment concentrations measured at site 11, during the three floods, with the concentrations measured at sites 11A and 11B. During all three floods, a substantial portion of the flood plains in this area was in a ploughed state, with no vegetative cover. The measured concentrations for sites 11A and 11B were 5 and 6 mg/l for flood A, 1 and 2 mg/l for flood B, and 2 and 3 mg/l for flood C. The respective concentrations for site 11 were 25, 91 and 8 mg/l. These figures indicate that a substantial proportion of the sediment, flowing past site 11, was probably coming from the fallowed land on the floodplains between site 11 and sites 11A and 11B.

The information shown in Table 5 suggests that the largest contributions to suspended load in the North Esk River system, during floods, probably came from recently denuded areas. Table 5 also suggests that, in the absence of recently denuded areas, there seem to be no preferred source areas for suspended sediment origins. These denuded areas include recently logged areas in the steep lands around Mount Barrow, and the fallowed areas of farmland on the floodplains of the Patersonia Rivulet (Figures 7 and 17). Each of these areas are subject to high rainfall (Figure 16). The remaining farmland, most of which is under pasture, provided insignificant amounts of sediment during the three floods. The undisturbed forest areas contributed the least amount of sediment, even those in high rainfall areas.

It is important to stress that due to a lack of supportive data, it was not possible to determine whether the characteristics of these three floods were indicative of an 'average' flood within the North Esk basin. This implies that conclusions drawn from Table 5 are only specific to those flood events. Therefore, any conclusions about suspended sediment origins are meaningful only with reference to the three flood events discussed in this chapter. These floods may or may not have been typical contributors to the total suspended sediment transport of the North Esk River.

b. A Logging Episode

The results of estimating the mean annual suspended sediment yield indicate that the North Esk River is a relatively clean river. However, as described earlier, construction of the sediment rating curve (used to derive these results) did not include the flood in October 1986 associated with unusually high levels of suspended sediment concentrations attributed to logging activity. The turbidity measurements, on which the sediment rating curve was based, followed the discharge trend until after the 540th hour of measurements (Figure 18). After the 540th reading the turbidity of the river began to rise without any increase in discharge. While the discharge remained consistently low over a period of 320 hours, the rate of sediment transport rose from almost nothing to a peak of 3.6 kg/s, after which it began to decrease until a secondary peak occurred, associated with a small flood. The sediment transport levels were back to "normal" after 380 hours (Figure 18). The timing of this event corresponded to the commencement of logging operations in the catchment upstream of Ballroom. Since sediment concentrations began to rise during a period of constant discharge, the episode may be due to direct disturbance of one of the tributary channels, possibly by dragging logs or driving machinery across the bed and banks.

The logging coupe covered approximately 50 ha and was situated on a north west facing slope, opposite site 9, see Figure 35 and Plate 12. It is possible to estimate the amount of sediment that came from this coupe by comparing the sediment transport at Ballroom predicted from the suspended sediment rating curve (Figure 23) with the actual sediment transport during this event.

Figure 37 is a graph of the suspended sediment transport (kg/s) of the North Esk River at Ballroom for 500 hours and includes the above mentioned "sediment event". Superimposed upon this graph is a graph of the predicted sediment transport calculated by applying the corresponding discharge values to the sediment rating curve. Since the rating curve is designed to predict the "normal" sediment

Plate 12: Logging coupe in the upper North Esk River. The top photograph is a wide view, with the coup centred, and the bottom photograph is a close-up of the same coupe.

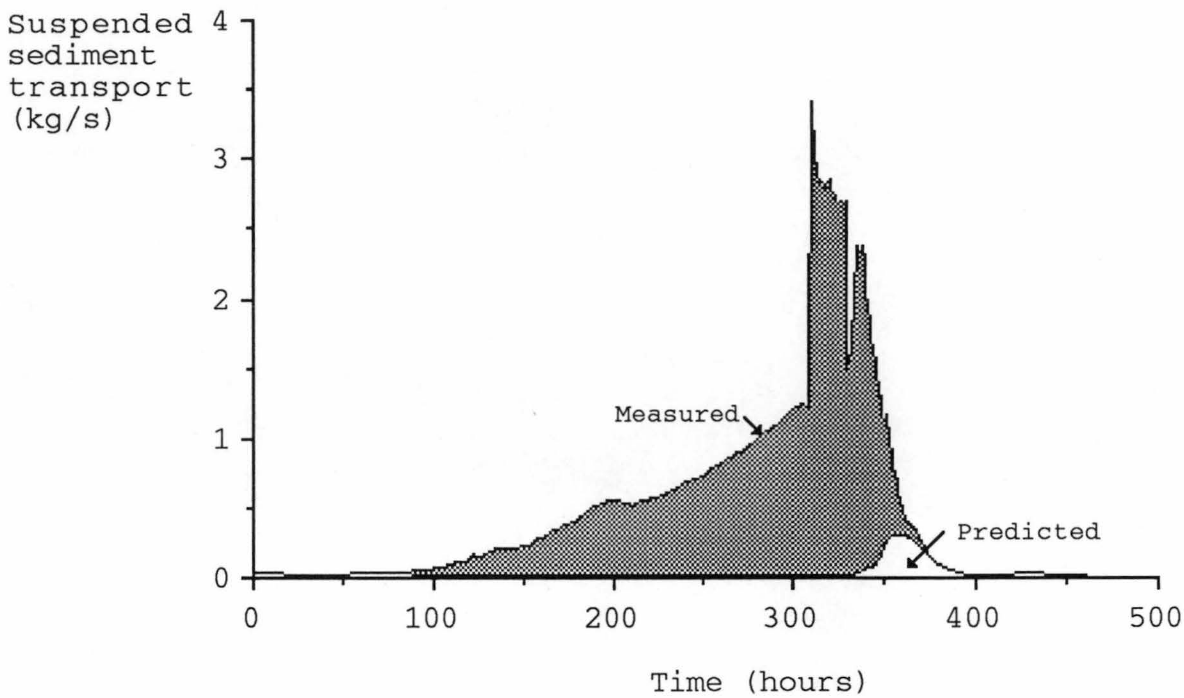


Figure 37: Predicted and Measured (shaded) Suspended Sediment Transport Rates for the North Esk River at Ballroom (1st to 17th October, 1986).

transport at Ballroom, the two graphs give a clear indication of the enormous difference between the measured and the predicted rates of sediment transport. If the assumption is made, that the observed logging activity was the only major landuse disturbance in the catchment during this period (and, to the best knowledge of the author, this appeared to be the situation), then the difference between the measured and predicted sediment transportation totals, is an estimate of the minimum quantity of sediment that came from the logging coupe.

The sediment rating curve predicted that 65.5 t would have been transported past Ballroom had there been no unusually large increases in erosion within the catchment. However, over the same period, a total of 825.9 t was measured. This implies that a minimum of 761.4 t of sediment had its origins within the logging coupe over the 320 hour period.

CHAPTER 6: DISCUSSION

No compelling evidence was found that would enable specific sediment sources to be identified. Obviously a study conducted over a much longer period, is needed to be able to make sound conclusions about the relative significance of sediment sources. However, it is possible to use the data obtained to speculate about sediment origins within the North Esk River.

Ketcheson *et al.* (1973) identify two potential contributions of sediment from soil erosion on sloping agricultural land and stream erosion of channelbanks and floodplains. In keeping with their findings, this study found circumstantial evidence of erosion from ploughed floodplains. Although evidence of bank erosion was observed (Plate 11), measurements made at site 5 (Figure 35) failed to confirm it as a significant contributor to the suspended sediment load. The reason appears to be that deposition on the floodplains was cancelling out the effects of bank erosion. Consequently, it is not possible to assess the importance of the contribution made by bank erosion to the North Esk River's sediment load. Visual observations in various parts of the catchment suggest that it may not be a major contributor.

The largest contributions to the suspended load of the North Esk River, appear to come from recently denuded areas during floods. These include recently logged areas on the steep slopes around Mount Barrow, and the fallowed areas of farmland on the floodplains of the Patersonia Rivulet (Figure 7 and 17). Both of these areas are subject to high rainfall (Figure 16). The remaining farmland, most of which is under pasture, seems to provide insignificant amounts of sediment. Non-agricultural land, including the undisturbed forest and alpine vegetation, contributes the least amount of sediment, even in high rainfall areas.

There have been many studies of sediment origins that have concentrated on the effects of logging activities. Olive *et al.* (1979 and 1980) conducted a study of a number of selected catchments near Eden, New South Wales. They estimated that the increase in suspended sediment load in the logged catchments could have been as high as 150% in the initial storm following the commencement of logging and that the increased erosion rates were reducing rapidly to 100% two months later. Also, in a study conducted in the Redwood Creek basin, California, Nolan and Janda (1981) found that harvested tributary basins became major sources of sediment.

Many studies conclude that the major contributions to river sediment from within a logging area come from its roads. For instance, Burgess *et al.* (1981) demonstrated that, in the upper Wallagarough River Basin (N.S.W.), following a logging program, suspended sediment transport was substantial, particularly from the logging roads. Also, Reid *et al.* (1981) demonstrated that a significant amount of sediment, found in the Clearwater River in Washington, U.S.A., originated from actively used logging roads.

Some farming practices have also been identified as sediment sources. Al-Ansari *et al.* (1977) found that farming techniques that caused major disturbances to the vegetation, can create areas of high sediment yield, for instance during harvesting of root crops such as turnips.

Imeson's (1974) conclusions were more general. After studying the Hodge Beck Catchment, England, he concluded that: "The results of this study illustrate the well-documented relationship between vegetation and soil erosion, and emphasize the role of unvegetated areas in supplying sediment to the drainage system.... ". This relationship, which Imeson talks about in the conclusion of his paper on sediment origins, is virtually considered as an axiom among scientists who study river sediment origins. The findings of this study seem to be in accord with those of most preceding studies.

During the fieldwork period, a new logging coupe was opened upstream of the Ballroom station. Its effects on suspended sediment load were monitored by the turbidity meter at Ballroom. It was estimated that in a 320 hour period, 761.4 t of sediment found its way into the North Esk River from the 50 ha coupe. This is equivalent to a yield of 41,700 t/km^2/year! If soil density is estimated as 500 kg/m^3 (Cruickshank, 1972), then a yield of 761.4 t of soil from 50 ha represents an average loss of 3 mm of soil thickness. This represents a considerable loss of topsoil and soil nutrients and can be expected to have a detrimental effect when forest revegetation is attempted (Attiwill and Leeper, 1987).

After a period of 14 days, the suspended sediment loads in the North Esk River at Ballroom had returned to pre-logging levels, even though logging continued. Other studies have found similar results (Kriek and O'Shaughnessy, 1975; Rieger *et al.,* 1979; and Burgess *et al.,* 1981).

In the Eden area, N.S.W., the impact of clear-fell logging in a dry sclerophyll catchment has been examined by Rieger, *et al.* (1979) and Burgess *et al.* (1981). Increases of up to 150% in sediment loads following the construction of roads and the start of logging were reported. The suspended sediment loads apparently returned to close to pre-logging levels after twelve months. Most of the increase in sediment load was explained by poorly sited and constructed roads, and sediment loads tended to decrease as logging continued.

Kriek and O'Shaughnessy (1975) have also reported on the impact of roads and logging in forested catchments. They examined two catchments in the Coranderrk experiment in Victoria. During logging, 50% of the timber stand was removed. The study plots showed an initial impact due to road construction with increases in suspended sediment loads but returning to pre-construction levels in approximately twelve months. A further episode of increased sediment transport accompanied the logging, with a trend towards pre-logging loads after two years. Langford *et al.* (1982) whilst working in the same catchment, found that after logging of the Blue Jacket Creek there was no return to pre-logging suspended sediment concentrations. The difference between these findings and those of Kriek and O'Shaughnessy (1975) was interpreted as being due to differences in road drainage, with Blue Jacket Creek having longer and steeper sections of road draining towards the stream.

Annual suspended sediment loads have been calculated for two points on the North Esk River, Corra Linn and Ballroom (Figure 7). The average annual suspended sediment transportation past Corra Linn was estimated to be 7225 t/year. With a drainage area of 921 km^2 this yields an average annual denudation rate of 7.8 t/km^2/year. The average annual suspended sediment transportation rate of the North Esk River at Ballroom was estimated to be 1472 t/year. At this point, the river has a drainage area of 373 km^2, which produces an average annual denudation rate of 3.9 t/km^2/year. This is only half the rate of the catchment at Corra Linn. If the drainage areas and transport rates for the two stations are compared, it is found that while the catchment at Ballroom has two fifths of the catchment area at Corra Linn, it provides only one fifth of the sediment load estimated for Corra Linn. This implies that the catchment downstream from Ballroom supplies a significantly larger amount of the suspended sediment per unit area than the headwater region upstream from this point.

It must be kept in mind that the accuracy of the Ballroom suspended sediment transport rates can be questioned. The relationship between suspended sediment transport and discharge has a relatively large spread (R^2 = 66.3%), and the suspended sediment rating curve was extrapolated significantly beyond the largest value used to derive it. These two sources of error may combine to produce a significant underestimate of the suspended sediment transport rate (Campbell, 1977; Olive *et al.*, 1980; and Geary, 1981).

Assuming that the estimates are reasonably accurate, it is not surprising to find that the catchment downstream from Ballroom has a larger denudation rate than the headwater region upstream from this point, if a comparison is made between the two catchment areas. The largest tributary between the two sites is the St. Patrick's River. Its valley has extensive areas of cleared farmland especially around the junction with the Patersonia Rivulet (Figure 17). Pinkard (1980) has also drawn attention to significant areas of mass movement in the drainage basin of the St Patrick's River.

As explained earlier, the annual suspended sediment transportation estimate of 7225 t/year for the North Esk River, did not incorporate the effects of clear felling. If it is assumed that the logging episode, described in Chapter 5C(b), is indicative of the average yield from clear felled logging coups within the North Esk basin, the figure of 761.4 t from 50 ha can be used to derive an estimate of the contribution of clear felled coups to the suspended sediment transportation of the North Esk River.

Over the last ten years, a total of 3112 ha have been clear felled from within the North Esk basin (The Tasmanian Forestry Commission, Forest Resources, and A.P.P.M.; pers. comm.). Therefore an average of 311.2 ha/year are clear felled from the North Esk basin. If a yield of 761.4 t from each 50 ha is assumed, then on average, clear fell logging contributes 4739 t/year of suspended sediment to the North Esk River system. This is a very significant contribution, since it represents 66% of the estimated average annual suspended sediment transportation of the North Esk River at Corra Linn. Unfortunately, unlike the latter estimate, the estimate of suspended sediment from the clear felled areas is unreliable. This is because there are many variables (such as the interaction of logging techniques and soil erosion, rainfall, slope steepness, coup distance from the river, etc.) which need to be understood before a model could be developed which would provide accurate estimates of suspended sediment yields. This would require a much larger and longer term study.

If clear fell logging in the North Esk basin contributes an average of 4739 t/year to the suspended sediment load of the North Esk River, then assuming that the logging rate of the past ten years will be maintained in the near future, it would be more realistic to add this to the previous estimate of annual suspended sediment transport (7225 t/year). Consequently, a better estimate of the annual suspended sediment transport rate of the North Esk River is 11,964 t. However, since this increase is based on only one logging episode, and since it is unreasonable to assume that this event was indicative of other events within the North Esk basin, there will be no validity attached to the increased estimate of average annual suspended sediment transport rate (i.e. 11,965 t). Therefore, in the absence of additional information on the effects of clear fell logging on suspended sediment transport in the North Esk River, the previous estimate of 7225 t/year will be considered to be the most accurate estimate of annual suspended sediment transport by the North Esk River for the remainder of this discussion.

The North Esk River was found to be carrying a relatively low suspended sediment load compared with many rivers elsewhere in the world (Holman, 1968 and Milliman and Meade, 1983). Walling and Kleo (1979) estimated that for catchments less than 10,000 km^2 with an annual rainfall between 1,200 and 1,500 mm (i.e. similar to the North Esk Basin), the world average suspended sediment yield is 600 $t/km^2/year$. Even if their estimate is biased towards higher yields, this is considerably greater than the value of 7.8 $t/km^2/year$ for the North Esk basin.

Adams (1980) found suspended sediment yields in New Zealand to be much higher than the North Esk basin. He found that for the Esk (253 km^2), Taruaru (260 km^2) and Taueru (373 km^2) Rivers, the respective sediment yields were 340, 250 and 210 $t/km^2/year$. However, due to the unstable nature of New Zealand soils when compared with the relatively stable soils within the North Esk Basin, the above comparison can be considered a comparison of extremes.

When a comparison was made with 25 other Australian studies (Table 2) the North Esk basin was found to have a sediment yield less than values found in 24 of the studies. Although these studies were conducted on much smaller runoff areas than the North Esk basin, their sediment yields were often over one thousand times greater than the sediment yield of the North Esk basin.

In the only other study of this type in Tasmania, Olive (1973) found similar, but slightly higher suspended sediment yields for three catchments in southeastern Tasmania.

He found that the suspended sediment yields were:

Browns River	12.0 km^2	11.0 $t/km^2/year$
Snug River	19.2 km^2	10.3 $t/km^2/year$
Mountain River	39.7 km^2	11.0 $t/km^2/year$

Although this study concentrated on the North Esk River, it would be useful to estimate the sediment yield of the South Esk River. This could be combined with the estimate for the North Esk River to obtain an estimate of the total sediment input, from tributaries, into the Tamar estuary. While investigating siltation in the Tamar estuary, the Water Research Laboratory staff calibrated a suspended sediment rating curve for the South Esk River, at a point just upstream of the Trevallyn dam (Figure 7). The equation to the curve is:

$$Y = 0.002\,X^{1.439}$$

with $R^2 = 88.1\%$

and the standard error of estimate = 1.8 kg/s

where Y is the suspended sediment transport rate (kg/s)

X is the river discharge (cumecs)

They used this rating curve in combination with recorded daily mean flows into the Trevallyn Reservoir to predict the average annual suspended sediment transport rate for the South Esk River over the period 1924 to 1979. Their estimate of mean annual suspended sediment transport was 39,300 t. However, if the RUME technique is applied to the same discharge data and rating curve, an estimate of 42,100 t/year is obtained. With a catchment area of 8609 km^2, this represents a denudation rate of 4.9 $t/km^2/year$. This rate is significantly lower than the rate calculated for the North Esk River (7.8 $t/km^2/year$), although it must be kept in mind that different time periods are being compared, i.e. 1924-79 for the South Esk River and 1950-79 for the North Esk River.

Together, the North and South Esk Rivers have an average annual suspended sediment transport rate of 49,325 t/year, and a combined drainage area of 9530 km^2 comprising 87% of the entire catchment area of the Tamar River. If it is assumed that the denudation rates of the combined North and South Esk Rivers are characteristic of the remaining 13% of the Tamar catchment, an estimate of the average annual suspended sediment input into the Tamar Estuary from its tributaries is 56,900 t/year. This figure does not take into account the suspended sediment load derived from the Launceston urban area and discharged directly into the estuary by storm water drainage. Foster *et al.* (1986) have suggested that additional siltation in the estuary could result from biomass growth and "salting out" of dissolved solids as large amounts of sewage effluent from the Launceston urban area react with increasingly saline water in the estuary. These last two sources have not been the subject of quantitative study but undoubtedly make a significant contribution to the siltation problems in the estuary.

The significance of the above sediment loads can be put into perspective if the siltation process, described by Foster *et al.* (1986), within the Tamar estuary is considered. As mentioned before, the siltation problem is confined to the upper reaches of the estuary, near Launceston. This is immediately downstream from the point at which the North and South Esk Rivers flow into the estuary. A high proportion of suspended sediment from the tributaries is transported into the estuary during large floods. These same floods also scour the upper regions of the estuary. The sediment from the rivers, together with any sediment scoured from the upper reaches of the estuary, is deposited further downstream in the estuary. During periods of low flows, tidal currents redistribute the sediment by transporting it from the lower reaches of the estuary back into the upper reaches, where it is deposited. This is considered to be the principal cause of the siltation problem. Foster *et al.* (1986) estimated that under non-flood conditions, the net siltation rate in Home

Reach (the upper 3 km of the estuary) is 89,200 t/year, which is of the same order of magnitude as the total sediment yield of the tributaries.

CHAPTER 7: CONCLUSION

A simple single beam turbidity meter, based on the principle of light attenuation, was designed and constructed. It was installed in the North Esk River at Ballroom. An in situ calibration demonstrated that this turbidity meter was able to accurately measure suspended sediment concentration.

Measurements of the cross-sectional profile of suspended sediment concentration revealed that unlike many other river systems, the North Esk River and its tributaries appear to have uniform cross-sectional concentrations of suspended sediment. This is in contrast to classical models of suspended sediment concentration in cross-section (Chow, 1964; Garde and Ranga Raju, 1978; and Shaw, 1983). Shaw suggests that the suspended sediment concentration from a near surface sample should be multiplied by 0.8 to give an estimate of a depth integrated value. This technique would result in underestimates, if used in the North Esk River System. Therefore, it is recommended that any assumptions made about the cross-sectional concentrations of suspended sediment, during the course of a study, should be validated.

The study found that the largest contributions to suspended sediment load in the North Esk River System came from recently denuded areas during floods.

A single logging event was estimated to have produced a minimum of 761 t of sediment in 320 hours from a 50 ha coupe. This is equivalent to an average of 3 mm of soil from the entire coupe. This accelerated erosion did not last and the area returned to its pre-logging erosion rates within a few weeks. Therefore the effect of this logging event on the suspended sediment rating curve was significant only in the short term. The main effect of the soil loss is the loss of nutrients which may effect the future revegetation of the area.

Total annual suspended sediment yields were derived by applying averaged discharge data to the suspended sediment rating curve, which was derived using pairs of instantaneous discharge and sediment data. Walling (1977a) has reported that this technique will provide underestimates of the true value. This study presents a running mean extrapolation (RUME) technique which overcomes this problem.

The North Esk River was found to have a low suspended sediment load. A yearly average of 1,472 t was derived for the transportation rate of the North Esk River at Ballroom. At Corra Linn the mean transportation rate was estimated to be 7,225 t/year, which corresponds to an average annual suspended sediment yield of 7.8 t/km^2/year.

If the estimated sediment yield from the single logging event is assumed to be indicative of the average, the estimated suspended sediment transport rate of 7225 t/year for the North Esk River at Corra Linn is increased by 66% to 11,964 t/year. This estimate is not considered to be reliable, since it is not known whether the assumption upon which it is based is realistic. However, this result demonstrates the significance of the contribution of logging to the suspended sediment load of the North Esk River, and as such deserves further investigation.

The South Esk River transports 42,100 t/year which is almost six times the average suspended sediment transport rate of the North Esk River. However, since the South Esk River's catchment (8609 km^2) is over nine times larger than the North Esk River's catchment (921 km^2 at Corra Linn), it has a significantly smaller average annual suspended sediment yield of 4.9 t/km^2/year.

It was estimated that the average annual suspended sediment input to the Tamar Estuary from its tributaries is 56,900 t/year. This figure does not include sediment from urban runoff from Launceston or sediment derived from sewage effluent, both of which could be expected to be significant contributors to the siltation of the estuary. Most of this sediment is transported to the estuary during large floods. These floods also scour Home Reach (the upper 3 km of the estuary). The sediment being transported by the floods is deposited further downstream in the estuary. During periods of low flow, tidal currents return this sediment to Home Reach at an estimated rate of 89,200 t/year (Foster *et al.*, 1986). Hence, in the short term, the rate of sediment supply from the tributaries is not the controlling factor of the siltation rate, since the tides will continue to redistribute the sediment until pre-dredging silt levels are reached. Foster *et al.* (1986) suggest that before dredging commenced, there was no long term nett siltation or erosion within Home Reach under the prevailing river flow and tidal conditions. In the long term however, the sediment from the tributaries will obviously have an effect on the continued rate of infilling of the estuary.

With regard to the Tamar siltation problem, the only solution which prevents the continued siltation of Home Reach is to maintain the status-quo by carrying out regular maintenance dredging within Home Reach (the upper most 3 km of the estuary). (Foster *et al.,* 1986)

This thesis has shown that turbidity meters provide a very effective method of collecting suspended sediment concentration data. Therefore a logical extension would be to maintain a turbidity meter at Ballroom for a number of years. This would provide the data necessary for the development of a physically-based model which would supersede the sediment rating curve. In addition, a size analysis study of the suspended sediment, during various flood stages, could help to explain the homogeneous cross-sectional profile of suspended sediment concentration in the North Esk River. Such a study could also have a valuable input into a physical model of sediment transport.

> "Purely spatial sampling of fluvial systems, and statistical techniques which treat the systems as spatial, both ignore much of the complex behaviour of the systems." (Rieger and Olive, 1984) A logical extension of this study is to use the turbidity meter to continuously monitor more points on the river over a much longer time period, so as to elucidate hysteresis effects. It is also possible to use other techniques to track down the sediment origins, e.g. Klages and Hsieh (1975) have used mineralogical indicators, Wall and Wilding (1976) report the use of clay mineralogy, Walling *et al.* (1979) used

magnetic measurements, Grimshaw and Lewin (1980) used sediment colour and Loughran *et al.* (1982) used caesium-137 as an indicator.

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APPENDIX 1

FILTRATION METHOD

Following is a description of the steps used in the filtration method used in this study to determine the suspended sediment concentration of a water sample. The technique is a standard suction filtration technique which is described in detail by McCave (1979).

1) Rinse clean filterpaper (Whatman GF/C Glass Microfibre filter) with distilled water.
2) Dry clean filterpaper in oven at a temperature of 100°C for a minimum of one hour. (Plate 13)
3) Cool filterpaper in desiccator. (Plate 13)
4) Weigh clean filterpaper (Record A). (Plate 14)
5) Filter sample through filterpaper using Millipore suction filtration equipment (Plate 15). In this procedure, open filter holders are mounted on a vacuum flask, the suction for which is provided by a vacuum nozzle which is attached to a running water tap. Large clamps are used to secure the filterpaper in the open filter holders (Plate 15). The volume of the water sample is measured (Record B) and care is taken to ensure that all the sediment had collected on the filter holders with distilled water.
6) Dry dirty filterpaper in oven at a temperature of 100°C for a minimum of one hour.
7) Cool filterpaper in desiccator.
8) Weigh dirty filterpaper (Record C).
9) Resultant sediment concentration is $\frac{C - A}{B}$ (mg/l)

Plate 13: Electric drying oven with desiccators (right).

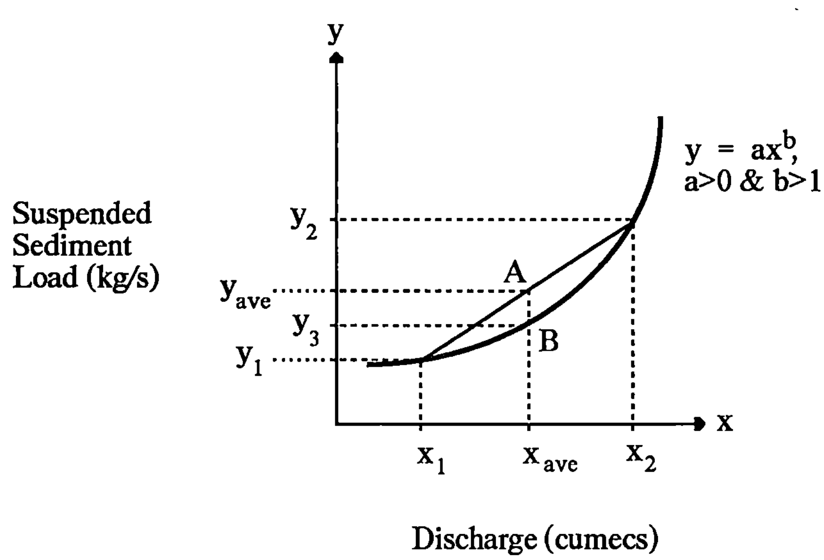
Plate 14: Electronic scale (resolution = 0.00005g) and Whatman GF/C microfibre filterpaper.

Plate 15: Millipore suction filtration equipment.

APPENDIX 2

UNDERESTIMATES OF SUSPENDED SEDIMENT TRANSPORTATION

The relationship between suspended sediment transport and discharge takes the form of a power curve. This relationship is usually derived from instantaneous measurements. If average discharges are applied to this relationship, the resultant calculation of suspended sediment transportation rate will always be an underestimate, as is demonstrated by the following theoretical consideration:



Consider the above power curve, then:

$$y = ax^b, \qquad a>0,\ b>1$$

$$\frac{dy}{dx} = \frac{bax^{(b-1)}}{dx}$$

$$\frac{d^2y}{dx^2} = b(b-1)a\,x^{(b-2)} > 0$$

Thus y is always concave and hence, the point A will always lie above the point B.

That is: $Y_{ave} > Y_3$

$$Y_2 + y_1 > 2y_3$$

$$ax_1{}^b = ax_2{}^b > 2a(a_{ave})^b$$

Hence, when an average discharge is applied to a sediment rating curve, which is derived from spot measurements, it will always yield an underestimate of the total suspended sediment transportation rate.

APPENDIX 3

TURBIDITY METER ELECTRONICS - A DESCRIPTION

Figure 6 is a circuit diagram of the electronics contained in the turbidity meter. This meter basically consists of a light source shining through a transparent tube through which the water flows. This light is received by a photodetector that is coupled to a data logger.

The light source is kept at a constant level via a feedback circuit. The output from the 2.5v Eveready bulb is sampled by a light dependent resistor and used to control the current flowing through the bulb. This ensures a constant light level and eliminates problems associated with warm up of the bulb. A reference voltage derived from the LM336Z2.5 is fed via a pot to pin 3 of the LM311. Before the bulb turns on, pin 2 is a high voltage as LDR 1 is high resistance, producing almost 2.5v on pin 2. This causes the output to swing more positive turning on the BD139 transistor. As the bulb illuminates and the light strikes LDR 1, its resistance falls, which reduces the voltage on pin 2. This continues until the voltage on pin 2 is equal to the reference voltage, which is selected using the pot on pin 3. The bulb will then remain at this light level. Adjusting the 10kΩ pot will thus set the desired light level. The 3 diodes between the base of the BD139 transistor and ground will prevent overdriving the bulb.

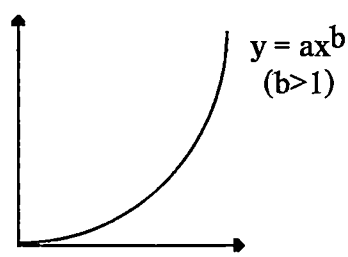
The receiver consists of another LDR (LDR 2) that has flowing through it a constant current (approximately 1.5 mA) set by the LM334 constant current source. This ensures that changes in the battery voltage will not affect the output. As the light level striking LDR 2 reduces with increased turbidity its resistance increases, resulting in a higher voltage drop across it. The LM301 was inserted as a buffer amplifier so that the data logger did not load the LDR. The meter runs off +12 volts and the supply is split and an earth established at +6v as an earth reference so that the op-amps can have a +/- 6v power supply.

APPENDIX 4

ESTIMATES OF SEDIMENT TRANSPORT - EFFECTS OF TIME AVERAGING

1) Assume that the suspended sediment rating curve takes the general form of a power curve; $y = ax^b$ where y is sediment transport and x is river discharge.

i.e.



2) Consider a simple flow model, where precipitation events occur at times t, t_1, t_2, ... For such an event at time t, we shall assume that a discharge x builds up instantaneously then decays exponentially with rate λ. The sizes of x and times t are random variables.

The total flow in time interval (t, t+h) due to precipitation at time τ is:

$$x \int_t^{t+h} e^{-\lambda(y - \tau)}\, dy = \frac{x\,(1 - e^{-\lambda h})}{\lambda}\, e^{-\lambda(t - \tau)}$$

if $\tau \leq t$,

or $$x \int_\tau^{t+h} e^{-\lambda(y - \tau)}\, dy = \frac{x}{\lambda}\, e^{-\lambda(t + h - \tau)}$$

for $t < \tau \leq t+h$

Thus the average flow rate in (t, t+h) is:

$\frac{1}{h}$(sum of all such terms, summing over x and τ).

The contribution to the sum from the term for $t < \tau \leq t+h$ gets relatively small as h -> 0, and ignoring it gives the average discharge.

$$\text{e.g.} \quad = \frac{(1 - e^{-\lambda h})}{\lambda h} \sum_{(x,\tau)} x\, e^{-\lambda(t - \tau)} = X \frac{(1 - e^{-\lambda h})}{\lambda h}$$

where X is a random variable.

3) Now using the basic power law in (1), the estimated sediment transport in time interval [0, T] is:

$$Y = h\,a \left[\frac{1 - e^{-\lambda h}}{\lambda h}\right]^b (X_1^{\,b} + X_2^{\,b} + \ldots.. + X_n^{\,b})$$

where nh = T, and if n is reasonably large, so that

$n^{-1} (X_1^{\,b} + X_2^{\,b} + \ldots.. + X_n^{\,b}) \approx E(X^b) = \mu$, where E denotes the expected value of a random variable.

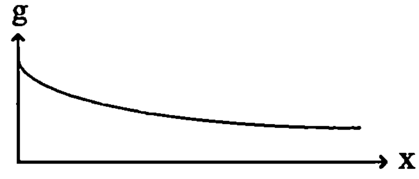
This becomes: $$Y \approx a\,T\,\mu \left[\frac{1 - e^{-\lambda h}}{\lambda h}\right]^b$$

i.e. for small h, estimated sediment transport has the form:

$$f(h) = \text{const. } \{g(\lambda h)\}^b,$$

$$\text{where } g(x) = x^{-1} (1 - e^{-x}) \approx 1 - \frac{x}{2} + \frac{x^2}{6} - \ldots..$$

for $x \to 0$



In general, without the arbitrary assumptions of instantaneous flow following rain, then exponential decay; a decreasing convex curve, approximately linear near $h = 0$, should be fitted to $\{f(h)\}^{1/b}$ to estimate the correct discharge:

$$f(0) = \text{const.}\ \{g(0)\}^b = \text{const.}$$