Sedimentation Resulting from Road Development, Cape Tribulation Area

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Great Barrier Reef Marine Park Authority
Technical Memorandum
GBRMPA-TM-24

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DATE
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SUMMARY

In 1985 the Cape Tribulation to Bloomfield Road was extended through an area of small rainforested catchments adjacent to fringing reefs. Results of stream sampling clearly show that below the road suspended sediment concentrations may be an order of magnitude greater than in undisturbed catchment areas above the road. An average of 22 times enhancement took place in March 1985 in response to the most intensive rainfall in two years and at a time when much recently disturbed land surface lay bare. Continued sampling into 1989 showed a smaller increase in sediment yield as streams crossed the road, but no rainfall event equivalent to that in 1985 has occurred.

Sediment traps were deployed over the adjacent reefs during 1986 in three contrasting areas: i) south of Cape Tribulation adjacent to the old road; ii) along the section of fringing reefs adjacent to the new road; and iii) along a northern section away from the road and used as a control. Results show that sedimentation rates adjacent to the new road were up to six times greater than in the control area, and adjacent to the old road section, more than three times greater. Highest sedimentation rates occurred over the reef front, with lowest rates usually associated with the reef crest. These patterns resulted almost completely from the deposition of the fine sand fraction and were statistically significant. The finer mud fraction was deposited more evenly over all areas and zones with maximum rates in the south close to the Daintree River.

Correlation with environmental variables suggested that sedimentation was related to resuspension of sediments already present. Rainfall factors appeared to be important for the new road section as disturbance made this area more sensitive to runoff processes. A major input of sediment into the reefal area took place during and immediately after road construction. This sediment subsequently becomes resuspended over the reefs. Mud is to be put into suspension in even moderate wind conditions occurring for over 50% of the time.

Cape Tribulation sedimentation is of the same order of magnitude as over other Australian fringing and inner shelf reefs. Rates from other areas in the world, apart from reefs adjacent to disturbed catchments in Puerto Rico, are considerably lower. Islands such as Guam or Barbados have limestone hinterlands with minimal runoff containing very low amounts of particulate matter. Variations in relative Holocene sea level histories indicate that the inner shelf of the Great Barrier Reef has experienced over 6000 years of stable sea level, with build-up of an inshore fine sediment wedge. However, Caribbean and north Pacific sites have experienced a continuously rising sea level with no comparable nearshore mud deposit.

Cape Tribulation reefs are delicately balanced having prograded little in the last 5000 years. Whilst the new road remains unsealed with steep gradients, unstabilised cuts and poor drainage there is great potential for massive sediment yield during intensive rainfall as might occur with a cyclone. This could pass the fringing reefs beyond a threshold from which they may not recover.

KEYWORDS: **Fringing reefs, Cape Tribulation, Great Barrier Reef, anthropogenic influences, sedimentation, rainforest catchments**

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CONTENTS

LIST OF TABLES

LIST OF FIGURES

1. INTRODUCTION

The Cape Tribulation area of far north Queensland provides a unique environment found nowhere else in Australia. The combination of a steep and deeply weathered hinterland with the ranges coming down to the coast, rainforest vegetation, and an almost continuous fringe of coral reefs gives this uniqueness. However, these environmental parameters also mean that the consequences of disturbance are great. Rainforest requires high rainfall and the average annual rainfall in the Cape Tribulation area exceeds 3 750 mm per year, one of the highest annual totals in Australia. Protection is given by the vegetation to the deep soils which clothe the steep slopes with elevations of 600 m or more being found within 3 km of the coastline. Without this protection, there is a great potential for rapid soil erosion and massive yield of sediment to the coastline. Coral reefs are susceptible to input of freshwater into their environment and also to excessive sediment loading.

Although access to the area was provided by a road constructed between 1955 and 1963 from the Daintree River to Cape Tribulation, much of this road in the southern section of the area under study lay 1 or 2 km back from the coast and was also on relatively flat ground. However, in 1968, a track was bulldozed from Cape Tribulation to the Bloomfield River, and although this soon became overgrown, it sufficed as a walking track giving access into what was otherwise a wilderness area. However, in 1983 bulldozing began again to create an unsealed road from Cape Tribulation to the Bloomfield. Much of this road north of Cape Tribulation lay within only a few hundred metres of the coastline where extensive fringing reef development occurred. Sections of the road were on grades steeper than 1:10 and this combined with poor engineering techniques (Bonham, 1985) gave the potential for dramatic increases in sediment transport onto the adjacent fringing reefs. This was perceived by the conservation movement who strongly opposed the development of the road (eg Veron, 1985).

Their fears seemed to be confirmed during the 1985 wet season when large plumes of red silt laden waters were observed extending from the mouths of the many small creeks which flow into the sea in the Cape Tribulation area. A pilot study of suspended sediment loads in a number of the streams was carried out by Bonham (1985) and Hopley (1985). Samples were taken from locations above and below the road at the mouths of the creeks and in some instances over the adjacent reef front (Table 1). Stream waters above the road were largely clear even though 324 mm of rainfall had occurred over the previous 24 hours (16 March 1985). Mean sediment concentrations were within the range 82-863 mg/l. Individual samples showed concentrations as high as 735 mg/l however, but concentrations higher than 300 mg/l were normally adjacent to small natural bank erosion scars or other local and transient natural features. In comparison, the waters of the streams downstream of the road were highly discoloured and quite clearly loaded with red silt derived from the road. Mean sediment concentrations ranged from 447 mg/l to 2 798 mg/l. Overall, this pilot study indicated that there was an average of a 22 times increase in the amount of suspended sediment below the road.

An aerial survey carried out in February 1985 after >100 mm of rainfall confirmed that a large proportion of this silt-laden water was reaching the sea. Clearly definable red plumes of sediment-laden water extended from the mouths of the majority of creeks to the north of Cape Tribulation adjacent to the New Road. The measurements taken by Bonham (Table 1) showed suspended sediment concentrations at the mouths of the creeks in March 1985 averaging between 169 and 12 600 mg/l, figures which in the context of coral reefs may be regarded with concern. Because of weather conditions, only a small number of samples were obtained over the reef front itself, and these ranged from 426 to 2 247 mg/l. However, not all this sediment was necessarily derived from the streams. Because of strong wind action, resuspension of sediments lying immediately in front of the reefs was also taking place and, as will be indicated in this report, is an important process at all times of the year.

Concern for the coral reefs of the Cape Tribulation area, particularly those close to the newly developed road north of Cape Tribulation, prompted the Great Barrier Reef Marine Park Authority to initiate a number of studies in 1985 (Craik and Dutton, 1987). The sedimentation study was initiated under the supervision of Associate Professor D Hopley, James Cook University, and was commenced as a PhD project in 1985 by Mr Paul Holthus. However, the return of Mr Holthus to the United States during early 1986 led to the division of the research into a number of sub-projects. The geological history and context of the Cape Tribulation reefs was undertaken by Mr Bruce Partain as an MSc thesis from the University of Texas under Associate Professor Hopley's supervision (Partain, 1988; Partain and Hopley, 1989). A pilot study of the hydrodynamics of the area close inshore was undertaken during 1988 by Dr KE Parnell (Auckland University), and the main sedimentation study was commenced as an Honours thesis by Mr DCJD Hoyal, also under Associate Professor Hopley's supervision, during 1986. However, as only some six months of field data could be incorporated in an Honours thesis, and a major wet season had not eventuated during 1986, the study was continued by staff of the Sir George Fisher Centre for Tropical Marine Studies, James Cook University until April 1989. Results from all data collected between 1985 and 1989 are incorporated in this report.

The original aims of the study were:

- To quantify the amount of sediment being carried by the streams of the Cape Tribulation area under both natural conditions and in disturbed areas adjacent to the New Road
- To quantify the amount of sediment in the water column adjacent to the reefs
- To put into context the amount of increased sedimentation directly due to road development

All these aims met with major logistic difficulties. Although water sampling could be undertaken in the streams in light rainfall conditions, access to the area during excessively heavy rainfall when most erosive activity was taking place proved difficult. Movement to the area on the basis of weather forecasts prior to predicted heavy rainfall was costly and largely unsuccessful. Travel to the area during heavy rainfall proved to be extremely difficult as roads were frequently closed. Access by way of helicopter was also attempted but this was also limited to times after heavy rainfall due to poor visibility during the rainfall events themselves. Placement of continuous recording equipment within the streams was also unsuccessful. Because of the intensity of rainfall and rapid rise and fall in these streams, most of the equipment was washed away. Continuous recording equipment was also placed over the reef fronts, but again success was limited as the exposure of the Cape Tribulation coastline meant that extremely rough conditions were experienced once south-easterly winds exceeded 15-20 knots. In spite of these difficulties, the data set collected is believed to be an accurate representation of the sedimentation record immediately after road construction and in the succeeding years.

2. THE EFFECT OF SEDIMENT AND RUNOFF ON CORALS AND CORAL REEFS

Sediment within the marine environment may originate from a number of sources:

- Fluvial input of terrestrial material
- Aeolian input from wind erosion of continental masses and man-made sources
- Re-suspension of sediment material by wave and current action
- Authigenic production by biota and precipitation of inorganic minerals

All have the potential to affect individual coral colonies and/or total reef communities.

Although numerous studies of these effects have been undertaken reviews of the literature (eg Hoyal, 1986; Holthus, 1987; Johnson and Carter, 1987) suggest great geographic variation in the response and tolerance levels of corals and coral reefs. Although this may be in part the result of variability in methodologies used, there is also some suggestion that differences in tolerance levels do exist at for example species levels and, more significantly, with what may be regarded as "normal" or "natural" ambient water quality conditions.

Probably the most intensive and widely reported study on anthropogenic impact on coral reefs is that from Kaneohe Bay, Oahu, Hawaii (Banner, 1974; Smith, 1977; Smith *et al*, 1981). Dredging destroyed small areas of reef during and prior to World War II, but a post war population increase of 8% per annum in the steep and deeply weathered volcanic catchments flowing into the bay has led to clearing and extensive urbanisation. This in turn has affected the hydrology of the area with rapid runoff and erosion. In May 1965 alone, quickflow response from between 460 and 830 mm of rainfall delivered freshwater to the bay equivalent to 16% of its capacity, producing mortality of corals to a depth of 1.5 m nearstreams and 0.3 m over the whole bay. In addition, extensive areas of reef flat were smothered by red silt. This produced an acute stress on a reef system already under chronic stress from a sewage input exceeding 8 million gallons per day. The combined effect of acute and chronic stress, producing intense eutrophication, was a massive overgrowth of the alga *Dictyosphaeria cavernosa*. In 1973, it was estimated that 70% of the former 96.6 km of growing reef front within the lagoon of the bay had been destroyed, 29.3% being removed by dredging, 23.5% killed by overgrowth of algae, 8.5% by the direct effects of algae and 9.8% by freshwater and sediment. This detailed study, extending over a fifteen year period has subsequently focussed much attention on coral reef degradation, especially in response to inputs of anthropogenically produced sediments, nutrients and freshwater runoff.

Siltation Effects at the Colony Level

There have been many experiments performed to determine the effect of sediment on corals on the small scale. These can be split into two groups, those that concentrate on the sediment rejecting properties of corals and those which emphasise the effects of reduced light on coral colonies. One of the earliest studies of rejection ability was by Marshall and Orr (1931) who covered living corals with sand and placed others in an aquarium with fine mud. They found that the corals were well able to remove the coarse and fine sediments from their living surfaces. Morphology of the colony and mucus secretions were considered the controlling factors in sediment removal. Later investigators (Hubbard and Pocock, 1972) stress four means of sediment rejection by corals:

- Distension by the stomodeal uptake of water
- Tentacular action
- Ciliary beat
- Mucus entanglement

Field studies on the response of corals to sediment application indicate large differences in the ability of different species to reject sediment (Rogers, 1979). Hubbard and Pocock (1972) ascribe the differences in sediment rejection of different species to two factors:

- Variations in the polyps' distensional capacity
- The geometry of the calyx

They determined that most corals are size-specific sediment rejectors, with all polyps being capable of moving silt-size particles. Sedimentation may have several other detrimental effects on corals, by inhibiting coral planulae settlement and modifying growth.

All of these processes represent an energy drain on the coral. Under high sediment loading, recovery from any wound or injury is likely to be hindered and sediment may interfere with the normal feeding processes of corals. Rejection of sediment particles by a coral requires time and energy which could otherwise be used for food capture, growth, skeletal repair or reproduction (Dodge and Vaisnys, 1977; Rogers, 1983). Coral respiration rates have been demonstrated to significantly increase during sediment rejection activities (Dallmeyer *et al*, 1982). They further suggested that sediments interfere with feeding processes. Recently Edmunds and Spencer Davies (1989) have described extensive metabolic stress and increase respiration rates in high turbidity environments. If excess sedimentation is evident, metabolic reserves may be depleted to a point where sediments can no longer be rejected. This may lead to burial of coral colonies. Most corals can withstand a low sediment supply to the living surface. Very high sedimentation rates, however, are lethal. It is known that corals do not survive burial for more than a few hours. The process of sedimentation may be amplified by algal growth, through eutrophication, with enhanced algal growth acting as sediment traps and adding stress to adjacent coral polyps (Birkeland, 1977; Smith, 1977; Walker and Ormond, 1982).

Turbidity or increased light attenuation by scattering within the water itself, the dissolved solutes, and suspended matter can also affect corals, or more particularly their algal symbionts which require a certain threshold of light in the photosynthetic range. Dustan (1982) found that although light flux varies considerably at any one depth, light levels decrease exponentially with depth, the greatest decrease occurring in the first 10 m. Thus reduction in the light available to corals appears to be one of the major causes of reef zonation with depth (Done, 1983). It is difficult to establish the direct relationship between light attenuation and suspended sediment concentrations (Baker and Weber, 1975). This is because the optical properties depend on "*the shape, refractive index, and size distributions of the suspended particles as well as their absorption spectra*" (Keller, 1970, p 13). Rogers (1979) showed experimentally that reduction of incident light by suspended sediments has a greater effect on corals than the sediment itself. She applied sediment on some shaded and unshaded corals and found that "*in contrast to shading the application of sediments to* Acropora cervicornis *did not affect them adversely structurally or functionally*" (Rogers, 1979, p 23). After a period of shading the coral community structure and function altered. There was a decrease in net primary productivity and respiration and many corals became bleached or died.

Sheppard (1982) considered that autotrophy may supply the total energy needs for corals down to 40 m but this only occurs in clear water. The degree to which light controls the distribution of corals depends on whether they are totally autotrophic. Sheppard (1982) has shown that some corals can survive without light but only if they have zooplankton to feed upon. As a result the corals with large polyps are more efficient heterotrophs. Rogers (1979) found that there is a fairly close correlation between increasing susceptibility to shading (demonstrated by bleaching) and decreasing polyp size. Light conditions controlled by turbidity can also influence coral colony morphology, ie with increasing depth or turbidity there seems to be a trend away from branching towards leafy and ramose forms (Roy and Smith, 1971) which offer a larger surface area for light collection.

Computer simulation experiments (Grauss and Macintyre, 1976) have been performed to determine the adaptive response of skeletal growth to light. They found that flattened shapes should be dominant in low light conditions. The model was based on the observation that buds on the edge of a colony orientate in the direction of maximum radiance. Weber and White (1976) have found that growth rate is a function of depth, and attribute the slower growth of hermatypic corals with depth to the reduced illumination.

An example of the immediate effects of suspended sediment were recorded by Bak (1978) during channel dredging in Curacao. For two days the sediment load reduced light levels at 12.3 m depth from a normal 30% to less than 1% of surface illumination. For a further two days light levels were less than 6% of surface. The dredging continued for another two weeks with less drastic reduction in light levels. However, after five days 10 mm of sediment covered much of the coral. However, only one platey colony subsequently died although all measured corals showed an abrupt decrease in calcification rates of up to 33% and rates remained depressed for more than one month. Similar decreases in calcification rates well after light levels had returned to normal after dredging operations have also been reported by Dodge and Vaisnys (1977).

In summary, research largely in the Caribbean but by a wide range of authors has shown that light is often the controlling factor in calcification. Since turbidity can cause huge reductions in the amount of light reaching corals, it must have a major control on coral growth. Therefore, any increase in turbidity in a reef environment may have great destructive potential. Some corals are better adapted to low light conditions than others, for example those with foliose or ramose forms. The direct application of sediment will also stress corals and smothering will kill them (Kinsman, 1968; Hubbard, 1973; Baker and Weber, 1975; Bak and Elgerschuizen, 1976). However, this is less likely to be a limiting factor since wave energy in the reef environment will continuously move sediment and many corals have the ability to move sediment themselves. Turbidity is much more likely to be a chronic stressor of corals than direct application since the addition of fine sediment to the marine environment leaves it continuously liable for resuspension by wave and tide energy, and as such may have a more detrimental effect on coral reefs.

An important consideration is whether the stress is chronic or acute. For example, the stress from a long term (chronic) slight increase of turbidity may be far more detrimental than a short term (acute) event such as a huge reduction in light over a short time. However, there are few data on how frequently siltation episodes can be tolerated or what are the critical levels of suspended sediment before corals are adversely affected.

Coral Reefs Affected by Sediment Stress

Fringing reef corals often grow in areas of chronic sediment supply or resuspension (eg Marshall and Orr, 1931), where the amount of suspended sediment is controlled by local wind and tidal conditions. Continued coral growth requires constant water flushing to prevent sediment blankets causing suffocation. Such communities growing in turbid waters have been regarded as having a lower percentage coral cover, lower growth rates and lower diversity and species composition. However, work in Australia has not altogether validated these observations. Veron (1986, p 16) states of fringing reefs *"species diversity may be very high - higher than that of outer reefs"* and that in the Palm Islands, *"more species have been recorded here than anywhere else in the world"*.

Growth rates also may not conform to the accepted responses based on Caribbean studies. Isdale (1981), based on x-radiographic studies of *Porites* species showed that inshore fringing reefs (including Magnetic Island) have fastest mean annual growth rates (>10 mm/yr) but with high variabilities compared to offshore reefs with lower (<7 mm/yr) growth rates but also lower variability.

Done (1982, 1983, 1987) has discussed the zonation of fringing and outer reefs and has noted (1987, p 35):

> *"While corals can obtain great size, very old age (to several centuries) and/or very high densities in many reef habitats, sheltered bays are characterised by coral populations with all three of these characteristics simultaneously (Potts* et al*, 1985). The development of such populations is an indication of the ability of individual corals to persist in conditions which, until recently, were presumed to be stressful for corals, namely high sediment loads, poor illumination, high variability in salinity.*
>
> *Should it be assumed that the coral species involved are tolerant to conditions which are deleterious to other corals, and by implication, capable of tolerating increased stresses imposed on the reefs by human or adjacent land practices? Or should we conclude that*

the conditions have not been stressful, that the present dense populations of large colonies have developed simply by the present colonies occupying space and pre-empting its occupation by other colonies or by more opportunistic species? A rider to the second interpretation is that physical and biological disturbance of a type that kills corals episodically and opens up space for new settlement must have been rare. This carries the implication that additional stresses and disturbances associated with human usage and adjacent landuse practices might not readily be observed, and that widespread coral mortality may result."

That such mortality can take place has been readily demonstrated although the most dramatic modifications appear to take place where nutrient and sediment influx occur together (eg Banner, 1974; Weiss and Goddard, 1977; Smith *et al*, 1981). Research on the Cahuita fringing reef in Costa Rica by Cortes and Risk (1985) is one such study which concentrated on the effect of changing land use on a fringing reef. These fringing reefs have naturally high levels of suspended sediment due to their proximity to the coast. The cavities in these reefs and the interskeletal pores are frequently filled with muddy quartz-bearing siliciclastic material and they often have reduced species diversity when compared to reefs further from land. Many of the corals found at Cahuita had good sediment rejecting properties, and many corals abundant on other Caribbean reefs but with poor sediment rejecting abilities were absent. Other adaptive features to cope with the high sediment load were a decrease in optimum growth depths, and colony morphologies suitable for low light intensities together with good sediment rejection capabilities. Cortes and Risk (1985) used sediment traps to determine the sediment resuspension rates in this environment, they found that the rate of sediment settlement varied from about 20-1000 mg cm^{-2} dy^{-1} much higher than other studies (for example, 0.45-1.1 mg cm^{-2} dy^{-1} Aller and Dodge [1974] at Jamaica and 1-21 mg cm^{-2} dy^{-1} Rogers [1977] at Puerto Rico). These are measures of the total gross sedimentation rate since the net sedimentation rate or the actual amount of material deposited on the sea floor cannot be determined with sediment traps. The aim of the study at Cahuita was to determine the features of a reef under siltation stress as it is believed that the extensive land use changes in this area have put stress on the reef. Cortes and Risk (1985) proposed features of a reef under stress as:

- High concentrations of suspended particulate matter (>6 mg 1)
- High concentrations of resuspended sediments (>30 mg cm^{-2} dy^{-1} 50 cm off the bottom)
- Large amounts of terrigenous material trapped in skeletons
- Reduced coral growth rates and diversity
- Low live coral coverage except for monospecific stands of siltation tolerant species
- Morphology changes in surviving coral species
- Size distribution of corals shifted towards larger colonies, indicating low recruitment.

3. SEDIMENT YIELD FROM NATURAL AND DISTURBED RAINFOREST CATCHMENTS

Considerable work has been carried out on the erosion rates and sediment yield of rainforested catchments under natural and disturbed conditions. Much of this has been carried out in north Queensland (see Pringle, 1986 for review). Douglas (1966) undertook research in this area in the early and middle 1960s and Bonell *et al* (see Bonell, 1983) followed this in the 1970s with work centred primarily on an experimental catchment near Babinda. More recently the Barron River Delta Investigation undertaken by the Queensland Department of Harbours and Marine (1981) involved a comprehensive programme to determine sediment transport mainly downstream from Camarunga at the head of the Barron Delta.

From these studies, it is clear that considerable geographic variation exists in denudation rates related to vegetation, topography and geology. Maximum sediment yield occurs in the dry areas where vegetation cover is less dense and ground flora less continuous thus allowing maximum effectiveness of the mechanical action of raindrops on the soil surface. Sediment yield may be expected to be less at higher rainfall totals as vegetation gives a greater protection to the ground surface, particularly inside the rainforest, just beyond the woodland boundary. However, as this boundary occurs at about 1500 mm annual precipitation, and maximum precipitation totals exceed 4000 mm in parts of north Queensland, there may be another peak in sediment yield in the higher rainfall areas. Maung Maung Aye (1976) found that in north Queensland many basin properties related to erosion rates such as stream numbers, densities and lengths, suggested minimal denudation rates at about 2500-3000 mm annual rainfall. Under natural rainforest conditions, Douglas (1967a,b, 1968, 1969, 1973) showed that denudation rates varied from 6.7 to 44.6 m^3 km^{-2} y^{-1} with the highest amounts removed being from basins with greatest runoff. Although rainfall and runoff in rainforest catchments is more evenly spread than elsewhere in coastal Queensland, over 50% of suspended sediment loads of rainforest streams is carried in less than seven days per year. After one heavy storm, Babinda Creek was shown by Douglas to have a discharge of 1.5 m^3 km^{-2} sec^{-1} with instantaneous rates of removal of dissolved and suspended matter of 600.5 and 1448.4 m^3 km^{-2} y^{-1}. Such sediment yields appear associated with intense cyclonic rains and damage to the vegetation canopy, events which are rare and damage which is rapidly repaired.

Even minor disturbance to rainforested catchments, particularly those which are steeply sloping, can rapidly increase the sediment yield. Gilmour (1977) for example, showed that logging can temporarily accelerate erosion rates two- to three-fold and clearing can produce a ten-fold increase in sediment yield. Sediment concentrations of up to 4000 mg/l as compared to peak suspended sediment concentrations of only about 180 mg/l under natural rainforests have been recorded by Gilmour *et al* (1982). Equally spectacular are increases in sediment yield in areas under agriculture. For example, Pringle (1986) quotes from the Innisfail area where after 2260 mm of rain between 1 and 14 January 1981, estimated erosion losses ranged from 10 tonnes/hectare on areas protected by plant residues to over 500 tonnes/hectare on bare cultivated fields on basalt with slopes up to 20% (see Pringle, 1986, for further examples and reviews of sediment yield).

Quite clearly, the data available from the mid 1960s for north Queensland catchments, indicate that in environmental conditions such as found in the Cape Tribulation coastal catchments, major disturbance of the rainforest can produce increases in sediment yield of 1-2 orders of magnitude. As indicated by O'Loughlin (1985), an increase in sediment output is an inevitable consequence of poorly located roads or careless construction and inadequate maintenance. This was illustrated by Hamilton (1983) working in tropical peninsular Malaysia. He indicated that sediment supply to streams close to road sources is an order of magnitude larger than from undisturbed catchments. Most importantly, he found that the amount of sediment produced during construction periods was many times that produced later, as frequently during construction soil was bulldozed directly into streams. Similar conclusions were drawn by O'Loughlin (1985) as indicated in Figure 1.

Accelerated erosion from roads in rainforest catchments is due to:

- Removal or reduction of the protective vegetation cover
- Destruction or impairment of natural soil structure and fertility
- Increased slope gradients caused by construction of cut and fill slopes
- Decreased infiltration rates on parts of the road due to compaction
- Interception of the subsurface flow by the road cut slope
- Decreased sheer stress, increased sheer stress or both on cut and fill slopes
- Concentration of generated and intercepted water, resurrected groundwater and storm flow which may overload natural channels and initiate a cycle of bank cutting

(Bullard, 1966; Megahan, 1977; Sim, 1984).

In larger catchments, much of this sediment may be deposited in temporary or permanent storages along the stream length. However, in short steep coastal catchments such as those found in the Cape Tribulation area, a very high percentage of material eroded can be expected to enter the marine environment.

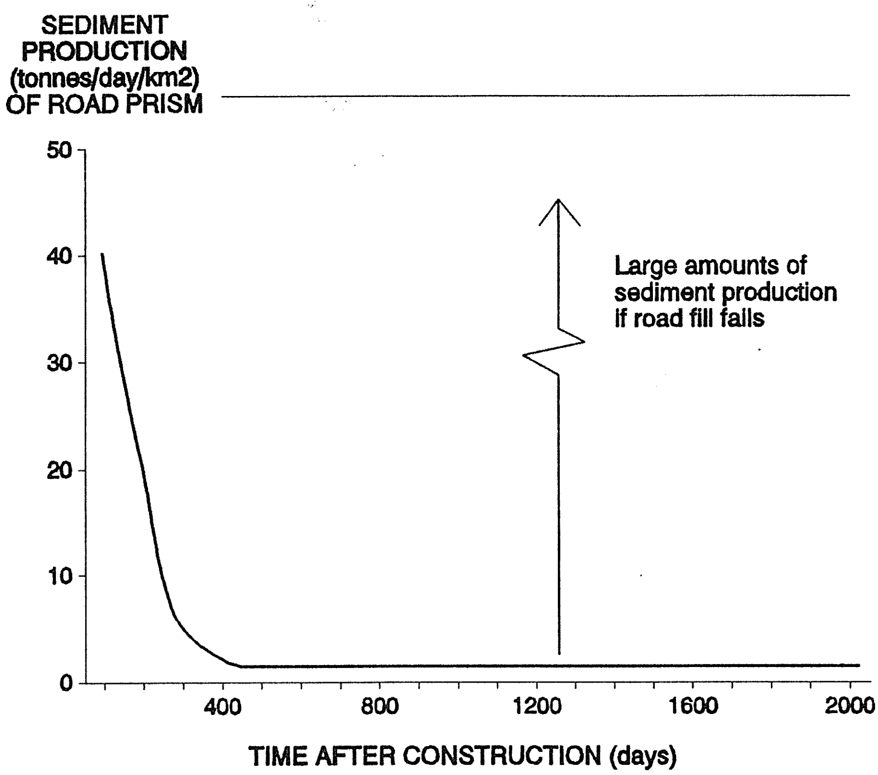

FIGURE 1. Response of rainforest catchments to road construction after O'Loughlin (1985).

4. THE CAPE TRIBULATION AREA

Location (Figure 2)

Situated in the wet tropics of far north Queensland, the area under study comprises an 18 km stretch of coastline (15°56'30" - 16°06'10") extending from Myall Creek to 3 km south of the Bloomfield River. The close proximity of the coastal ranges, the dense cover of tropical rainforest, and the nearshore fringing reefs, combine to make this a beautiful and unique section of the Australian coastline.

Climate and Hydrology

The climate of the area is dominated by two large scale features of the atmospheric circulation, the intertropical convergence zone (ITCZ) and the south Pacific convergence zone (SPCZ). During most of the year, the region is dominated by south-east trades. During summer the ITCZ shifts into the Southern Hemisphere causing the movement of the north-west monsoon into the region (Downey, 1983). This monsoon causes the trades to take a more easterly component, with north-west winds prevailing from January to March and associated increased rainfall (Pickard, 1983). Local coastal and sea breeze effects cause local variations in these wind patterns (Downey, 1983).

Tropical cyclones occur in the Western Coral Sea from November to May with 75% of occurrences in January or February. Generally two cyclones make landfall on the Australian coast per year. Statistics show the maximum frequency of landfall to be in the Cairns region (Downey, 1983). These cyclones may cause extensive (sometimes complete) vertical mixing of water over the shelf region (Holloway, 1983). The Cape Tribulation area has a total average annual rainfall in excess of 3750 mm/yr, one of the highest annual rainfall totals in Australia. A large proportion of this falls from January to March.

Experimental work by Gilmour and Bonell (1979) in a drainage basin near Babinda with similar annual rainfall has shown that in this situation overland flow or storm quickflow is very important because the intensity of the rainfall exceeds the infiltration capacity of the soil. Also

> *"The effect of more frequent heavier downpours is that the kinetic energy of the rain falling at intensities greater than 25 mm/hr ... is about 16 times greater than that of temperate rainfall"* (Gilmour and Bonell, 1979, p 2)

This, together with an increase in drop size means that tropical storms have greater erosion potential. A close agreement between the overland flow graph and the stream hydrograph for Babinda is evidence that in steep catchments with high annual rainfall most overland flow reaches the streams. In the Daintree catchment (910 km^2) just to the south where rainfall totals are between 1250 mm and 2500 mm, mean annual runoff is as high as 1352 mm (Pringle, 1986). It may be expected that runoff for Cape Tribulation will be even higher.

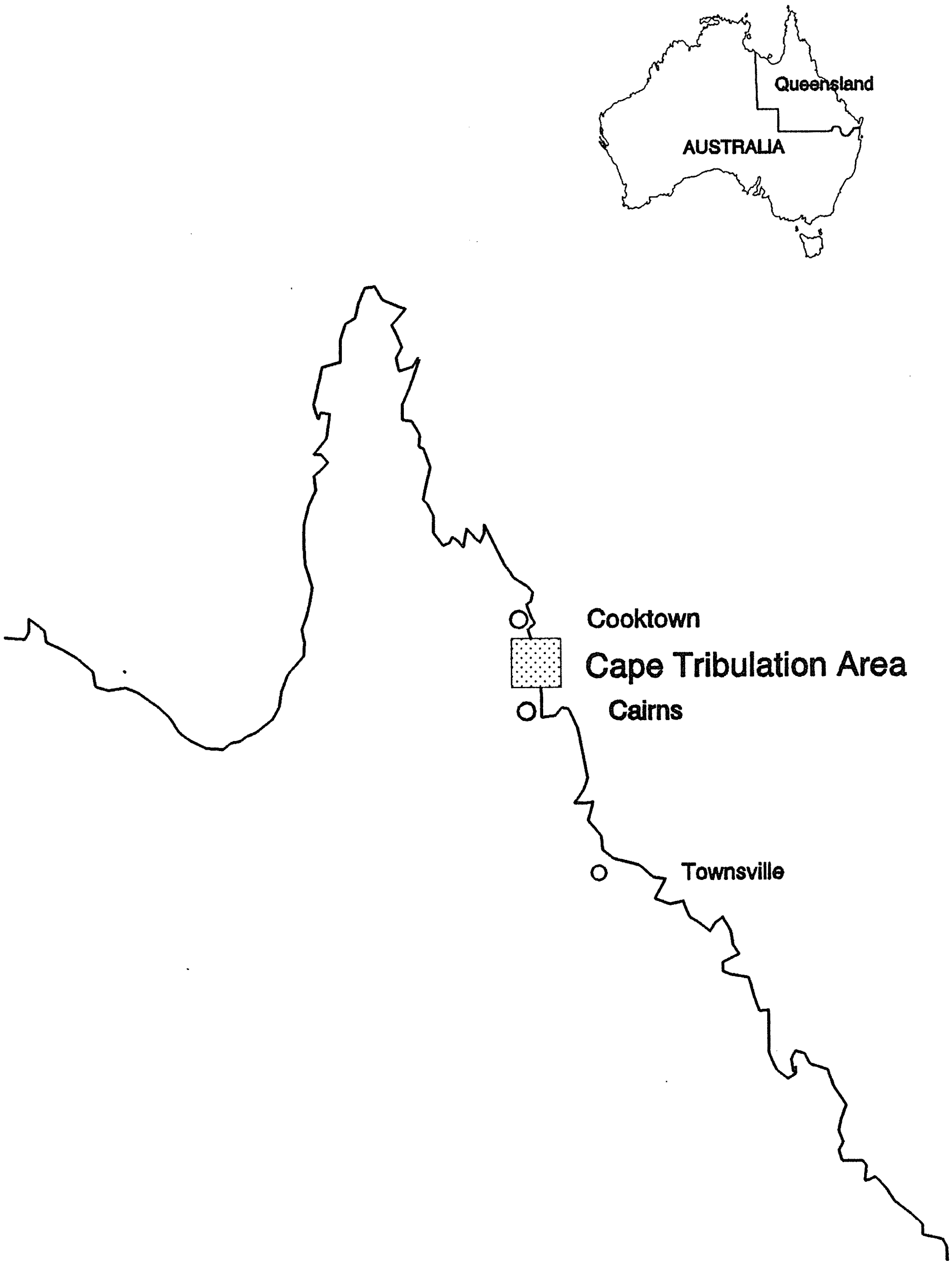

FIGURE 2. Location of the study area

Rainforest

The area is covered with many rainforest types and contains some of the last vestiges of humid tropical lowland rainforest in Australia. The most diverse is complex mesophyll vine forest considered to be the optimum development of rainforest in Australia (Monteith, 1985; Tracey, 1982). The preservation of this lowland rainforest is particularly imporant since *"few areas have escaped sugar cane cultivation and grazing, and practically all the remaining areas have been logged"* (Tracey, 1982, p 4). The forest on the coastal ranges is altitudinally zoned allowing the development of many different forest types in a relatively small area.

Geology and Geomorphology of the Terrestrial Environment

The coastal ranges in the study area are composed of a Permian muscovite biotite adamellite, of the Thornton Batholith. These rocks have intruded deformed Devonian sediments, the Hodgkinson formation, made up of greywacke, siltstones, shales, greywacke conglomerates and rare limestones. A thermal metamorphic aureole surrounds the intrusives (Henderson and Stephenson, 1981). Spillitic lavas of submarine origin occur to the south and south-east of the batholith. The granites are generally composed of quartz and perthite with minor oligoclase, andesine and biotite. The greywackes contain quartz plagioclase and muscovite (Ewart, 1985).

The dominant soil types in the area are red podzolic soils typical of high rainfall areas. They are strongly leached and highly acidic pH 4.5-5.5 (Date and Ross, 1985). The metamorphics are generally covered with fine sandy clay loams, *"structured earths with bleached A2 horizon and red moderately structured subsoils"* (Date and Ross, 1985, p 6). Over the granite, soils are dominated by moderately textured yellow earths, they have a gradational texture profile, yellowish sandy loam with a massive earthy fabric. X-ray diffraction analysis of soils in the study area shows them to be rich in amorphous oxides and oxyhydroxides of iron and aluminia (approx 20%) with clays being kaolinite (approx 30%), illite/mica (approx 10%) and smectite/hydromica (approx 10%). This predominance of kaolinite is expected in a strongly leached soil. Soils in the area are particularly susceptible to erosion and this is accentuated by the steep terrain and high rainfall.

The ranges adjacent to the study area rise in places to 600 m within 3 km of the coast. These steep ranges lead to compact drainage systems with the largest catchments only 15 km^2 in area, and headwaters only 3-4 km from the mouth. This combined with the high rainfall and dominance of overland flow produces rapid current velocities. Streams become raging torrents within minutes of rain falling in their catchments. An interesting feature of a number of the larger streams is the discovery of discrete freshwater layers above the saltwater up to 1 km offshore. This phenomenon may be explained by high current velocities at the mouths of streams. These high velocities also cause the deposition of rocky bars at the mouths of some streams, and almost all streams have a deposit of cobbles at their mouth, often colonised by mangrove communities. Because of the compact nature of the streams mangroves only extend a few hundred metres along them and the environments are often high in energy and flushed of any finer sediments.

Fringing Reefs: Surface Morphology (Figure 3)

Fringing reefs on average 80 m in width, extend intermittently along the entire length of the study area. They occur in two types of location:

- As very narrow fringing reefs attached to exposed rocky headlands
- As broader cuspate shaped reefs occurring along the beaches and steeper coastline between the main headlands.

Frequently, these cuspate reefs are found in front of embayments associated with stream estuaries and are immediately backed by beach ridges formed predominantly of fine grained quartz sands. Partain and Hopley (1989) have identified five intertidal and subtidal zones on these reefs consisting of:

i) *Terrigenous cobble facies.* Cobble sized clasts consisting of well-sorted 20-40 cm diameter igneous and metamorphic cobbles are most commonly found the in the vicinity of stream mouths. They form irregular deposits and grade laterally into other longshore beach features. Individual cobble deposits adjacent to and in front of stream mouths are sometimes fan shaped.

ii) *Beach and tidal flat facies.* The beaches and tidal flats are composed predominantly of fine grained, well sorted, quartz and calcium carbonate sand. Biogenic components include sponge spicules, foraminifera, coral fragments and shell fragments. The calcium carbonate component of the beach sediment increased with proximity to the reef.

iii) *Back reef facies.* The back reef facies is found behind all the larger fringing reefs in the Cape Tribulation area. Surface elevations range from 0.15 m below to 0.5 m above Cairns Port Datum. Live corals are sparse or non-existent in this back reef area. However, the most common characteristic is a zone of dead microatolls very similar to present living microatolls. Their surface is often covered by crustose coralline algae, and towards the beach the older microatolls are buried in moderately well-sorted tidal flat sands. Deeper back reef pools contain loose coral rubble and brown algae such as *Sargassum* sp proliferate. The more landward side of the back reef facies is frequently covered by terrigenous sand and the more seaward side by calcareous rubble.

iv) *Reef crest facies.* The outer reef crest forms a ridge elevated approximately 0.5 m above the adjacent back reef and ranges from 0.7 to 1.4 m above Cairns Port Datum. On the extreme seaward margin, algae such as *Laurencia* sp and *Gelidiella acerosa* are found. Encrusting algae such as *Porolithon* are also present. In many places, the front of the reef crest is dissected by a rudimentary spur and groove system. Within the grooves, typically 1-10 m in width, and 2-20 m in length, small colonies of living corals are often found.

v) *Reef front living coral facies.* A steep drop-off in front of each reef extends to a depth of 2 m below Cairns Port Datum. Below this deep drop-off a more gentle seaward slope begins. Living coral communities flourish in a 30-100 m wide strip parallel to the reef just below the fore reef drop off. Large *Porites* species and *Faviid* colonies exceeding 4 m in diameter as well as *Acroporid* communities are found here.

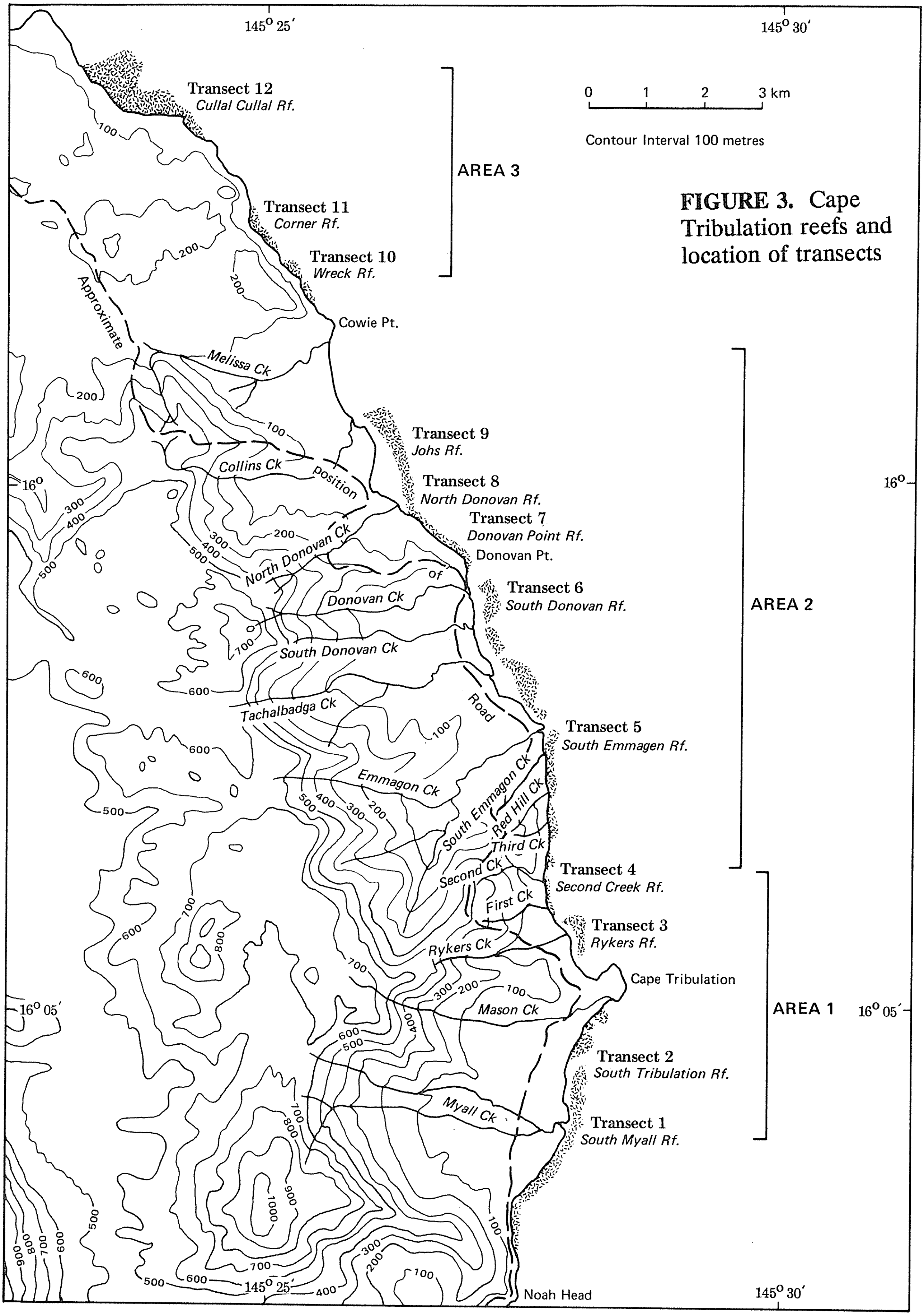

FIGURE 3. Cape Tribulation reefs and location of transects

Fringing Reefs: Evolution

Partain and Hopley (1989) report on the drilling and dating of three of the Cape Tribulation reefs:

- Rykers Reef
- South Myall Reef
- Emmagen Reef.

They conclude that the Cape Tribulation reefs are Holocene in age and began developing approximately 7800 yrs BP. Coral growth on the reef crest and most of the back reef ceased approximately 5400 yrs BP, probably in response to increasing turbidity and water quality deterioration as fine sediments accumulated offshore and became resuspended during strong winds. Significant coral growth is now restricted to the subtidal fore reef, but reef progradation has been minimal over the last 5000 years.

The height of the reef crests relative to present day sea level, and the absence of low magnesium calcite cements in the fringing reefs, suggest that they have not been subjected to extensive subaerial exposure, with a maximum Holocene relative sea level of only 0.6-1.0 m above its present position being responsible for the height of the present algal covered reef crest. Partain and Hopley (1989) suggest that the reefs appear to be in a delicate state of balance having grown under environmental conditions more favourable than present. Further deterioration of the environment produced by anthropogenic factors such as increased sediment yield from the Cape Tribulation road they suggest have the potential to push water quality conditions beyond the point where reef growth can be maintained.

Fringing Reef Communities

The fringing reefs of the Cape Tribulation area contain some of the most diverse coral communities on the Great Barrier Reef. Veron counted 147 different species of coral from 55 genera, out of the 72 genera found on the Great Barrier Reef. He considers these reefs to be the most diverse, extensive fringing reefs of Eastern Australia (Veron, 1985). This conclusion may be misleading, since although the number of species in the area is great, the dominant coral community is restricted to a small number of species of foliose morphology. The foliose habit gives colonies a large surface area and is most useful in low light conditions. It may be related to high turbidity in this area but it is a hindrance in sediment rejection. Some corals were observed to contain small amounts of coarse sediment but remain vigorous. This may imply that light is controlling coral growth rather than sedimentation. If sedimentation were the controlling factor, branching and hemispherical forms would be expected. Ayling and Ayling (1987) report 70% coral cover below 5 m depth compared to 30-50% on offshore reefs. However, the biotic zone is markedly compacted at Cape Tribulation with all communities being restricted to <10 m LWD. The corals which grow in the area are considered to be silt tolerant as they must normally cope with a high silt content and severely reduced light penetration for long periods when south-easterlies are blowing. Most of the corals are dark brown in colour (Ayling and Ayling, 1987). Light absoprtion may be maximised by an increase in the actively photosynthesising endo-symbiotic zooxanthellae *Gymnodinium microadriaticum*. An increase in these unicellular algae will maintain sufficient metabolism in low light conditions. Many of the species listed for the area are found in diverse communities on the bommies. These bommies rise almost vertically for many metres, and may be up to 3 m across; they are normally about 2 m below the surface on a high tide.

Nearshore Environment

Apart from a short stretch of coastline off Cape Tribulation, the inner shelf adjacent to the study area is shallow. The 10 m isobath is always less than 1000 m offshore from the seaward edge of the outer exposed reef flat. Vibracores collected by the James Cook University Geology Department in a transect immediately north of Donovan Point reveal that approximately 1 km offshore mud values in the surface sediment are as high as 60% (Johnson and Carter, 1987). Consequently, an abundant supply of fine sediment is available for resuspension above the fairweather wave base. Tides at Cape Tribulation are semi-diurnal with a maximum range of 3.02 m. Tidal levels are MHWS 2.2 m, MLWS 0.5 m, MHWN 1.6 m and MLWS 0.5 m (Department of Harbours and Marine Qld, 1985). The currents in the Great Barrier Reef have a mean net flow to the north or north-west at 0.5-1.0 knot driven by the south-easterly tradewinds. In the central zone (where the study area is situated) there is a reversal to a net southward flow from October to December (Pickard, 1983). Seas are generally smooth under the monsoonal influence from January to March with light winds. However for most of the year the seas are moderate due to the consistent 10-20 knot south-easterly trades.

In the nearshore area, Parnell (see appendix) has suggested that wind and wave generated circulation dominates but is modified by local morphology. As offshore surficial sediments contain a high proportion of muds, resuspension of these sediments occurs under modal wind and wave conditions. River derived sediments may add to offshore suspended sediment concentrations during extreme weather events, but are only significant in the near vicinity of the stream mouths, with sedimentation likely only in zones of very low velocity. Parnell considered that Cape Tribulation reefs are likely to have developed in conditions of high turbidity and high suspended sediment concentrations.

Settlement and Land Use

A number of aboriginal tribes originally populated the area, their main camps being on the Bloomfield and Daintree Rivers. However, their nomadic lifestyle probably had little effect on erosion rates in the area. Erosion rates may not have increased until cedar cutters arrived in 1880. The area was then left relatively uninhabited until 1928 when clearing began on the banks of Myall Creek and in the valley between Cape Tribulation and Noah Head. This cleared land has been used to grow vegetables and raise beef cattle after timber was cut from it. From 1955 to 1963 a road was constructed from the Daintree River to Cape Tribulation. Tourists first began to visit the area about 1975 and their numbers have increased significantly since then. During the 1970s there was much public pressure for a National Park in the area. This combined with the impetus of the World Wilderness Conference in Cairns in 1981 persuaded the government to act. The Cape Tribulation National Park was gazetted in October 1981. In 1968 a track was bulldozed from Cape Tribulation to the Bloomfield River. This track soon became overgrown but sufficed as a walking track and gave good access to the wilderness area. In 1983 bulldozing began again on this track to form the road from Cape Tribulation to Bloomfield.

5. THE MEASUREMENT OF TURBIDITY AND SILTATION RATES IN THE NEARSHORE ENVIRONMENT

Two parameters are important for coral reefs under siltation stress:

- The amount of sediment suspended in the water column (turbidity)
- The amount of sediment settling on the reef.

Measurement of both has problems. Turbidity or water density is dependent not only on the suspended sediment but also on the amount of organic matter in the water column particularly phytoplankton chlorophyll and to a lesser extent on the exact chemistry of the seawater. The two are not independent. Walker (1981) has shown that in relatively shallow regions of the lagoon of the Central Great Barrier Reef, phytoplankton chlorophyll *a* concentrations are dependent on intermittent resuspension of bottom sediments by wind generated waves. This results in a strong inverse correlation between chlorophyll *a* levels and transparency.

Settlement of sediment is particularly difficult to measure as most collecting devices interfere with the micro hydrodynamics and bias results. Further, sediment traps give *gross* figures as in most instances sediment once settled in the trap does not get a chance to re-entrain. Net figures for the natural surface are the results of a total of settlement minus the re-entrained sediment.

Measurement of Turbidity

Use of Optical Instrumentation

A number of instruments are available to measure the attenuation of a light beam between source and a photo-electric cell receiver usually placed up to 1 m away (Alphameter). Such turbidity meters have been deployed in a number of situations and measure percentage attenuation of the light beam after standardising for 100% transparency in clear water. Use of filters can provide information on sediment size. Results incorporate the effects of interception by both organic and inorganic particles.

In the reefal environment, little use of this instrumentation has been made apart from Hopley (1978, 1982a, b) who used it to determine the temporal pattern of sediment movement around coral cays. Walker (unpublished) has produced a calibration curve for a beam attenuation meter which allows suspended particulate matter to be estimated from the beam attenuation coefficient. However, available data from Alphameters in reefal environments is limited.

Secchi Disc Measurements

The most commonly used method for measuring turbidity has been with a Secchi disc, usually a matt-white 37 cm diameter disc which is lowered into the water and the depth at which it disappears from sight of an observer 1.0 to 1.5 m above the sea surface recorded. Frequently the Secchi disc measurement is converted into a light attenuation coefficient though published conversion formulae appear to be environment specific (for discussion relative to Cleveland Bay, see Walker, 1982). A relationship between the quanta attenuation coefficient and the Secchi disc depth was established by Walker. Walker's unpublished work is also of value as he also calibrated beam attenuation meter measurements and the reciprocal of the Secchi disc depth measured in the middle of Cleveland Bay.

Suspended Sediment Concentrations

Collection of water samples can be made in a number of ways (Nansen bottles, syphons) from homogeneous strata within the water column. Suspended matter is then extracted through filtration, weighed and converted into standard figures, usually milligrams per litre (mg/l). However, the literature also reports concentrations in parts per million (ppm) although there is some ambiguity on these figures and most seem not to take into account the density of the sediments vs water and figures are interchangeable as mg/l.

Measurement of Sediment Settlement

Important research on sediment traps was performed by Gardner (1980a, b) in his laboratory calibration and evaluation of sediment trap dynamics. Through flume experiments using fluorescent dyes Gardner (1980a, b) found that particles are collected by a process of fluid exchange rather than falling freely into a trap. He concluded that the efficiency of the trap is a function of residence time and circulation pattern within the trap. This is controlled by trap geometry and current velocity. Gardner (1980 a, b) considered symmetric traps to be the most efficient since in multidirectional currents they have the same properties in all directions. Rather than falling directly into the trap most of the vertical sediment flux follows fluid path lines and is carried into the traps by turbulent eddies from the trap geometry. Gardner (1980a, b) considered height to width ratio as the controlling factor in the mass of sediment collected by a cylindrical trap, the most efficient trap having a height/width ratio of 3:1. A trap of this shape will best approximate the vertical flux of sediment. If higher than this, the trap will tend to "overcollect" sediment and vice versa. Traps with a higher ratio tend to skew towards a relative increase in the finer (less than 63 μm) sediment fractions. The height of the trap above the substrate has also been reported to influence depositional rates. Height was demonstrated to be inversely related to sediment deposition rates, where a high rate of sedimentation near the substrate logarithmically declines with height (Hakanson *et al*, 1989).

Gardner (1980a) also considered sediment trap efficiency to depend on the concentration of suspended particles, and the size and density of particles as well as the trap geometry and current velocities. Little work has been carried out in currents with velocities >20 cm/s. However, a personal communication to Gardner by Von Brokel states that in currents of velocities >50 cm/s a vortex action may lift particles up and out of the trap. Gardner (1977) found that sediment in water samples collected near traps is often different from the trap sediment. He attributes this to the fact that traps are collecting larger falling particles and not just an equivalent mass of suspended particles. These velocity dependent regimes were examined by Staresinic *et al* (1978) using tracer dyes. Turbulent wakes developed over traps. Although, during extreme weather conditions, these current velocities are possible, they have not been recorded as yet in the Cape Tribulation area.[1] Gardner makes the point that sediment traps often only vaguely approximate the amount and type of sediment that is actually deposited on the sea floor. In high energy conditions resuspension is a problem since this may be many times greater than the deposition of new particles. Gardner (1980b, p 43) states *"the flux of new particles to the sediment surface is not necessarily equal to the net sedimentation rate of the region or the accumulation rate"*. Net sedimentation may include sediment resuspended elsewhere and carried horizontally. The accumulation rate is the net sedimentation rate minus the effects of dissolution and biodegradation and is best measured from sediment cores (Gardner, 1980b). However, this is not always possible in short term monitoring studies unless the net sedimentation rates are especially high.

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1 This may pose a problem with the sediment traps within the surf zone, which often contain less sediment than may be expected. These resuspension processes however would act in a similar manner on the biological communities.

As traps are artificial devices which portray specific fluvial properties in accordance with their shape, angle and size, the depositional characteristics are independent of the amount of suspended sediment available. It seems, therefore, that sedimentation rates calculated from sediment traps may be used for comparative purposes between areas, however a direct application inferring actual sediment rates onto coral communities must be treated with caution.

In situ micro-hydrodynamic processes and the affect of coral morphology on sediment rejection processes have not as yet been reported. Hubbard and Pocock (1972) examined adult colonies and undertook experiments to observe the various quantities and qualities of sedimentation. They found that silt was most effectively removed by all species examined. A large part of the study was undertaken in aquaria where currents and wave action were lacking. The micro-scale hydrodynamics in and around coral colonies have rarely been examined. The onset of micro-eddies and fluvial turbulence may vary sediment rejection potential, where neighbouring colonies may experience completely different micro-environments unlike aquaria situations.

6. METHODOLOGY

Selection of Sampling Sites

The area chosen for sampling broadly extends from Noah Head in the south to the Bloomfield River in the north, a distance of approximately 25 km. For the purposes of this study this length of coastline subdivides into three distinct areas:

i) *Area 1 (Figure 4), the Old Road section.* The southern area from Noah Head to just north of Cape Tribulation at Rykers Reef. This is the area within which a road has been providing access for at least twelve years prior to the commencement of this study. It was anticipated that incorporation of this area into the study would give an indication of the long term effects of disturbing a rainforest catchment through the development of a road on the sediment influx and movement within the marine environment.

ii) *Area 2 (Figures 5, 6), the New Road section.* From north of Rykers Reef to Cowie Point. This middle section of the study site covers part of the area within which the road was constructed, generally referred to as the "New Road". Considerable earthworks have been undertaken on the road since its development in 1981. Generally, the road is within 1 km of the coastline, often within 100 m. There are extensive fringing reefs along this section.

iii) *Area 3 (Figure 7), the Northern Control section.* The northern area from Cowie Point to Cullal Cullal Creek. The northern section of the study site is devoid of roads and has undergone little anthropogenic alteration. The area acts as a control site and enables comparisons to be made between the three areas. North of Cowie Point the New Road passes inland and creeks crossing it drain away from the coast, towards the Bloomfield.

Field Methods

The field study comprised two parts: the collection of water samples from creeks within the area and at times from inshore areas and the establishment of sediment traps along selected transects.

FIGURE 4. The southern old road section showing Tribulation, South Tribulation and Myall Reefs

FIGURE 5. The central new road section, Emmagen Reef to Cape Tribulation

FIGURE 6. The central new road section in February 1985 shortly after heavy rain

FIGURE 7. The northern control area, Corner Creek transect

Water Sampling

Streams sampled in Area 1 (Old Road) included: (1) Myall, (2) Mason and (3) Rykers Creeks.

Streams sampled in area 2 (New Road) included (4) First, (5) Second, (6) Third, (7) Red Hill, (8) South Emmagen, (9) Emmagen, (10) Tachalbadga, (11) South Donovan, (12) Donovan, (13) North Donovan, (14) Collins and (15) Melissa Creeks.

Inaccessibility prevented sampling of any streams in the Northern Control area. However, control was provided in the streams investigated by taking samples above any disturbance. Initially, rising stage samplers were deployed in streams to collect samples at different rates of stream discharge. These devices consisted of one litre plastic bottles attached to a steel picket at 0.5 m intervals. However, rapid stream velocities and large amounts of debris (logs) from the rainforest caused these to be detached with the onset of the first substantial rainfall. This method was subsequently discarded and replaced with a hand sampling programme. Samples were collected mid-stream in one litre bottles. Samples in March 1985 had been collected in 60 cc sampling jars, five upstream of the road and five downstream, as reported in Bonham (1985) and Hopley (1985). Samples upstream of the road were collected approximately 10 m horizontally above any roadworks and were unaffected by any artificially produced sediment entering the stream. Downstream samples were collected where the suspended sediment concentration appeared to become homogeneous, usually within 50 m of the road.

Sediment Traps

The threefold division was also used in the sediment trap study. However, for the purposes of measuring sediment settlement over the reef each area was further divided into a number of transects set from the shoreline to the outer reef front. Twelve transects were established (Figure 3). Dumpy levels on the reef flat and depth sounders used in the subtidal region determined the vertical profile of the transects. Accumulation of sediment at these transects was examined with the aid of sediment traps. Traps were placed in such a manner that the entire range of environmental conditions were examined, from nearshore to the living reef down the reef front at 3-5 m below LWD.

The traps were considered to be located in one of three zones for convenient statistical analysis:

i) *Inner reef flat*, comprising the terrigenous cobble facies, beach and tidal flat facies and back reef facies, ie dominated by depositional materials of a range of sizes (Figure 8).

ii) *Reef crest*, comprising the reef crest facies, dominated by algae (Figure 9).

iii) *Reef front*, comprising the reef front living coral facies (Figures 10 and 11).

Transect sites (Figure 12) were as follows:

FIGURE 8. Sediment dominated back reef zone, Myall Reef

FIGURE 9. Algal dominated reef crest and narrow inner reef zone, south of Emmagen Creek

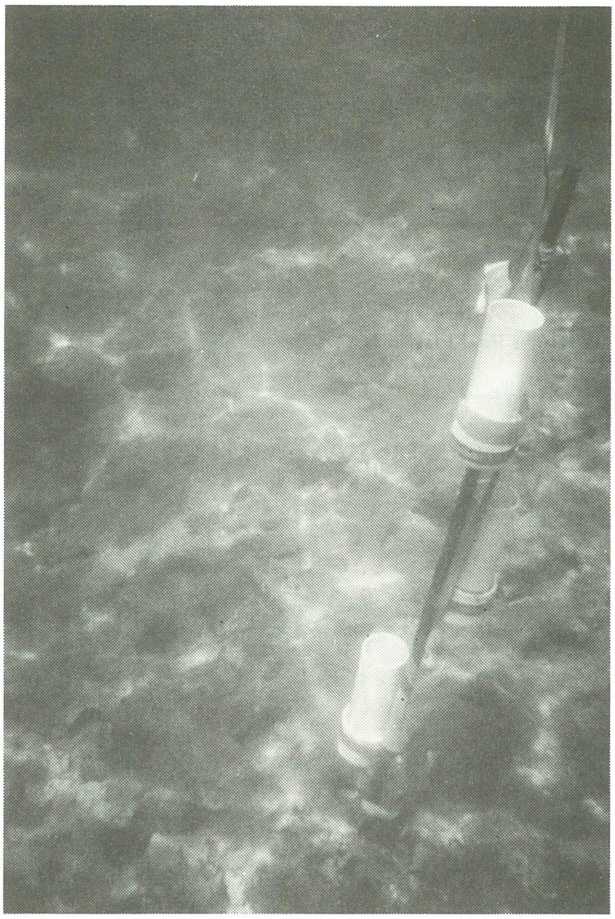

FIGURE 10. Sediment traps located on the reef front, Rykers Reef

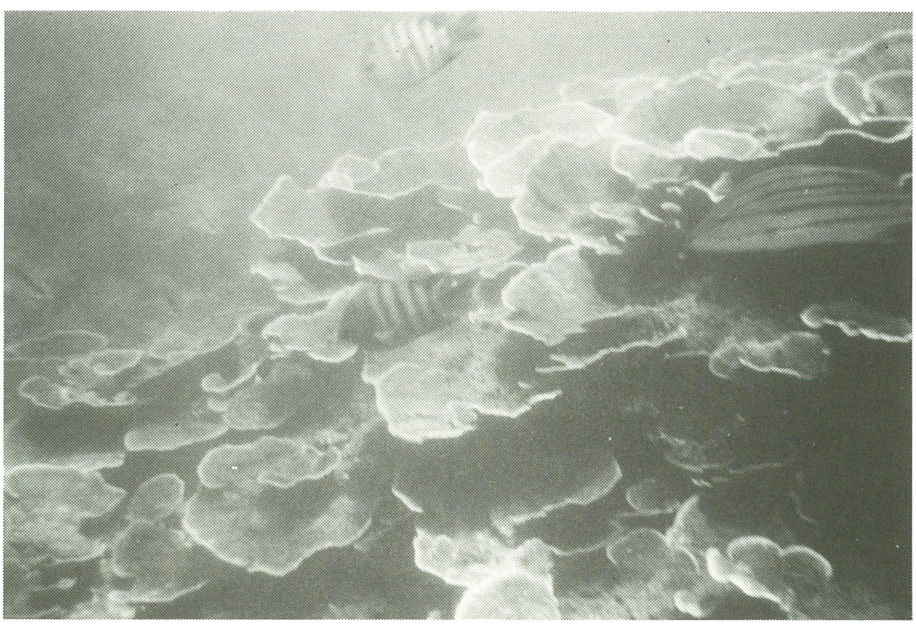

FIGURE 11. Typical foliose *Montipora* sp, potentially sediment collectors, but adapted to low light intensities

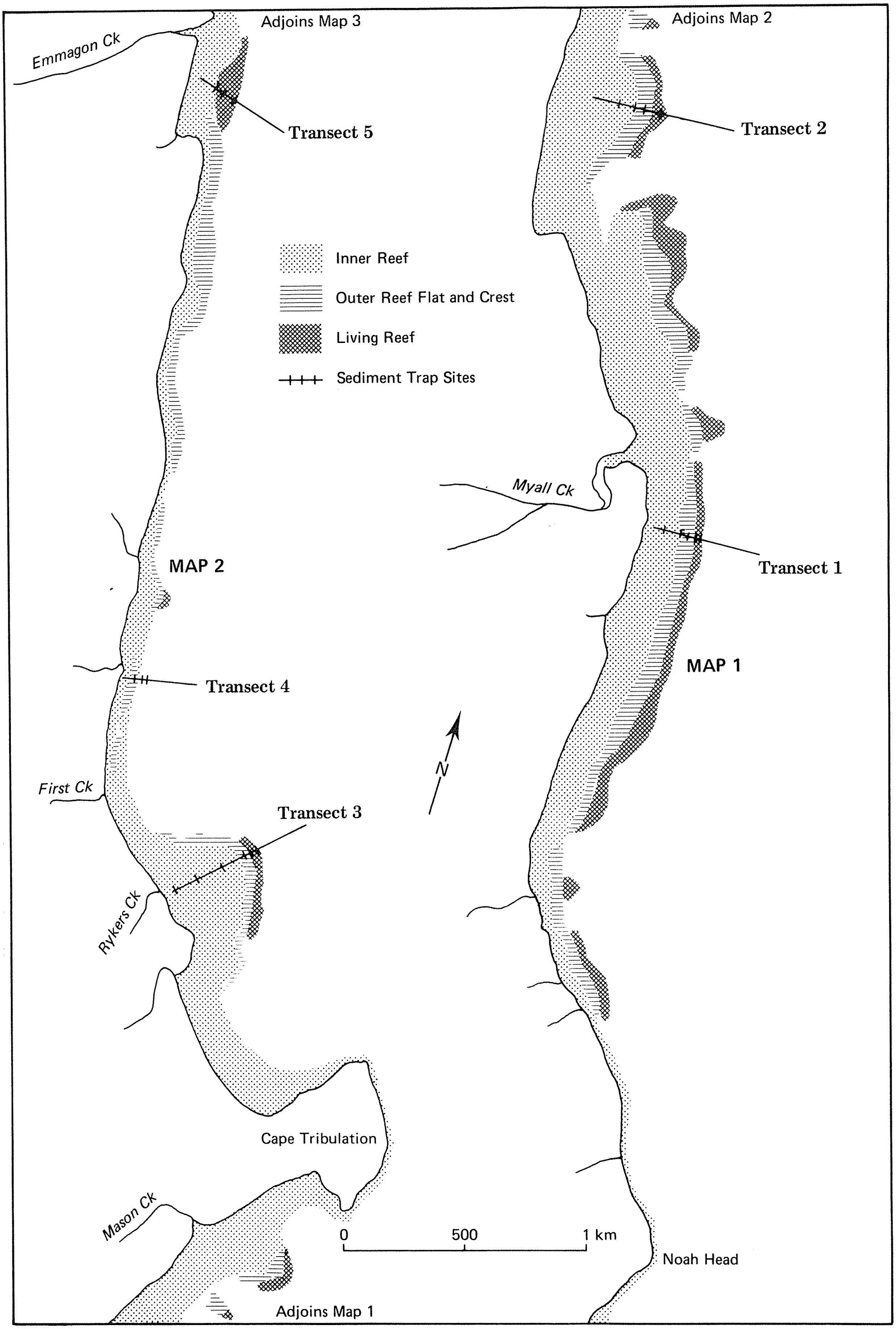

FIGURE 12. Reef transects, trap sites and morphological zones

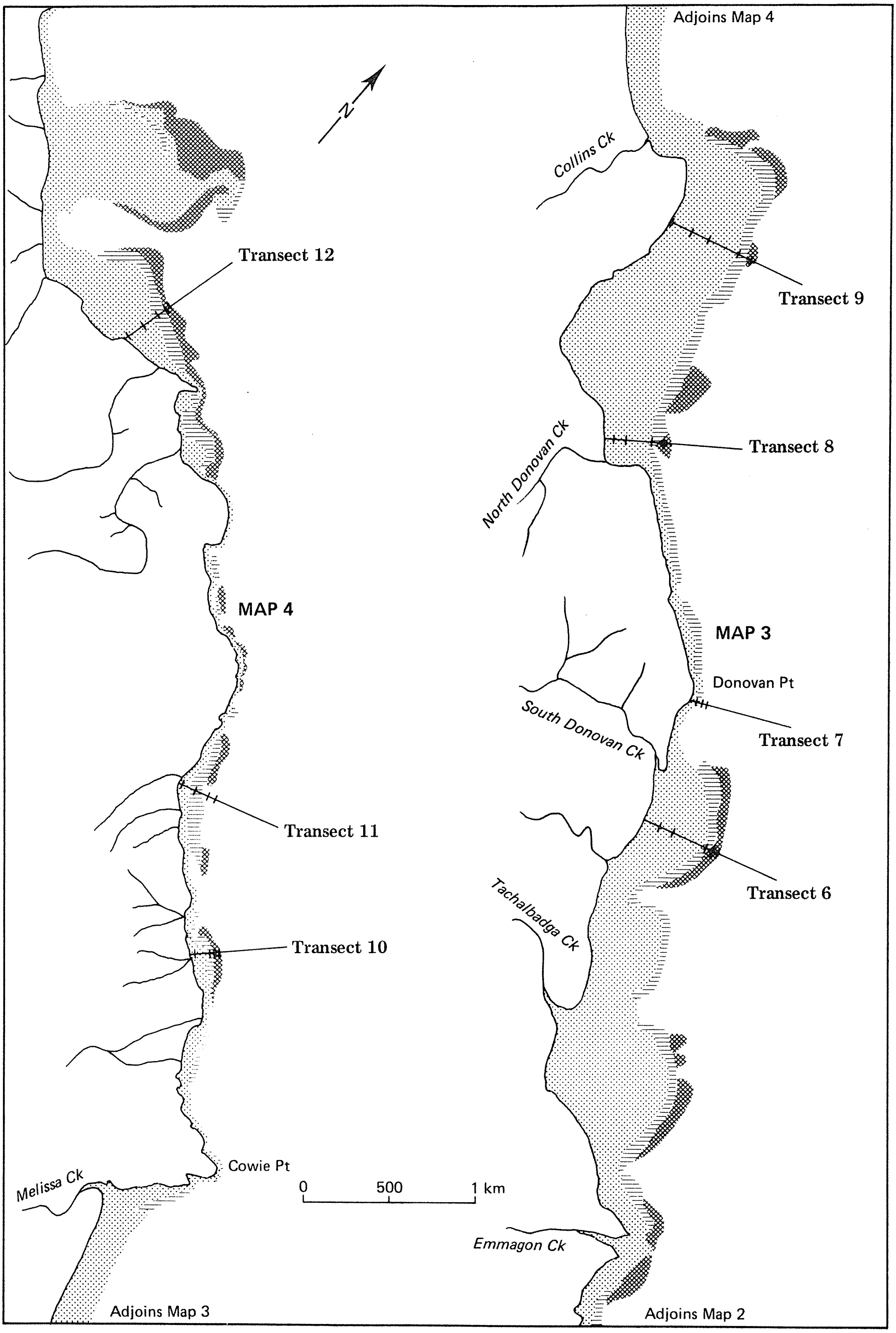

FIGURE 12. Continued.

Area 1 (Old Road)

1 *South Myall.* This area is located a few hundred metres to the north of Myall Creek, the largest creek in Area 1. The transect crosses a 300 m stretch of coral rubble, microatolls, outer exposed reef flat and living reef.

2 *South Tribulation.* This transect crosses a 320 m intertidal and subtidal section north of Myall Creek and south of Cape Tribulation. Zones are coral rubble, outer exposed reef flat and living reef.

3 *Rykers Reef.* North of Cape Tribulation and protected from the south easterly winds, this is the widest transect in Area 1 (350 m). This transect is more morphologically complex than the other two sites comprising cobble stones and mangroves, coral rubble, outer exposed reef flat and living reef.

Area 2 (New Road)

4 *Second Creek.* This short (70 m) transect is situated adjacent to the steep range where mud loaded water has been observed discharging directly into the marine environment. No living reef is found in the vicinity of this site. The zones are outer exposed reef flat and sand.[1]

5 *South Emmagen.* This comprised a 150 m transect situated across the bay, 100 m south of Emmagen Creek. Living coral is prolific within this area.

6 *South Donovan.* This location was chosen for its proximity to Donovan Creek which runs directly off the steep Donovan Point section of the New Road. Waters containing high suspended particulate material was reported by Bonham (1985). The transect is 300 m long and covers sand flat, coral rubble, outer exposed reef flat and living reef.

7 *Donovan Point.* This transect is 100 m long crossing the outer exposed reef and living reef. However, due to the prevailing conditions and the constant loss of equipment at this site, minimal data was collected here.

8 *North Donovan.* This transect is located in the proximity of North Donovan Creek which runs across the road below Donovan Hill. The transect extends for 300 m and traverses the mangroves, sand flat, outer exposed reef flat and living reef. Large quantities of red silt and clays were observed within the mangroves below the road.

9 *Johs Reef.* This transect encompasses the widest intertidal section of any of the sites in the study. The transect is 450 m long dominated by sand flats. Morphological zones comprise cobbles near the mangroves, sand flat, coral rubble, outer exposed reef flat and living reef.

Area 3 (Northern Control Area)

10 *Wreck Reef.* A narrow reef is located on the rocky coastline adjacent to a steep rainforest catchment. The transect is 80 m long and covers the outer exposed reef flat and living coral reef.

11 *Corner Reef.* Another narrow site within close proximity to one of the largest creeks in Area 3. Sand flats are absent in this area and the reef has developed over a substrate of

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1 Samples were often washed away at these sites.

fluvial cobbles. The transect is 130 m long and morphological zones are cobbles, ancient exposed crest and living coral reef.

12 *Cullal Cullal Reef.* The transect at this site is protected behind a headland at the northern-most extent of the study area. It has a wide intertidal zone. The site extends from fine sand and mangroves though a coral rubble zone to the outer exposed reef flat and living reef.[1]

Sediment Traps

The traps consisted of lengths of PVC tubing capped at one end. Trap dimensions were: length 150 mm, mouth diameter 45 mm, mouth area 1592 mm^2. The traps selected were designed to be left unattended over a number of weeks. During this period it was anticipated the traps would collect a representative sample of the vertical sediment flux from each study site. To yield an indication of the amount of reworked sediment found at different heights above the substrate, each study site contained three sediment traps clamped to a supporting steel bar at intervals of 20, 40 and 60 cm above the substrate. The supporting steel bars were firmly anchored into the existing substrate. The mouth of the traps were angled at 120° to each other to avoid interference of vertical fluxes. The total sampler consisting of one bar and three traps is described as a unit, with 3-6 units erected at each transect. The total number of traps originally set was 150, combined into 50 units. As some traps were consistently washed away, data collected at these sites was limited. The total number of continuously sampled traps is approximately one hundred.

Prior to collection 5 ml of 0.001 sodium azide solution was added to each 500 ml plastic bottle in order to kill all organisms and prevent further biological action. Traps from the intertidal flats were unclamped, covered with a cap, shaken and the contents transferred to numbered 500 ml bottles. Traps from deeper water were collected using SCUBA. Wind data was derived from the Brisbane Bureau of Meteorology for Low Isles, 35 km to the south. Rainfall data was collected on a daily basis by three independent local residents.

Although a considerable data bank was collected from the sediment traps a number of problems were encountered:

- Traps, placed in the high energy zones, were constantly washed away.
- High current velocities created turbulent eddies which washed out sediment in reef crest environments (pers obs).
- Since the traps were sometimes left unattended for a number of months, bioturbation caused by worms and hermit crabs which were frequently found in the traps.
- Epilithic algae were often found in the openings of sediment traps. The effect of the algae will vary according to biomass, where it may initially baffle sediment and so lead to an over-estimation of the vertical sediment flux, however prolific algae may act as a sediment trap.
- Small fish (Gobies), Hermit crabs (Amnurans) and other crabs (Brachyurans) settled within the traps after several days. It was found that fish were territorial and had to be relocated.

Nonetheless, the results reported below are considered to be representative of the sedimentation patterns taking place in the Cape Tribulation area.

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1 Samples were often washed away at these sites.

Laboratory Analysis

Marine derived samples from sediment traps

Each sample was sieved through a 63 µm sieve using a high pressure water jet to separate the <63 µm mud and silt fraction from the >63 µm sand sized fraction. Excess salt water was removed by siphon. The >63 µm sand (and occasionally gravel) fraction left in the sieve was then washed, dried and weighed. The <63 µm fraction was washed through the sieve into one litre plastic bottles. Sediment was then allowed to settle for four days. After settlement, water was siphoned off. The remaining residue was washed through a pre-weighed filter paper into a 250 ml beaker. This was allowed to settle for a further three days. The clear water was again siphoned off and the beaker containing sediment and water placed in an oven to dry at 100°C. After drying the sediment and filter paper were scraped from the beaker and weighed. The mass of the <63 µm fraction was divided by the number of days which the trap was effective and the mouth of the trap was used to obtain an estimate of sedimentation per surface area. The gravel and sand were examined under microscope. The mud fraction was split. One split was dissolved in 10% HCL to determine carbonate content (acid soluble). A number of samples were analysed using X-ray diffraction analysis (XRD) to determine the mineralogy of sediment.

Suspended sediment samples

Samples were filtered using Whatman GFB filter papers, dried and the mass of suspended material determined by weight, expressed in mg/l.

Statistical Analysis

Multi-factorial analysis of variance (ANOVA) was used to test the significance of spatial and temporal factors of variability, considering sand accumulation rates, mud accumulation rates and total sediment accumulation. Assumptions of independence and heterogeneity of variance were assessed using residual analysis. A three-way nested ANOVA (type III sum of squares) was performed treating area and habitat factors as fixed and transects as a random factor. A three factor ANOVA was performed to understand the variation of sediment accumulation over time for areas and zones. Area and zone were treated as fixed factors and time as a random factor. An indication of the extent to which atmospheric variables correlated with sediment accumulation parameters was accomplished by creating a correlation matrix.

7. RESULTS FROM SUSPENDED SEDIMENT SAMPLING

Between March 1985 and May 1989, water samples were collected from the Cape Tribulation area on nine separate occasions under conditions in which rainfall totals for the previous twenty-four hours had ranged from 0 to 324 mm. The results are presented in Table 1.

TABLE 1. Stream samples taken between March 1985 and May 1989.

Creek: Creek sampled
Site: 1 - above road, 2 - below road, 3 - at stream mouth, 4 - over reef
Sediment: Suspended sediment (mg/litre); Magn Incr: magnitude of increase below the road
Cont Coef: Contribution coefficient $\frac{[\text{Below road - Above road}]}{\text{Standard ambient (100 mg/l)}}$

DATE	RAINFALL	CREEK	SITE	SEDIMENT (mg/l)	MAGN INCR	CONT COEF
16/03/1985	324.0 mm	4 (First)	1	260.3		
			2	725.1	2.8	
			3	169.3		4.65
		5 (Second)	1	82.4		
			2	447.8	5.4	3.65
			3	276.1		
			4	534.0		
		6 (Third)	1	229.6		
			2	2 798.4	12.2	
			3	1 570.2		
			4	1 032.3		25.69
		7 (Red Hill)	1	263.7		
			2	2 582.1	9.8	
			3	829.9		23.18
		8 (S Emmagen)	1	193.1		
			2	486.0	2.5	
			3	850.9		2.93
		10 (Tachalbudga)	1	152.1		
			2	436.7	2.9	
			3	1 348.7		2.85
		12 (Donovan)	1	223.7		
			2	3 760.5	16.8	
			3	12 600.1		35.37
		13 (N Donovan)	1	191.3		
			2	19 336.9	101.1	191.46
			3	2 250.2		
		14 (Collins)	1	194.6		
			2	3 334.2	17.1	
			3	2 745.3		31.40
		15 (Melissa)	1	224.0		
			2	10 825.4	48.3	106.01
05/04/1986	118.0 mm	1 (Myall)	1	0.3		
			2	3.6	12	
			3	6.7		0.03
		2 (Masons)	1	192.5		
			2	226.0	1.2	0.34

Continued ...

TABLE 1. Continued

DATE	RAINFALL	CREEK	SITE	SEDIMENT (mg/l)	MAGN INCR	CONT COEF
20/04/1986	6.5 mm	4 (First)	1	0.9		
			2	301.0	334.4	2.92
		5 (Second)	1	2.1		
			2	527.1	251.0	5.25
		6 (Third)	1	0.7		
			2	555.3	793.3	5.55
20/07/1986	6.5 mm	4 (First)	1	0.9		
			2	301.0	334.4	3.00
		5 (Second)	1	0.1		
			2	402.5	4 025.0	4.02
		6 (Third)	1	0.7		
			2	555.3	793.3	5.55
		10 (Tachalbadga)	1	0.3		
			2	19.0	63.3	0.19
		12 (Donovan)	1	1.0		
			2	104.4	104.4	1.03
21/07/1986	12.0 mm	3 (Rykers)	1	0.5		
			2	402.5	805.0	
			3	1.2		4.02
		9 (Emmagen)	1	4.1		
			2	1.2	0.3	None
		10 (Tachalbadga)	1	0.3		
			2	1.9	6.3	0.02
		11 (S Donovan)	1	3.3		
			2	168.4	51.0	1.65
		12 (Donovan)	1	0.1		
			2	104.4	1 044.0	1.04
28/01/1988	2.0 mm	9 (Emmagen)	1	1.1	5.0	0.04
			2	5.5		
		10 (Tachalbadga)	1	14.2	4.4	0.48
			2	61.9		
		13 (N Donovan)	1	4.6	6.5	0.25
			2	29.9		

Continued ...

TABLE 1. Continued

DATE	RAINFALL	CREEK	SITE	SEDIMENT (mg/l)	MAGN INCR	CONT COEF
05/07/1988	No rain	9 (Emmagen)	1	0.3		
			2	3.3	11.0	0.03
		10 (Tachalbadga)	1	12.6		
			2	11.3	0.9	None
		12 (Donovan)	1	0.9		
			2	7.3	8.1	0.06
		13 (N Donovan)	1	5.3		
			2	54.6	10.3	0.49
		15 (Melissa)	1	18.3		
			2	8.3	0.5	None
25/04/89	No rainfall	3 (Rykers)	1	12.5		
			2	11.5	0.9	
			3	18.0		
			4	20.0		None
		4 (First)	1	34.5		
			2	16.5	0.5	
			3	24.4		
			4	70.5		None
		9 (Emmagen)	1	23.0		
			2	19.5	0.8	
			3	14.0		
			4	14.0		None
		10 (Tachalbadga)	1	15.0		
			2	27.2	1.8	0.12
		12 (Donovan)	1	15.0		
			2	18.0	1.2	
			3	12.0		
			4	29.2		0.03
		14 (Collins)	3	29.6		
			4	42.8	1.4	0.13
		15 (Melissa)	1	75.0		
			2	64.0	0.9	None
25/05/89	28.0 mm	2 (Masons)	1	126.3		
			2	158.7	1.3	0.32
		3 (Rykers)	1	13.0		
			2	23.9	1.8	0.10
		4 (First)	1	2.6		
			2	5.6	2.1	0.03
		5 (Second)	1	0.4		
			2	9.0	22.5	0.23
		6 (Third)	1	0.4		
			2	7.8	19.5	0.07

Problems and Limitations

The data set is extremely patchy. Access into the area during any major rainfall event was very difficult. The maximum number of streams sampled in any one collecting period was ten. This was the collection of Bonham on March 16 1985 when access was gained entirely from the sea. During the 1986, 1987, 1988 and 1989 wet seasons, although researchers spent considerable periods of time within the Cape Tribulation area, none coincided with major rainfall events. Travel to Cape Tribulation from Townsville when heavy rainfall was forecast or actually falling proved to be unrewarding as access into the area even with four-wheel drive vehicles was limited or impossible. When the aid of local residents was enlisted, this too proved to have its limitations as only one or two streams were accessible due to the road being cut at low points along its length. Attempts in 1989 to gain access to the road after heavy rainfall by helicopter also provided limited results. Because of flying conditions, access could not be obtained during the heavy rainfall and by the time streams were sampled major flow in the streams had terminated.

As indicated above, any attempt to locate instrumentation within the stream beds met with failure due to the amount of debris coming down the steep catchments of the area. Quantitative estimates of the amount of sediment entering the sea, therefore, are speculative. However, what the results do show is the impact of the road in terms of increasing sediment concentrations within the streams. Even here comparison between different sampling periods and even different streams sampled on the same day is limited as both the literature and experience from this project indicates that suspended sediment concentrations vary considerably according to the stage on the flood hydrograph. In small steep catchments and in areas where rainfall intensity and totals will vary considerably over short distances, significant variation will take place in both time and space.

Rainfall intensity is more important than daily totals over the previous twenty-four hours even though this is the only data which are available. Studies of hydrology and erosion in rainforest catchments similar to those of Cape Tribulation (Gilmour and Bonell, 1979; Gilmour *et al*, 1982) show that a large proportion of flow increase is storm flow combined with overland flow. Instantaneous erosion takes place once rainfall intensity reaches a certain threshold. Observations indicated that overland flow on the road contained large volumes of suspended sediment during moderate to heavy rainfall but soon after rainfall ceased or reduced in intensity, the runoff cleared. For example, suspended sediment loads in a small gully running into Second Creek were 5411.3 mg/l during moderate rain, but dropped to 194.4 mg/l five minutes after the rainfall ceased. Elsewhere, within fifteen minutes of rainfall ceasing, it was observed that creeks changed from highly turbid loaded with red sediments to absolutely clear. Rainfall totals for the previous twenty-four hours, therefore, are only indicative, as it would appear that instantaneous rainfall intensities at the time of sampling are the most important factor. This makes representative sampling in the Cape Tribulation area almost impossible as precipitation is often in the form of localised high intensity showers.

Results from Cape Tribulation Streams

Results from each sampling period are shown in Table 1. Mean suspended sediment levels are shown for sites above and below the road, and where available also at the mouth of the creek and over the adjacent reef front. Also shown is the magnitude of increase in suspended sediment concentrations below the road and a contribution coefficient (see below).

Collecting periods were:

i) *15 March 1985.* This was the most intensive sampling period and was undertaken during and after the highest rainfall event for two years. Roadworks were still underway at that stage and large areas of bare ground over steep slopes were still present. Results are indicative of sediment yield during the highly disruptive construction period. Nonetheless, upstream of the road suspended sediment concentrations were generally low averaging just over 200 mg/l; the highest concentration from a single sample being 512 mg/l. Such localised elevated levels can be expected close to small bank slumps. Only small variations were noted between catchments above the road. Downstream of the road, suspended sediment loads were on an average twenty-two times greater than upstream; greatest increases being (in order) North Donovan Creek, Melissa Creek, Collins Creek, Donovan Creek and Third Creek. Notably, it is the northern-most catchments which have the greatest increase, particularly north Donovan Creek where concentrations in individual samples were as high as 37 000 mg/l. All concentrations in individual samples from these northern catchments were higher than 1000 mg/l. Smallest increases were associated with First Creek, South Emmagen Creek and Tachalbadga Creek, but even in these, increases greater than 2.5 times were recorded.

ii) *5 April 1986.* These samples were again taken after heavy rainfall during the previous twenty-four hours (118 mm) and only the two southern-most creeks (Myall and Masons Creeks) along the Old Road section could be sampled. Myall Creek had extremely low sediment concentrations, but at the point of sampling is in a large embayment with negligible slopes. Masons Creek showed a small increase across the road but figures lay within what may be considered normal for rainforest catchments and are comparable with those obtained upstream of the road during the March 1985 sampling period.

iii) *20 July 1986.* Three creeks (First, Second and Third Creeks) were sampled after light rainfall. Above the road, little or not sediments were present in the water column. However, below the road even under light rainfall there was a great enhancement of the sediment yield, with figures between 300 and 555 mg/l being recorded.

iv) *21 July 1986.* Five creeks were sampled on this day following 12 mm of rainfall. Again, concentrations above the road were negligible. Emmagen Creek provided an anomalous result in that the sediment concentration was lower below the road at the time of sampling. However, the remaining creeks all showed dramatic increases although figures all lie within the ranges found above the road following the heaviest rainfall event in March 1985.

v) *28 January 1988.* Only three of the northern-most creeks (Emmagen, Tachalbadga, and North Donovan Creeks) could be sampled after a period of minimal rainfall. Sediment concentrations above the road were low with magnitude increases of approximately four to five times below the road. However, levels were still within the range normally associated with natural rainforest catchments.

vi) *5 July 1988.* Although streams were running, no rainfall had been recorded in the previous days. Five of the northern creeks were sampled, with sediment concentrations above the road extremely low. Two creeks showed no increase below the road whilst the remaining had increases which may be regarded as insignificant.

vii) *25 April 1989.* Seven creeks were sampled, although no rain had fallen over the previous twenty-four hours. Only two of the creeks showed an increase in sediment concentration below the road but the amount is insignificant. Effectively, this data set shows no effect on sediment concentration from the road.

viii) *25 May 1989.* Five creeks were sampled after 28 mm of rainfall. Only Masons Creek showed concentrations of sediment approaching those recorded even above the road in March 1985. Significantly, enhanced samples from Masons Creek came from above the road. All other concentrations were low, although a small increase in suspended sediment was recorded below the road in each case.

Natural and Enhanced Suspended Sediment Concentrations

Data collected from sites above the road from the Cape Tribulation area showed that considerable variation can exist under natural rainforest conditions. After no rainfall or only very light rainfall during the previous twenty-four hours, sediment concentrations were generally below 10 mg/l. However, it is clear that a high intensity shower can quickly increase this towards 200 mg/l. This closely matches the result of Gilmour *et al* (1982) who showed that peak suspended sediment concentrations in natural rainforest within their small catchment were about 180 mg/l.

Figures obtained in March 1985 can be considered close to maximum, as these were obtained after the heaviest rainfall for two years in the area. Nonetheless, the maximum mean figure was only 263 mg/l, a concentration at which the stream will still appear largely clear of sediment. Under natural conditions, figures higher than this may be expected only after a major event such as a cyclone when the effects of intense rainfall and damage to the protective vegetation cover may be combined.

Below the road, increases in suspended sediment concentrations were recorded at all times except those following long periods of dry weather. Although enhanced concentrations were obvious, the actual levels within the streams were still well below peak concentrations found during heavy rainfall events under natural conditions. Concentrations exceeded 200 mg/l only after heavy rainfall events even where total rainfall may not have been great. Results clearly show that rainfall intensity rather than rainfall totals was the most important factor.

Figures for March 1985 are quite exceptional for the reasons outlined above, ie the intensity of the rainfall recorded and the fact that the amount of ground disturbance was very great. That the ground disturbance factor is important is illustrated by the figures obtained during 1986. Although rainfall totals were generally not high, maximum suspended sediment concentrations below the road still exceeded 200 mg/l.

Regional Variability and Influence of Road Characteristics

Because of the uneven nature of sampling over both time and space, only tentative conclusions can be reached about the effects of the road on sediment yield. Undoubtedly, the road has had a major impact on the amount of sediment reaching the streams. However, even taking into account the difference in rainfall intensities, as early as 1986 it was suggested by Hoyal (1986) that sediment concentration downstream of the road had decreased significantly. Data collected subsequently and observations made within the region suggests that this process has continued. Figures for July 1986 were more than five times lower than those recorded in March 1985 and even allowing for the differences in rainfall intensity, this is a result which might be expected. For example, O'Loughlin (1985) showed reductions in suspended sediment concentrations of up to 800% over a 12 month period following road construction in similar tropical environments (Figure 1).

However, visual evidence from the road and streams in the area suggests that erosion is still occurring at significant rates. On the road, the cut and fill slopes are steep and continue to erode producing large numbers of washouts and gullies. Soil slips are a prevalent feature on the high cut slopes and the rainforest above is being continuously undermined. There is a practice for debris which falls onto the road being pushed over the embankment to provide further loose material for erosion. Given major rainfall events such as those which occurred in March 1985, it is still possible for very high sedimentation rates to be recorded.

Bonham (1985) highlighted the poor engineering aspects of the road construction. This makes particular sections of the road especially prevalent to high sediment yield and is expressed in the contrasting figures recorded in the different creeks. Three particularly steep sections of road have the potential for highest sediment yield. These are:

- North of Pilgrim Sands
- Donovan Point
- Cowie Point

Donovan Point and Cowie Point have gradients of up to 30° and all three areas have thick, red and yellow clays which are easily eroded. To a large extent, the sediment yield characteristics of each creek can be explained in terms of their location with respect to the new and Old Roads and the quality of the engineering works on the section of road which they cross.

- As might be expected, the Old Road has minimal impact on Myall and Masons Creeks. However, Masons Creek has exceptionally high background suspended sediment values upstream of the road. These are thought to be the product of the subdivision and road building upstream, combined with the fact that it is the upstream section which is closer to the ranges. The lower parts of both these creeks cross a relatively wide coastal plain.
- First, Second and Third Creeks cross a steep range section as this southern end of the New Road and all have high suspended sediment values below the road.
- Below the road, Emmagen and Tachalbadga Creeks cross flat, stony, alluvial deposits which appear to influence the relatively low suspended sediment values.
- South Donovan and Donovan Creeks collect sediment from the southern side of Donovan Hill.
- Melissa Creek crosses a spur of Mt Cowie with slopes of 1:3 and this section of the road had deep, excavated cuts and fills about 1 km in length. All evidence suggests that it is the steep range sections of the road which are producing the greatest problems with regards to sediment yield, a fact which was observed during a reconnaissance flight in February 1985.

Vegetation growth is extremely rapid in wet, tropical environments and a cover of secondary growth should quickly provide some protection to the ground. However, some sections of the road appear to be too steep to stabilise rapidly, and it is notable that on these steep range sections, secondary vegetation has been disturbed by further landslips.

In addition to the variation produced by engineering works, a number of natural contrasts were observed in the morphology of streams in the area. Some such as South Donovan Creek, meander and cut through steep clay banks up to 10 m high upstream of the road. These banks are currently being undercut during high flows and therefore the stream has a high natural suspended sediment level. Other streams flowing predominantly over coarse alluvial pebbles and boulders with limited clay banks have naturally low suspended sediment levels.

8. SEDIMENTATION ON THE FRINGING REEFS OF THE CAPE TRIBULATION AREA

The Sediment Trap Programme

The stream sampling programme has clearly established that suspended sediment levels increased dramatically as creeks in the region cross the new section of the Cape Tribulation road. However, the effect on the nearshore zone may be minimal if the total volume of water within which this sediment is being carried is small in comparison to the oceanic water body into which it flows. Pringle (1986) estimated that the mean annual runoff for the Daintree was 1352 mm. The steeper characteristics of Cape Tribulation streams and their relatively small catchment size would suggest that under higher rainfall conditions runoff may represent as much as two-thirds of precipitation, ie approximately 2000-2500 mm. Although high, this would still represent a total annual volume of 98 megalitres (Table 2) for the total area under consideration, approximately equivalent to the volume of water between the coast and the 10 m isobath.

TABLE 2. Catchment areas and annual runoff volumes based on 2000 mm annual runoff

	AREA (km^2)	RUNOFF (megalitres)
Area 1 (Old Road)	13.8	27.6
Area 2 (New Road)	34.6	65.2
Area 3 (Northern Control)	2.6	5.2
TOTAL	51.0	98.0

Although total volume is possibly significant, its localised effect close to stream mouths has the potential to seriously affect local reefs. The potential for this can be seen in Table 1 which a contribution factor from each of the catchments examined has been calculated for each of the sampling periods. Water samples offshore were collected at various times during the research period under different wind and rainfall conditions. Typically, the figures for January and July 1988 (Table 3) represent summer and winter turbidity levels without major rainfall events (see Parnell, in press).

TABLE 3. Replicate averages of suspended sediment measured offshore in January and July, 1988

	28 JANUARY 1988	5 JULY 1988
Surface	98.3 mg/l	54.1 mg/l
Middle	96.4 mg/l	59.1 mg/l
Bottom	147.6 mg/l	72.4 mg/l

Levels of 100 mg/l would appear to be at the upper end of the scale at most times of the year. It has therefore been taken as a conservative high ambient level. In order to estimate the level of contribution of each stream, the contribution coefficient has been calculated by subtracting the mean suspended sediment measurements above the road from the elevated levels measured below the road in each sampling period and dividing this by the standard ambient level of 100 mg/l. Results confirm that only after major rainfall events are the creeks providing suspended sediment yields higher than the high ambient level of 100 mg/l. The figures also confirm the pattern with regards to the streams providing major input of sediment in relation to the characteristics of the road section which they crossed. The most important creeks providing sediment to the nearshore zone in declining order are:

- North Donovan
- Melissa
- Donovan
- Collins
- Third Creek
- Red Hill

This was confirmed by sediment samples taken from the mouth of the creek and over the adjacent reef front, particularly during the March 1985 sampling period (Table 1). Creek mouth figures sometimes exceeded those found immediately downstream of the road. Time of sampling of these waters appeared to be critical as tidal damming appears in some instances to have created artificially elevated turbidity readings. For example, in March 1985 the mean suspended sediment concentration at the mouth of Donovan Creek exceeded 12000 mg/l. Also during this same sampling period, concentrations over adjacent parts of the fringing reef exceeded 1000 mg/l.

Although these figures are extreme for any reefal environment, observations indicated that the excessively high turbidity levels occurred for only very short periods whilst moderate levels of turbidity up to 100 mg/l could occur at any time of the year due to resuspension of sediments already in the nearshore zone. The light attenuation factor, therefore, would appear to be less important than the potential for sediment to be dropped on the reef from the stream catchments. It was for this reason that an intensive sediment trap programme was initiated between January and July 1986. Sediments were collected from the traps six times during this period:

- 27 January - 12 February 1986
- 13 February - 26 February 1986
- 27 February - 3 April 1986
- 4 April - 24 April 1986
- 25 April - 21 May 1986
- 22 May - 16 July 1986

Data from the traps was organised by zone on the reef, by area as defined above (Old Road, New Road, Northern Control), by time of collection and by height above substrate (20, 40 and 60 cm). The sediment collected in each trap was also divided into the sand fraction greater than 63 μm and the finer mud silt fraction.

Differentiation was made between the sand fraction and mud and silt on the basis that the coarser sand carried by the streams would be expected to be deposited close to stream mouths as transportation velocities rapidly reduced. On the other hand, the finer fraction could be maintained in suspension for considerable periods of time and moved some distance from the source.

Sediment Deposition by Area

The raw data from the sediment trap programme can be seen in Appendix E of Hoyal (1986). Results relating to the three defined areas are seen in Tables 4 to 8 and in Figure 13. Over the six month collecting period, the overall mean for each sediment trap was 110.3 mg cm^{-2} dy^{-1}. This is an extremely high figure, but shows considerable regional and zonal variation.

The total data set by area is seen in Table 4. The mud accumulation rates show surprisingly little variation along all transects varying from 12.8 to 25.4 mg cm^{-2} dy^{-1}. In contrast, sand accumulation rates showed marked differences varying from 8.9 to 272.3 mg cm^{-2} dy^{-1}, and it is these which are responsible for the overall variation in total sediment accumulation rate (varying from 22.7 to 285.1 mg cm^{-2} dy^{-1}. Even at this level, it can be clearly seen that a hierarchy exists in the rates of sediment accumulation (Figure 14). Lowest accumulation rates are associated with the northern-most control area and highest with the New Road section. Particularly high rates of sedimentation were associated with transects adjacent to Second Creek and Donovan Point. Data from Area 1, the Old Road section, lies intermediate between that of the Control Area and the New Road section with only the Rykers Reef transect providing figures which overlap with those in Area 2. Rykers Reef lies to the north of Cape Tribulation and is at the point where Old and New Roads meet.

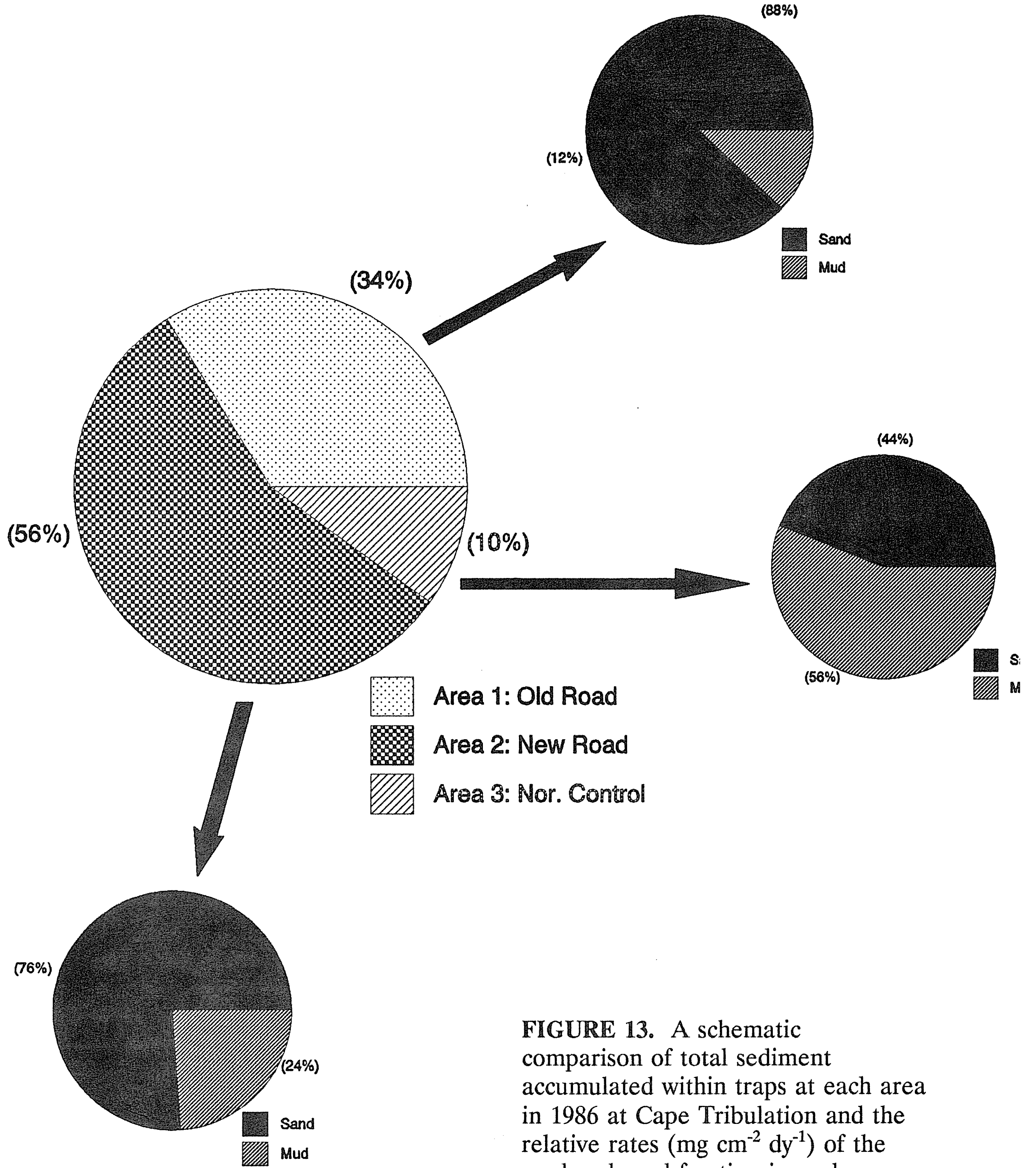

FIGURE 13. A schematic comparison of total sediment accumulated within traps at each area in 1986 at Cape Tribulation and the relative rates (mg cm^{-2} dy^{-1}) of the mud and sand fraction in each area

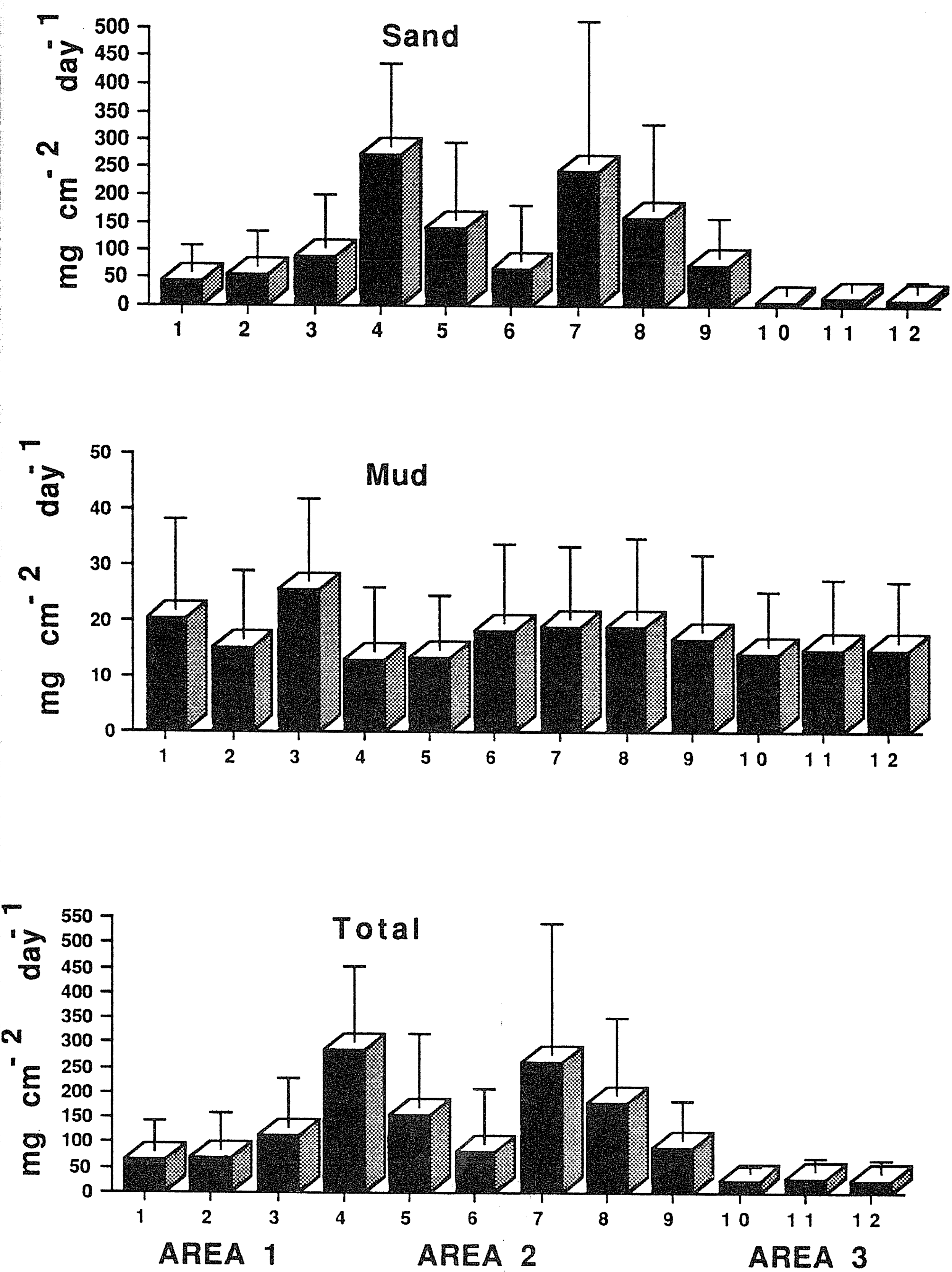

FIGURE 14. Histograms displaying mean (+ 1 SD) total, sand and mud rates (mg cm^{-2} dy^{-1}) at each transect.

TABLE 4. Mean and standard deviation of total sand and mud sedimentation rates (mg cm^{-2} dy^{-1}) each transect

AREA	TRANSECT	N	MEAN	SD
	SAND SEDIMENTATION RATES			
1 Old Road	1	56	43.8	48.3
	2	51	55.7	61.6
	3	82	90.4	94.1
2 New Road	4	26	272.3	150.5
	5	26	141.6	139.2
	6	59	65.2	101.8
	7	14	242.6	255.6
	8	60	160.3	154.2
	9	67	72.4	71.0
3 Control	10	12	8.9	13.2
	11	23	13.2	14.6
	12	22	11.1	17.0
	MUD SEDIMENTATION RATES			
1 Old Road	1	56	20.5	16.3
	2	51	15.1	12.3
	3	82	25.4	15.1
2 New Road	4	26	12.8	11.6
	5	26	13.4	9.4
	6	59	18.3	13.9
	7	14	18.9	12.8
	8	60	18.8	14.6
	9	67	16.7	13.5
3 Control	10	12	13.9	9.7
	11	23	14.9	10.9
	12	22	15.0	10.5
	TOTAL SEDIMENTATION RATE			
1 Old Road	1	56	64.3	60.5
	2	51	70.9	71.2
	3	82	115.8	97.1
2 New Road	4	26	285.1	151.2
	5	26	155.1	144.9
	6	59	83.5	106.9
	7	14	261.5	258.8
	8	60	179.1	156.5
	9	67	89.1	78.2
3 Control	10	12	22.7	14.5
	11	23	28.0	24.3
	12	22	26.0	23.2

Comparative data for the three areas is given in Table 5. Again, the mud accumulation rate shows no significant difference between the three areas, although there is a tendency for a decline from south to north. It is the sand accumulation rates which account for most variability, with rates for the New Road section being an order of magnitude greater than in the Control Area and twice as great as along the Old Road section. Contrast in total sedimentation rates are not as great, but nonetheless show the same pattern.

TABLE 5. Mean and standard deviation of total sand and mud sedimentation rates (mg cm^{-2} dy^{-1}) for each area

AREA	N	MEAN	SD
	SAND SEDIMENTATION RATE		
1 Old Road	189	67.2	77.1
2 New Road	252	128.9	147.6
3 Control	57	11.4	15.1
	MUD SEDIMENTATION RATE		
1 Old Road	189	21.2	15.3
2 New Road	252	16.9	13.3
3 Control	57	14.7	10.4
	TOTAL SEDIMENTATION RATE		
1 Old Road	189	88.4	84.1
2 New Road	252	145.8	150.5
3 Control	57	26.1	22.0

Sedimentation Rates by Zone and Area

Table 6 shows a further breakdown of the data according to sediment type, area and reef zone. Sedimentation rates by zone are considered important for management. Whilst the inner reef flat is clearly a zone of natural sediment accumulation, and a small additional sediment loading is unlikely to affect the flora and fauna, the reef crest zone although dominated by algae contains some corals in deeper pools and is more susceptible. The reef front zone dominated by corals is considered to be the most susceptible. Data for each transect is contained in Table 6 and is summarised by area in Table 7. Within each zone, the overall regional patterns are the same. There is little variation in mud accumulation rates across zones as well as between areas. For each of the three zones, the overall regional pattern remains for sand accumulation rates and total accumulation rates, ie highest rates are recorded in each zone adjacent to the New Road and lowest rates are found in the Northern Control Area. The differences between zones are not great although sedimentation rates tend to be highest in the living coral zone and lowest on the outer reef flat. This pattern is clearly indicated in the Northern Control Area (Area 3). However, in Area 1, highest sedimentation rates occur on the inner reef flat with very little difference between the outer reef flat and the living coral reef front. In Area 2 adjacent to the Old Road, there is a steady increase in sedimentation rates across the reef. In absolute terms, these zonal differences are not as high as those between areas.

This small variation with zones is also reinforced by examining sedimentation rates according to height above substrate within zone (Table 8, Figure 15). As would be expected largest amounts accumulated in the lowest traps due to a large proportion of the sediment being of fine sand size and thus not equally distributed throughout the water column.

TABLE 6. Mean and standard deviation of total sand and mud sedimentation rates (mg cm^{-2} dy^{-1}) for each zone

AREA	TRANSECT	ZONE	N	MEAN	SD
		SAND SEDIMENTATION RATE			
1 Old Road	1	1	28	67.7	57.5
	1	2	14	19.8	18.0
	1	3	14	20.1	14.7
	2	1	29	71.4	72.1
	2	2	14	24.5	28.0
	2	3	8	53.4	43.4
	3	1	53	111.7	107.4
	3	2	14	55.4	41.9
	3	3	15	47.9	43.0
2 New Road	4	1	1	248.9	0.0
	4	2	9	219.5	127.2
	4	3	16	303.5	162.3
	5	2	15	221.6	130.9
	5	3	11	32.5	41.6
	6	1	34	97.7	123.8
	6	2	15	26.9	17.9
	6	3	10	12.1	21.3
	7	2	2	9.2	8.6
	7	3	12	281.5	256.2
	8	1	37	168.2	173.1
	8	2	17	157.1	116.6
	8	3	6	120.7	136.9
	9	1	47	74.5	73.6
	9	2	14	66.8	46.7
	9	3	6	68.7	104.2
3 Control	10	1	6	15.2	16.9
	10	2	3	2.1	0.4
	10	3	3	3.1	0.8
	11	1	5	15.2	18.9
	11	2	6	7.9	9.6
	11	3	12	14.9	15.2
	12	1	11	17.9	21.6
	12	2	5	6.7	8.3

NB Zone 1: Inner reef flat; Zone 2: Outer reef crest; Zone 3: Living coral zone - reef slope

Continued ...

TABLE 6. Continued.

AREA	TRANSECT	ZONE	N	MEAN	SD
		MUD SEDIMENTATION RATE			
1 Old Road	1	1	28	27.3	18.5
	1	2	14	11.6	9.6
	1	3	14	15.8	10.3
	2	1	29	19.6	13.5
	2	2	14	7.4	7.9
	2	3	8	12.5	5.1
	3	1	55	25.8	16.1
	3	2	14	25.3	14.8
	3	3	15	24.1	12.7
2 New Road	4	1	1	18.9	0.0
	4	2	9	5.6	2.1
	4	3	16	16.6	13.0
	5	2	15	17.3	9.9
	5	3	11	8.2	5.8
	6	1	34	18.6	15.9
	6	2	15	14.7	9.8
	6	3	10	22.5	10.5
	7	2	2	1.9	1.1
	7	3	12	21.7	11.4
	8	1	37	21.8	17.3
	8	2	17	12.2	5.9
	8	3	6	18.5	5.9
	9	1	47	14.5	12.5
	9	2	14	24.8	15.3
	9	3	6	14.9	12.0
3 Control	10	1	6	7.7	3.1
	10	2	3	10.9	2.1
	10	3	3	29.1	3.6
	11	1	5	12.0	11.7
	11	2	6	6.3	6.1
	11	3	12	20.3	9.9
	12	1	11	16.0	12.4
	12	2	5	9.3	7.6

NB Zone 1: Inner reef flat
Zone 2: Outer reef crest
Zone 3: Living coral zone - reef slope

Continued ...

TABLE 6. Continued.

AREA	TRANSECT	ZONE	N	MEAN	SD
		TOTAL SEDIMENTATION RATE			
1 Old Road	1	1	28	94.9	70.4
	1	2	14	31.4	27.1
	1	3	14	35.9	19.8
	2	1	29	91.0	81.9
	2	2	14	31.9	35.6
	2	3	8	65.9	47.3
	3	1	53	137.5	109.7
	3	2	14	80.7	52.1
	3	3	15	72.0	47.4
2 New Road	4	1	1	267.8	0.0
	4	2	9	224.8	128.7
	4	3	16	320.1	160.5
	5	2	15	238.9	135.3
	5	3	11	40.7	44.4
	6	1	34	116.3	130.3
	6	2	15	41.6	23.4
	6	3	10	34.5	29.2
	7	2	2	11.1	9.7
	7	3	12	303.2	256.6
	8	1	37	190.1	174.4
	8	2	17	169.3	120.8
	8	3	6	139.3	142.6
	9	1	47	89.0	81.1
	9	2	14	91.6	54.7
	9	3	6	83.7	111.4
3 Control	10	1	6	22.9	18.5
	10	2	3	13.0	2.4
	10	3	3	32.2	4.3
	11	1	5	27.2	30.3
	11	2	6	14.3	15.7
	11	3	12	35.2	24.1
	12	2	11	33.9	29.3
	12	3	5	16.0	15.7

NB Zone 1: Inner reef flat
Zone 2: Outer reef crest
Zone 3: Living coral zone - reef slope

TABLE 7. Mean rates of sedimentation by zone and sediment type for the three areas (mg cm^{-2} dy^{-1})

AREA	ZONE 1	ZONE 2	ZONE 3
	Sand Accumulation Rate		
Area 1	89.7	33.2	38.6
Area 2	111.7	129.5	161.5
Area 3	15.2	6.2	12.5
All areas	94.8	84.4	101.5
	Mud Accumulation Rate		
Area 1	24.6	14.8	18.5
Area 2	18.0	15.1	17.1
Area 3	12.8	8.4	22.1
All areas	20.5	14.3	18.2
	Total Accumulation Rate		
Area 1	114.3	48.0	57.1
Area 2	129.7	144.6	178.6
Area 3	28.0	14.6	34.6
All areas	115.3	98.7	119.7

TABLE 8. Mean and standard deviation of total sedimentation rates (mg cm^{-2} dy^{-1}) for traps heights above the substrate, where 1-60 cm, 2-40 cm and 3-20 cm

ZONE	HEIGHT	N	MEAN	SD
1 Inner reef flat	1	83	82.2	79.3
	2	85	101.9	95.9
	3	83	158.9	150.0
2 Outer reef crest	1	45	87.1	96.1
	2	45	95.6	108.4
	3	38	116.2	128.1
3 Reef slope	1	37	84.1	94.7
	2	41	101.7	117.3
	3	41	154.9	217.9

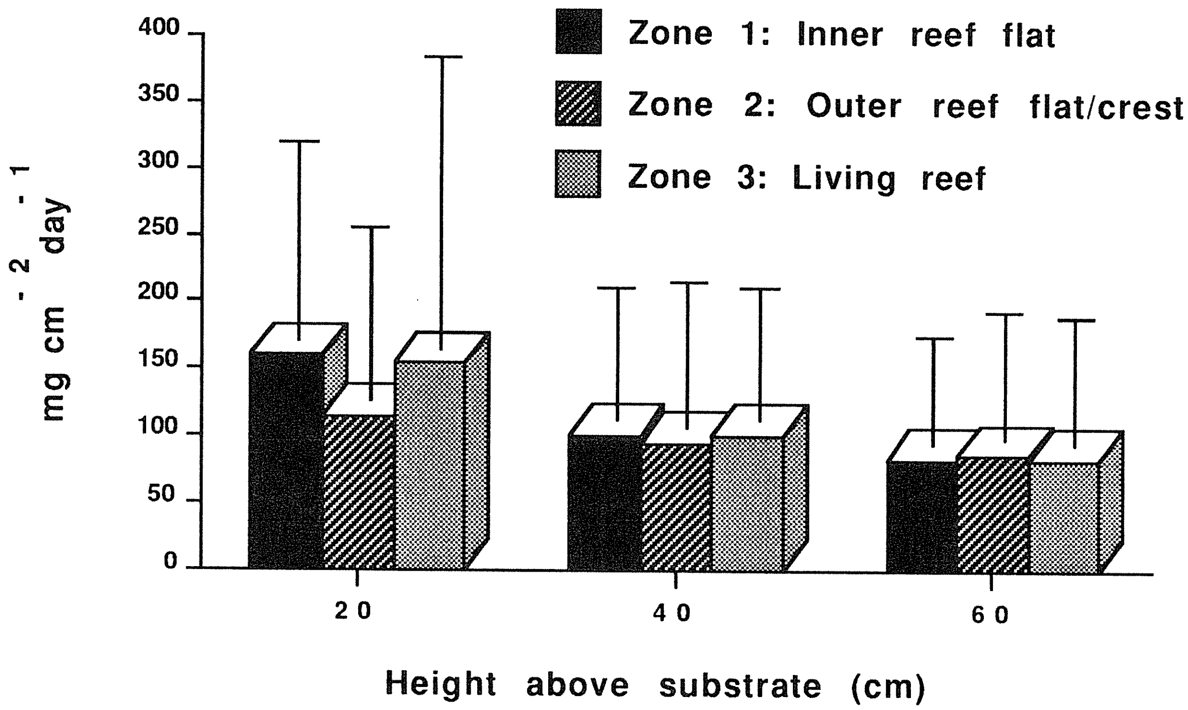

FIGURE 15. Mean (+ 1 SD) sedimentation rates (mg cm^{-2} dy^{-1}) for trap heights above substrate for the three habitat zones

Significance of Differences

A three-factor analysis of variance (ANOVA) was applied to the data set to determine if the patterns in sand, mud and total sedimentation rates discussed above were significant (Table 9).

Differences between total sedimentation rates at the area ($P < 0.001$) were all significant with similar results also being obtained for the sand fraction alone: for areas ($P < 0.0001$), for transects ($P < 0.0001$) and for zones ($P < 0.0001$). Although the variations within factors were significantly different, they were not homogeneous. Considerable variation was evident between zones within areas, and zones within transects, expressed by significant interaction effects.

For the finer mud fraction, the analysis of variance testing showed that rates of settlement did not vary significantly between areas. However, differences between transects ($P < 0.001$) and between zones (< 0.001) were significant for the mud fraction. Interaction effects were evident for area-zone and transect-zone factors. Although variation in the settlement of sediment finer than 63 µm is occurring along the Cape Tribulation coastline, this appears to be unrelated to proximity to the new road works.

TABLE 9. A three-factor Analysis of Variance (ANOVA) of total sand and mud rates with sites as a random factor and other factors fixed

SOURCE OF VARIATION	MEAN SQUARE	Df	F-VALUE	SIGNIFICANCE LEVEL
	SAND RATE			
Area	35 274 695.5	2	27.9	***
Transect (Area)	1 577 659.9	9	1 502.4	***
Zone	148 416.2	2	24.2	***
Area * Zone	21 950.3	4	3.6	**
Transect * Zone (Area)	6 139.5	15	5.8	***
Error	1 050.1	464		
	MUD RATE			
Area	1.5	2	0.6	NS
Transect (Area)	3.0	9	3.5	**
Zone	9.4	2	3.0	*
Area * Zone	2.4	4	0.7	NS
Transect * Zone (Area)	3.1	15	3.6	**
Error	0.8	457		
	TOTAL SEDIMENT RATE			
Area	29.3	2	4.9	*
Transect (Area)	7.1	9	3.9	***
Zone	5.9	2	1.4	*
Area * Zone	3.2	4	0.7	NS
Transect * Zone (Area)	4.3	15	2.4	**
Error	1.8	463		

* indicates $p < 0.05$
** indicates $p < 0.001$
*** indicates $p < 0.0001$

Variation in Sedimentation Rates Over Collecting Periods

A comparison of the sedimentation rates for total sediment, and mud and sand ractions over each of the six collection periods is made in Table 10 (Figure 16). These data are broken down further in Table 11 which presents the information for each area for each of the collection periods (nb because of inaccessibility only two collections were possible in the Northern Control Area).

Highest mean sedimentation rates occurred in the first collection period (219.7 mg cm^{-2} dy^{-1}). This was over seventeen days in January-February 1986 but was followed by lowest rate in February. Duration of the time between collections did not seem to affect the average sedimentation rate which is related more to other environmental variables (see below). Every collection period produced the pattern already established from the total data set:

- The New Road section produces the highest sedimentation rates at all times
- The Northern Control area produces the lowest rates
- The sand fraction dominates and a largely responsible for the total sedimentation pattern
- Mud accumulation rates show a relatively homogeneous pattern throughout the collecting periods.

These data were also subjected to an analysis of variance (ANOVA) testing (Table 12). The differences in the amount of sediment collected in traps at different times was significant for total sediment and sand rates, but was of low significance only for mud sedimentation rates.

TABLE 10. Mean and standard deviation for total, sand and mud sedimentation rates (mg cm^{-2} dy^{-1}) over time

TIME	N	MEAN	SD	TOTAL
		SAND SEDIMENTATION RATE		
1	74	200.9	182.7	14 866.6
2	143	33.7	86.6	4 819.1
3	62	105.7	74.7	6 553.4
4	45	152.5	151.1	6 862.5
5	109	72.1	85.5	7 858.9
6	65	74.9	53.8	4 868.5
		MUD SEDIMENTATION RATE		
1	74	18.8	13.7	1 391.2
2	143	10.0	8.1	1 430.0
3	62	30.2	18.7	1 872.4
4	45	28.2	16.0	1 269.0
5	109	19.4	10.9	2 114.6
6	65	16.4	9.4	1 066.0
		TOTAL SEDIMENTATION RATE		
1	74	219.7	185.8	16 257.8
2	143	43.8	91.1	6 263.4
3	62	135.8	73.6	8 419.6
4	45	180.6	148.7	8 127.0
5	109	91.2	86.8	9 940.8
6	65	91.3	54.6	5 934.5

TABLE 11. Mean and standard deviation of total, sand and mud sedimentation rates for each area at each time

TIME	AREA	VARIABLE	MEAN	N	SD
Time 1 (17 days)	1	Mud rate	23.7	28	16.9
		Sand rate	126.3	28	98.1
		Total rate	150.0	28	111.6
	2	Mud rate	15.8	46	10.3
		Sand rate	246.4	46	206.9
		Total rate	262.2	46	208.9
Time 2 (14 days)	1	Mud rate	9.0	42	5.3
		Sand rate	13.6	42	49.5
		Total rate	22.6	42	52.2
	2	Mud rate	10.5	68	9.2
		Sand rate	61.6	68	113.4
		Total rate	72.1	68	119.6
	3	Mud rate	10.3	33	8.7
		Sand rate	1.9	33	2.7
		Total rate	12.2	33	10.2
Time 3 (36 days)	1	Mud rate	36.2	25	18.5
		Sand rate	75.9	25	52.6
		Total rate	112.2	25	57.8
	2	Mud rate	26.1	37	18.0
		Sand rate	125.7	37	81.1
		Total rate	151.8	37	9.3
Time 4 (21 days)	1	Mud rate	38.2	12	11.6
		Sand rate	132.7	12	140.6
		Total rate	170.9	12	132.9
	2	Mud rate	24.6	33	16.0
		Sand rate	159.6	33	156.2
		Total rate	184.2	33	155.8
Time 5 (27 days)	1	Mud rate	20.6	41	11.5
		Sand rate	64.3	41	59.0
		Total rate	84.9	41	61.0
	2	Mud rate	16.7	44	10.9
		Sand rate	105.5	44	111.9
		Total rate	122.2	44	114.2
	3	Mud rate	20.7	24	9.6
		Sand rate	24.4	24	15.5
		Total rate	45.1	24	19.6
Time 6 (56 days)	1	Mud rate	18.4	41	10.4
		Sand rate	60.3	41	38.2
		Total rate	78.7	41	41.3
	2	Mud rate	13.1	24	6.4
		Sand rate	99.8	24	66.9
		Total rate	112.9	24	67.7

TABLE 12. A three-factor Analysis of Variance (ANOVA) of total, sand and mud sedimentation rates with time specified as a random factor

SOURCE OF VARIATION	MEAN SQUARE	Df	F-VALUE	SIGNIFICANCE LEVEL
		SAND RATE		
Area	8.3	1	4.1	*
Zone	1.9	2	0.9	NS
Time	10.9	5	5.5	**
Area * Zone	7.4	2	3.6	*
Area * Time	1.8	1	0.9	NS
Zone * Time	1.4	5	0.7	NS
Area * Zone * Time	1.5	6	0.7	NS
Error	2.0	114		
		MUD RATE		
Area	0.2	1	0.3	NS
Zone	1.4	2	1.8	NS
Time	2.1	5	2.8	*
Area * Zone	1.4	2	1.8	NS
Area * Time	1.1	1	1.4	NS
Zone * Time	1.6	5	2.0	*
Area * Zone * Time	0.9	6	1.3	NS
Error	0.8	111		
		TOTAL SEDIMENT RATE		
Area	8.3	1	4.1	*
Zone	1.9	2	0.9	NS
Time	10.9	5	5.5	***
Area * Zone	7.3	2	3.6	*
Area * Time	1.8	1	0.9	NS
Zone * Time	1.4	5	0.7	NS
Area * Zone * Time	1.5	6	0.7	NS
Error	2.0	114		

Significance level * $p < 0.05$

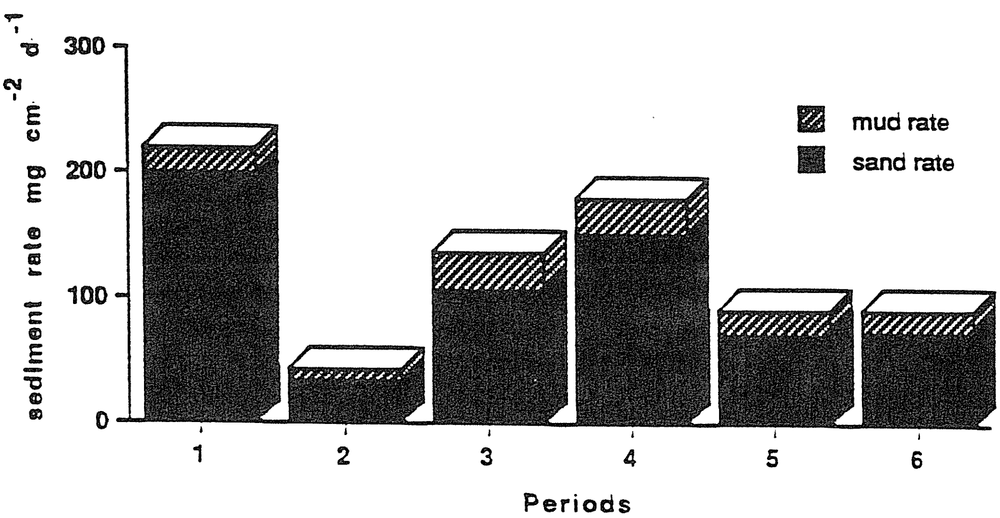

FIGURE 16. Histograms displaying mean sedimentation rates (mg cm^{-2} dy^{-1}) for each collection period showing proportion of sand and mud

Sediment Rates and Environmental Variables

The sediment within the traps may come from one or a combination of three sources:

- From the local streams
- From movement of sediment already emplaced on the reef
- From resuspended sediment and sediment plumes coming from major rivers such as the Daintree.

A stream source should correlate most closely with rainfall events in the area whilst resuspension of sediments on the reef and offshore will be more closely related to wave conditions controlled by wind.

From the data already presented, intense rainfall events are required for input of large amounts of sediment into the marine environment from the local streams. Three rainfall stations were maintained by local residents during the period that the traps were in position on the reef. Two were located near Rykers Creek and a third at Myall Creek. Rainfall data with which the sedimentation rates were correlated included total rainfall during collection period, mean rainfall per day during that period, and the maximum daily rainfall recorded at one of the gauges (Table 13). Whilst rain fell in all collection periods, periods 2 and 6 were notably dry for the Cape Tribulation area. Mean daily rainfalls during other collecting periods appear similar. However, the data from stream sampling has indicated that it is the high intensity falls which cause maximum suspended sediment yield. Notably, the highest twenty-four hour fall was 671 mm on the 27 April 1986 in collection period 5.

TABLE 13. Environmental variables

PERIOD	DATES	DURATION	TOTAL RAIN (mm)	MEAN RAINFALL (mm/dy)	MAXIMUM 24 HOUR RAINFALL (mm [date])	VECTOR WIND INTENSITY (kts)	MAXIMUM WIND SPEED (kts)	MEAN WIND
1	27/01-12/02/86	17 days	526.3	30.9	192.5 [31/1]	113	40	13.9
2	13/02-26/02/86	14 days	12.3	0.9	14.0 [16/2]	52	20	8.2
3	27/02-03/04/86	36 days	903.0	25.1	271.0 [27/3]	610	28	17.8
4	04/04-24/04/86	21 days	532.8	20.6	148.0 [06/4]	350	26	16.3
5	25/04-21/05/86	27 days	744.6	27.6	671.0 [27/4]	320	20	12.2
6	22/04-16/06/86	56 days	66.7	11.9	115.0 [03/6]	730	25	14.2

The closest daily wind records available for the Cape Tribulation area are from Low Isles, some 11 km offshore and 35 km to the south. Input data to be correlated with the sedimentation rates included mean wind speed, maximum wind speed during each collection period (Table 13). A vector wind direction during the collection period proved largely insignificant: winds were largely from the south-east throughout the period of research so wind direction variability was not included in further analysis.

Wind speeds varied considerably over the six-month period but averaged 14.4 kts. Highest average speeds were during collection periods 3 (17.8 kts) and 4 (16.3 kts), lowest during collection period 2 (8.2 kts). As resuspension of sediments appears to be related to periods of wind speeds over 20 kts, the highest average daily wind speed during each collection period was also included in the environmental variables. Highest record was a remarkable 40 kts on 30 January 1986 during collection period 1.

Indications of the dynamics underlying the sedimentation patterns on the Cape Tribulation reefs are revealed by a correlation analysis with the following environmental variables determined for each collection period:

- Total rainfall between collection periods
- Mean daily rainfall
- Maximum twenty-four hour fall recorded
- Residual wind magnitude determined from vector analysis
- Maximum wind speed for any twenty-four hour period.

The correlation coefficients (Table 14) were determined between each of these variables and the total amount of sediment collected from the traps, the mud fraction and the sand fraction for:

- All traps
- Traps from Area 1 (Old Road section)
- Traps from Area 2 (New Road section)

Because of its inaccessibility, collections were made from the Northern Control area (Area 3) on only two occasions, and data were insufficient for meaningful correlations to be obtained from this area on its own. As the degrees of freedom are only four (n=6), significance levels of the correlation coefficients are as follows:

- 5% - 0.811
- 1% - 0.917

TABLE 14. Cape Tribulation correlation matrix

							TOTAL			AREA 1			AREA 2		
		Max wind	Wind intensity	Max rainfall	Total rainfall	Mean rainfall	Mud rate	Sand rate	Sediment rate	Mud rate	Sand rate	Total rate	Mud rate	Sand rate	Total rate
	Max wind	■													
	Wind intensity	0.1267	■												
	Max rainfall	-0.2000	0.0866	■											
	Total rainfall	0.2036	0.7163	0.6003	■										
	Mean rainfall	0.5828	0.0776	0.6329	0.7048	■									
TOTAL	Mud rate	0.2493	0.4494	0.2405	0.6434	0.6154	■								
	Sand rate	0.8897**	-0.1460	-0.0452	0.2214	0.7129	0.4871	■							
	Total rate	0.8643*	0.0852	-0.0164	0.2812	0.7391	0.5723	0.9949	■						
AREA 1	Mud rate	0.3300	0.3812	0.1347	0.5464	0.5995	0.9836	0.5916	0.6688	■					
	Sand rate	0.7023	0.0137	0.0681	0.3125	0.7252	0.6426	0.9417	0.9579	0.7439	■				
	Total rate	0.6555	0.0911	0.0849	0.3752	0.7307	0.7419	0.9099	0.9395	0.8299	0.9902	■			
AREA 2	Mud rate	0.1896	0.3654	0.2073	0.5515	0.5509	0.9890	0.4387	0.5258	0.9720	0.5914	0.6967	■		
	Sand rate	0.9305**	-0.2251	0.0051	0.2093	0.7318	0.3543	0.9800	0.9608	0.4501	0.8732	0.8231	0.2994	■	
	Total rate	0.8613*	0.0213	0.1586	0.8465*	0.8464*	0.5496	0.9641	0.9682	0.6208	0.9309	0.9069	0.4755	0.9569	■

* Significance level - 0.05%; ** Significance level - 0.01%

If a high proportion of the sediment were coming from the local streams, then it would be expected that high correlation coefficients would occur with the rainfall factors. However, for sedimentation rates from all areas no rainfall factor reached a correlation with a 5% significance level, though correlation coefficients were highest with mean rainfall. Similar results came from the old road section (Area 1). However, in the new road section (Area 2) total sedimentation rates correlate withboth mean rainfall and total rainfall (significances < 0.05%). Mud rates show no significant correlation with any rainfall variable. As results from the suspended sediment yield sampling from the streams suggested that it was high intensity falls which were most important in producing suspended sediment, the very low correlation with maximum twenty-four hour falls during collection periods is surprising. The relationship with rainfall therefore appears to be limited.

More consistent results were achieved with the wind factors. Although mean wind speeds appear unimportant, maximum daily wind speeds during the periods of collection appeared to be highly significant. For the whole area the total sedimentation rate falls just short of the 1% significance level and has a greater than 1% significance level for the sand faction. For Area 2 adjacent to the New Road, these relationships had even greater significance particularly for the sand faction.

These results strongly suggest that during the period in which the sediment traps were located on the Cape Tribulation reefs, the contribution to sediment settlement by local streams was subordinate to resuspension except in the New Road area. As might be expected with larger areas of bare ground on steep slopes, and with a proven record of enhanced suspended sediment yields below the road, this area appears far more sensitive to rainfall events than Areas 1 or 3. In contrast, the resuspension of sediment already located on the reef front and offshore appears to have been an important process, particularly during periods of higher wind speeds. That it is the sand fraction and not the mud which correlates most closely with maximum wind velocities suggests that it is the finer sand of the reef flat and immediately offshore which is settling on the reef. Most of this sand is fine enough to be held in suspension or as continuously moving bedload when wind speeds are exceeding 20 knots. In contrast, the mud fraction is agitated into resuspension at much lower wind speeds. Observation suggests that resuspension of the finer fraction is taking place at times when wind speeds are as low as ten knots. For this reason, the correlations with the mud fraction are not significant. No great variation existed in the deposition of the mud fraction in either time or space supporting the concept of more or less continuous resuspension of the finer than 63 μm fraction, leading to highly turbid conditions along the Cape Tribulation coastline for more than 50% of the time.

9. CHARACTERISTICS OF SEDIMENTS FROM SEDIMENT TRAPS

The characteristics of selected samples of sediments from the traps were determined using microscopy, acid digestion and x-ray diffraction techniques as it was thought that this would help determine the origin of the sediments, ie from local fluvial sources, from the reef itself, or from offshore.

The Sand Fraction

The >63 μm sand fraction collected in the traps appears to be relatively homogeneous along the 20 km section of coastline studied. Petrographic descriptions of selected sand samples may be found in Table 15. They are made up of four major components:

i) *Fine-grained angular elongate quartz and fine-grained mica (predominantly muscovite).* The elongate platey shape of the quartz and the predominance of muscovite suggest that this fraction is of metamorphic origin, perhaps from the Hodgkinson formation.

ii) *Medium-grained rhombic quartz and feldspar, and medium-grained chloritised biotite.* The size, shape and predominance of biotite suggests that this fraction is probably of plutonic origin, perhaps from the Thornton Ademellite.

iii) *Fine-grained fragmented unidentifiable carbonate.* To become so fragmented these grains may have travelled from reefs further south. Alternatively, they may be the result of local reef bioerosion processes.

iv) *Gravel-coarse-grained carbonate.* This component was found only in samples from the living reef or in close proximity. The grains are whole or only slightly fragmented. They consist of foraminifera tests, spicules, shell fragments and coral fragments.

The relative proportions of the carbonate and terrigenous components were observed to be a function of proximity to the living reef, with more of the *in situ* coarse carbonate grains found in the living coral zone.

Acid digestions were also carried out on the samples examined petrographically (Table 17). Typically, the results show a slight increase in carbonate content from the shore to the outer edge of the reef crest. At the living coral zone, there is a massive increase in carbonate content within a short distance. The carbonate content then drops off suddenly at the outer edge of the living reef.

TABLE 15. Detailed microscopy assesment of sand fraction >63 μm samples from the Myall Creek area.

	QUARTZ	MICA	FELDSPAR	CARBONATE	PLANT LITTER	OTHER
Inshore	75%	5%	2%	10%	8%	
Inner reef flat	76%	7%	2%	11%	4%	
Reef flat	80%	5%	-	10%	5%	
Outer reef flat/crest	20%	5%	1%	70%	2%	2%
Living reef	46%	3%	2%	45%	4%	2%

The Silt and Mud Fraction

The <63 μm mud and silt fraction from the sediment traps varies in colour from reddish to grey depending on the collection site. Reddish samples are often found inshore close to road disturbance areas. However, grey samples predominate in all other areas. The percentage carbonate in these samples (determined by acid digestion) varies from 13 to 27% (Table 16). The results exhibit the same trends as the sands. However, the variability is much lower. This suggests that, even though much of the subtidal zone is dominated by carbonate, most of this area has very low productivity (coralline algae and some other calcifying algae). The area actually controlling the carbonate content of the sands and muds is the living coral zone with its high carbonate productivity rates.

TABLE 16. Results of mud and silt samples >63 μm that were dissolved in 10% HCL to determine carbonate content. Where samplng period: 3 - 27/2/86 to 3/4/86, 4 - 4/4/86 to 24/4/86, 5 - 25/4/86 to 21/5/86; habitat: 1 - inner reef flat, 2 - reef flat, 3 - outer reef flat, 4 - shallow living reef, 5 - deep living reef.

SAMPLE NUMBER	TRANSECT	HABITAT	SAMPLING PERIOD	%$CaCo_3$	% TERRIGENOUS
1	South Donovan	1	3	24.1	75.9
2		2	3	25.9	74.0
3		3	3	25.3	74.7
4	North Donovan	1	3	22.5	77.5
5		2	3	28.5	71.5
6		3	3	26.5	73.5
7	South Myall	1	5	13.4	86.6
8		2	5	16.6	83.4
9		3	5	19.4	80.6
10		4	5	22.4	77.6
11		5	5	17.5	82.5
12	Rykers	1	3	16.6	83.4
13		2	3	19.3	80.7
14		3	3	18.7	81.3
15		4	3	18.5	18.3
16		1	4	16.7	83.3
17		2	4	19.3	80.7
18		3	4	19.5	80.5
19		4	4	18.7	81.2

More compositional information about these samples is provided from XRD results (Table 17).

i) The dominant clay type in the trap samples is smectite compared to the soils in the area in which kaolinite dominates. It is not known if this is a feature of deposition, ie the kaolinite is carried offshore and the smectite is preferentially deposited in the nearshore zone. Since no great buildups of kaolinite have been found across the shelf it is assumed that this is a diagenetic effect caused by alternate wetting and drying in mangroves and longer term effects of the marine environment (Cuff, 1986, *pers comm*).

ii) The proportion of high Mg calcite and calcite varies in the samples. This is indicative of the range of flora and fauna contributing and the possibility of incorporation of inorganically precipitated carbonates and recycling of older Pleistocene deposits.

A major problem in the study was the extreme difficulty involved in determining a way to differentiate recent fluvial input (ie suspended sediment from the New Road which falls out of suspension into the sediment traps) from terrigenous material that has been in the nearshore environment for longer periods and which has been resuspended. Clay mineralogists are still uncertain about many processes operating on clays. The relative percentage of kaolinite or smectite is of little use as an indicator of recent terrigenous input, since clays alter by a kinetic processes. There are many different starting products and a variety of mechanisms and shortcuts involved in their diagenesis. Another problem with using the smectite/kaolinite ratio is that the Pleistocene surface (a weathering profile containing significant quantities of kaolinite) is exposed offshore (Johnson and Carter, 1987).

TABLE 17. Results of three X-ray Diffraction Analyses (XRD) to determine the mineralogy of the sediment. One sample was collected in upper second creek (Transect 5), the other two were collected in the living reef zone of South Donovan (Transect 11) and of South Myall (Transect 1).

	TERRIGENOUS COMPONENT	CARBONATE COMPONENT
Second Creek (13/2/1986)	60-70% Clays and Amorphous Oxyhydroxides of Al and Fe: 10% Smectite/Hydromica 10% Illite, some Muscovite 30% Kaolinite, some derived from Halosite 20% Oxyhydroxides of Fe and Al 30-40% Quartz	
South Donovan (13/2/1986) Calcite	60-70% Clays and Oxyhroxides of Al and Fe: 30-35% Smectite, some Hydromica 5-10% Illite, some Mica 10-15% Kaolinite, some derived from Halosite 10% Al and Fe oxides, Hydroxides 20% Quartz 10% Plagioclase	20% Carbonate: <5% Aragonite 10% Calcite 10% High Mg
South Myall (25/4/86)	60-70% Clays and Amorphous Oxyhydroxides of Al and Fe: 20% Smectite, little Hydromica 20% Illite, some Mica 15-20% Kaolinite, some derived from Halosite 20% Quartz 10% Plagioclase	20% Carbonate: 13% Calcite 7% High Mg Calcite

10. DISCUSSION

Enhanced Sedimentation Rates in the Cape Tribulation Area

In spite of the numerous difficulties encountered, we believe that the information collected for the Cape Tribulation area, forms the largest data set for sedimentation rates on any fringing reef in the world and confirms the concerns expressed at the time that the New Road was being constructed.

Above the New Road, streams in the area appeared to behave in exactly the same way as other small rainforest catchments (see Pringle, 1986, for review). Under low intensity rainfall conditions sediment concentrations are frequently below 10 mg/l. High intensity showers can increase this towards 200 mg/l. Even very intense falls such as occur once every two or three years increase these figures to about 250 mg/l. Under natural conditions figures higher than this may be expected only after a major event such as a cyclone when the combined effects of intense rainfall and high winds with consequent damage to the protective rainforest canopy are combined. Enhanced sediment yield has been clearly demonstrated below the the disturbed areas along the road. Nonetheless, concentrations exceed 200 mg/l only after heavy rainfall events, ie are within the limits normally found in undisturbed catchments. However, figures obtained in March 1985 shortly after the completion of roadworks show that exceptionally high sedimentation rates are possible. Although there is an indication in the results that sediment yield is declining with time as revegetation of disturbed bare soil areas takes place as suggested by O'Loughlin (1985) (Figure 1), the lack of a rainfall event equalling that of 1985 during subsequent sampling periods makes such a conclusions tentative.

Results of studies of the sediment settlement on the fringing reefs show regional and zonal patterns which are statistically distinct. The Northern Control area may be regarded as having sedimentation rates close to natural conditions. In comparison, the Old Road section (Area 1) has a sedimentation rate more than three times that of the control, whilst the New Road section has a sedimentation rate approaching six times as great. Concerns that suspended sediment from the New Road section may be transported northwards by longshore currents do not appear to be justified. Accumulation of mud in this northern area is less than in the two areas to the south. However, mud makes up only a small part of the total sediment settling on the reefs, and does not show the same areal or zonal distinctions as the sand fraction and total sediment accumulated. Disturbance does not seem to have increased the sedimentation rate of fines. Indeed, the highest figures are found in the southern-most area corresponding to the largest and widest nearshore mud wedge just north of the Daintree River as indicated by Johnson and Carter (1987). Lack of significant correlation between the mud sedimentation rates and any rainfall factors appears to confirm that most of the mud is originating from resuspended material picked up from the nearshore zone by waves of even modest size.

Nonetheless, there is a clear indication that the New Road section has significantly higher total sedimentation rates whilst the Old Road section in the south has levels which are intermediate. These intermediate levels may represent conditions in disturbed but more stable conditions several years after major disruption. They may indicate the expected sedimentation rates along the New Road section in ten years time.

As the high sedimentation rates in the New Road section are the result almost entirely of high sand accumulation rates (even though the sand is extremely fine), there is the suggestion that the mud component of the fluvial sediment yield passes straight over the reef as the streams enter the sea and contribute only a small amount to the total of resuspended sediment in the nearshore zone. In contrast, the fine sand fraction also carried in suspension by the streams is being dumped almost immediately on the reefs. Where the reefs are wide much of this sediment is being deposited in the backreef zone. However, considerable proportions are also being carried into the living coral zone of the reef front. Lowest settlement rates associated with the reef crest are probably the result of two factors. First, the reef crest is in part an emerged mid-Holocene high sea level feature and is the highest part of the reef, and is therefore out of water for the longest period. Second, this outer crest feature at high water is also the location of wave breaking and severe agitation which may also limit the amount of settlement taking place.

There is an apparent contradiction in the fact that whilst highest sedimentation rates are associated with the New Road section, there are few correlations with rainfall factors but several significant correlations with wind factors. It is suggested that major sediment input from the local streams was not taking place during the measurement period and that the sediment, particularly the sand fraction, may have already been present on the reef flat having been brought down from the disturbances along the New Road during the period of construction, particularly when this coincided with a major rainfall event. Such a massive sediment input during early 1985 has already been indicated by the stream sampling programme. Much of the sand is being retained in the nearshore zone and as indicated by the correlation with strong wind factors is being resuspended generally when wind speeds exceed 20 knots. Whilst larger areas of unsealed roads on steep gradients and associated ground disturbance remain, the potential for further sharp short inputs of sediment into the New Road section of the coastline remain. The fact that this sediment subsequently may be moved around in weather conditions which can occur more than 50% of the time in the Cape Tribulation area suggests that the chronic sedimentation stress which these reefs have suffered ever since sea level stabilised more than 6000 years ago (see Partain and Hopley, in press), may reach acute thresholds at some stage in the future.

Comparison with Sedimentation Rates from Other Areas of the Great Barrier Reef

The enhanced sedimentation rates established for the New Road section of the Cape Tribulation area can be evaluated in terms of their detrimental influence on coral growth by comparison with sedimentation rates from elsewhere. The contrast between the highly turbid inner shelf and the transparent waters of the outer shelf has long been recognised (Hedley, 1925; Orr, 1933; Pickard, 1977). Typically, suspended sediment concentrations on the outer shelf are in the order of 3 mg/l (Wolanski *et al*, 1981). In contrast, a wide range of readings have been determined for inner shelf waters dependant on weather conditions and proximity to stream mouths. Closer inshore, values of approximately 6 mg/l appear ubiquitous, but higher values between 35 and 115 mg/l have been recorded under strong wind or tidal current additions.

Most significantly, sediment trap data is also available from several sites in the Great Barrier Reef region. These can be evaluated with respect to distance offshore.

i) *Mid to outer shelf, John Brewer Reef, 75 km north-east of Townsville.* Hoyal (1986) carried out a pilot study in the lagoon of John Brewer Reef with sediment traps identical to those used at Cape Tribulation. The range of sedimentation rates for this mid-shelf reef is 0.17-2.87 mg cm^2 dy^{-1}. These low figures may be considered representative of mid to outer shelf locations and compare well with other data from elsewhere in the world where terrigenous influences are non-existent.

ii) *Inner shelf reef, Low Isles, 10 km north-east of Port Douglas.* A study well ahead of its time was carried out in 1929 by Marshall and Orr (1931) on the Royal Society Expedition to the Great Barrier Reef. Sediment traps 24 cm high and with an opening of 44 cm^2 were fixed to the reef flat of the Low Isles Reef. Sediments were collected at weekly intervals over a six-month period. Sedimentation rates ranged from 0.6 to 899.9 mg cm^2 dy^{-1} with an average value of 69.7 mg cm^{-2} dy^{-1}. The composition of the sediments was a combination of sand and mud with carbonate values ranging from 35-98%. Whilst the carbonate values are higher than those found in Cape Tribulation sediments, this site lies only 35 km to the south and is affected by the plume of the Daintree River. Resuspension of muddy, terrigenous sediments occurs around this reef and the mean sedimentation rate is more than twice that recorded in the Northern Control site of Cape Tribulation. The figures are comparable with those obtained from the southern Old Road area. Although considerable clearing had taken place on the mainland by 1929 and sugarcane was established in the Cairns area, the compatibility of figures from the southern area of Cape Tribulation and at Low Isles suggests that proximity to the Daintree River and resuspension of sediments derived from the Daintree may be an important factor influencing reef sedimentation in the region.

iii) *Daydream Island within the Whitsunday Passage.* A study of sedimentation rates using traps identical to those at Cape Tribulation has been undertaken by Steven and van Woesik (*pers comm*) with respect to a dredging programme in the area. Sedimentation rates at a control site unaffected by the dredging range between 5 and 15 mg cm^2 dy^{-1}, but exceeded 40 mg cm^2 dy^{-1} at stations affected by dredging.

iv) *Magnetic Island, 10 km offshore from Townsville.* Sediment trap data using traps similar to those in the Cape Tribulation area has been collected recently for Magnetic Island (Mapstone *et al*, 1989) as part of a baseline study related to hotel and marina developments at Nelly Bay. For the four-week period during which traps were deployed (collections were made weekly), average sedimentation rates ranged from 6.6 mg cm^{-2} dy^{-1} to 114 mg cm^{-2} dy^{-1}. Like Cape Tribulation, the reef slope traps collected most sediment with concentrations ranging from 2.6 to 356 mg cm^2 dy^{-1}. Although their values in general are much lower than for the New Road section of Cape Tribulation, they are similar to values obtained for the Northern Control area and for the southern Old Road section. Morphologically, the bays of Magnetic Island are most similar to the southern road section with wide embayments and bayhead coastal plains. However, rainfall totals are considerably less (approximately 1300 mm/yr) and the geology of the eastern side of the island consists largely of granite.

Mapstone *et al* (1989) noted:

> *"Sedimentation on the reefs during January and February 1989 was greater than that measured in most coral reef environments elsewhere in the world".*

There is an indication that in general inshore fringing reefs off north-east Australia experience very high sedimentation rates, perhaps under even completely undisturbed conditions. Thus the figures for Cape Tribulation though high when compared to data compiled from elsewhere in the world are consistent with sedimentation rates for comparable sites within the Great Barrier Reef Province.

Sedimentation Rates from Sites Other than the Great Barrier Reef and Tolerance Limits of Coral Reefs

Sedimentation rates quoted from sites elsewhere in the world are frequently an order of magnitude lower than those discussed above from the Great Barrier Reef. For example, Aller and Dodge (1974) report natural sedimentation rates of only 0.45 to 1.1 mg cm^2 dy^{-1} from Jamaica. Similarly, Rogers (1979) also in the Caribbean, reported rates of 1-21 mg cm^{-2} dy^{-1} producing sub-lethal effects with mortality being produced more readily by shading than sedimentation. Marzalak (1982) described the effects of dredging in Florida where control site sedimentation rates were

19.9 g m^{-2} dy^{-1} and dredge site rates 38.2 g m^{-2} dy^{-1} with some siltation events several orders of magnitude higher. Stress symptoms in corals included loss of zooxanthellae, polyp swelling and excessive mucus secretion with the range of affected corals being between 3% and 32.4% (average 9.7%). In the long term, mass mortality of corals did not occur, though after two dredging seasons 5% of corals near the dredge showed a partial loss of zooxanthellae and after four seasons as many as 32.3%. However, the corals appeared to be tolerant to short term (few days) sediment loading.

Maragos (1972) recorded rates of 35 to 41 mg cm^{-2} dy^{-1} from Kanehoe Bay, Hawaii. However, the stress which produced most reaction here came from freshwater inflow and eutrophication. Only Cortes and Risk (1985) have reported rates from the Caribbean which compare with those from Australia. Their data came from Puerto Rico and were enhanced by land clearance. Sedimentation rates ranged from 12.8 to 1179.9 mg cm^{-2} dy^{-1}. They considered that figures >30 mg cm^{-2} dy^{-1} produced stress if maintained.

Probably the most referenced studies on sedimentation effects are those from Guam of Randall and Birkeland (1978) as discussed and used in Pastorak and Bilyard (1985). They produce graphs indicating coral species richness, percentage cover and colony size as a function of sedimentation rate. They quote figures for average sedimentation rates measured over extended periods in natural coral reef habitats as ranging from 0.3 to 37 mg cm^{-2} dy^{-1} for the Caribbean and 0.1 to 228 mg cm^{-2} dy^{-1} in the Indo-Pacific region. Pastorak and Bilyard produced a table (their Table 3) which estimated the degree of impact on coral communities by various levels of sedimentation. They suggest that sedimentation rates of 1-10 mg cm^{-2} dy^{-1} produces slight to moderate degrees of impact, 10-50 mg cm^{-2} dy^{-1} moderate to severe impact, and >50 mg cm^{-2} dy^{-1} severe to catastrophic impact. These figures have been widely quoted and suggestions have been made that they should be used as controls for assessing impact in Australian waters. However, it can be seen that even John Brewer Reef would be considered to have a slight to moderate impact from its low sedimentation rate whilst all other Australian sites examined to date would be considered to be moderately to catastrophically affected by sedimentation. Pastorak and Bilyard, however, put limitations and provisos on their data. For example (p 179):

> *"In shallow waters of both regions highest sedimentation rates which are beyond the upper ends of the quoted ranges may be found."*

And further (p 180):

> *"In general coral species inhabiting the seaward margins of a reef are less tolerant of high sediment loads than species found in nearshore areas."*

Of their own table 3 they quote (p 182):

> *"Because limited data are available in the literature, the degree of impact assigned to each level of sediment deposition should be considered tentative"*

and as a footnote to their table 3, they state:

> *"Data used to generate this table are for reef communities at moderate depth and moderate exposure. Some variation occurs among authors in the sedimentation rates associated with the degree of impact."*

Clearly, the new data obtained over the last four years for the Great Barrier Reef confirms the importance of the provisos made by Pastorak and Bilyard (1985). Why then, are the figures for sites quoted by Pastorak and Bilyard so different from those of the Great Barrier Reef? First, great emphasis was put on the figures derived from Guam. Guam is an island some 50 km long and up to 15 km wide, the northern half of which consists of an elevated limestone plateau without surface drainage (Tracey *et al*, 1964). Input of sediment to the marine environment from the land is therefore very restricted. This is confirmed by examining sedimentation rates from a similar environment in the Caribbean, ie Barbados. Tomascik and Sander (1985) report suspended sediment values between 4 and 7 mg/l, quite clearly at the lower end of the scale of figures found in Great Barrier Reef waters and a reflection of the uplifted coral reef limestone environment of which Barbados consists.

Second important factor influencing the amount of sediment resuspended in the water column has been the relative sea level history of the Australian region compared to the northern Pacific and the Caribbean. For isostatic reasons the relative Holocene sea level history of different parts of the world varies (see for example Clark *et al*, 1978). Off the Australian mainland coast, sea level has been stable or close to its present position for approximately 6500 years during which time, fluvial sediment yield from the mainland has been able to build up a significant nearshore terrigenous sediment wedge consisting largely of fine sediments (eg Searle *et al*, 1980; Johnson and Searle, 1984; Johnson and Carter, 1987). It is this material which is resuspended by even moderate wave activity. In contrast, parts of the north Pacific and even more importantly the Caribbean have seen a continuously rising sea level throughout the Holocene period. The shoreline has not been stable in its present position, but has continued to move inland and therefore sedimentation in the nearshore zone has been spread over a much wider area. Fine sediments available for resuspension are considerably less than in the Great Barrier Reef region.

Johnson and Carter (1987) suggested that the Cape Tribulation reefs have always lived under heavy, terrigenous sedimentation influence. It would appear that the coral communities of the Cape Tribulation area and other inshore reefs of north Queensland have become acclimatised to heavy high rates of sedimentation. However, as Mapstone *et al* (1989) have pointed out, these high rates of sedimentation can be tolerated only under the conditions that are likely to be their cause, ie rough seas and great water movement. Under these conditions, it is unlikely that sediment would remain on the surface of the corals for more than a short period, and accumulation of sediment and consequent physiological stress of corals seems unlikely. Under natural conditions, high sedimentation rates do not take place when seas are calm.

11. CONCLUSIONS AND MANAGEMENT IMPLICATIONS

Under natural conditions, sedimentation rates on north Queensland fringing reefs are high. However, sediment movement takes place mainly during high energy periods and whilst sediment may be collected in the artificial sediment traps, it does not normally remain on coral reef communities.

Cape Tribulation reefs have clearly had an additional load of sediment imposed upon them by the development of the new Cape Tribulation to Bloomfield Road. Sedimentation rates on the reef are up to six times those on reefs adjacent to undisturbed catchments in the same area. This research programme has shown that much of this additional sediment was provided during and shortly after road construction when large areas of bare soil combined with unusually intensive rainfall. Much of the sediment moving on the reefs subsequently is resuspended.

From a light attenuation viewpoint, the extra sediment may not be significant. Ayling and Ayling (1987) report that normal visibility in water adjacent to Cape Tribulation reefs is in the range of 2-6 m, and only occasionally reaches 10 m in calm weather. During strong south-easterlies, visibility is reduced to 0.5-2 m. The result is a vertically compressed biotic zonation on the reefs, and is clearly produced by turbidity levels which have occurred over a very long period of time. Large amounts of sediment are moving around and over the reefs, but this sediment can remain on the corals for a long time only during calm periods when the amount of sediment in the water column is very much reduced. The possibility that coral formations of shapes similar to the sediment traps (vase shaped) may also collect sediments should not be dismissed. However, Ayling and Ayling (1987) concluded from their survey that there was no evidence of hard coral death due to siltation, and Fisk and Harriott (in press) could find no evidence from three years of data that the consequences of the New Road affected juvenile corals or availability and recruitment of coral larvae.

The amount of sediment moving in the nearshore zone suggests that the Cape Tribulation reefs may be approaching critical thresholds. Partain and Hopley (1989) have already indicated that there has been negligible reef accretion over the last 5000 years and that the Cape Tribulation reefs over this period have been under a chronic siltation stress. Kinsey (1989) suggested that whilst reefs seemed to be well able to tolerate chronic stresses and are able to be maintained through extended time without dramatic visible response from the reef system, it is possible that system function may be modified appreciably without concomitant obvious community changes. He further suggests that when acute stresses are then applied to such reefs, recovery may be difficult. The chronic stress of high turbidity levels is something which will not alter in the Cape Tribulation area. An acute stress could easily result from exceptionally high intensive rainfall events such as those associated with a cyclone. Even under natural conditions, destruction of the rainforest canopy could result in exceptionally high sediment loadings from the small catchments. Results from March (1985) suggest that the disturbed catchments of the area will yield what may be catastrophically high sediment amounts.

FIGURE 17. Typical road section with steep grades, unstabilised cut and fill sections

FIGURE 18. Gullying and landslips are frequent after heavy rain especially on steeper road sections. Potential remains for complete slope failure and massive sediment yield.

In their conclusions, Partain and Hopley (1989) state:

> *"The Cape Tribulation reefs appear to have already passed beyond the threshold which allows for active reef growth due to a natural deterioration of water quality over the last 6500 years. Their present mode is one of maintenance rather than growth in spite of the diversity of corals which places them in a highly vulnerable position. Further deterioration, however small, has the potential to pass the system beyond the threshold where the reef can be maintained, ie producing an irreversible turnoff as defined by Buddemeier and Hopley (1989). As the adjacent rainforest system is one of high energy, maintained within a recycling system and expended on vegetative growth (see Douglas, 1969, for discussion), any disturbance to this system has the potential to cause a rapid and irreversible turnoff through increased sediment yield, release of nutrients and more intensive runoff response."*

Observations along the new section of the Cape Tribulation road, suggest that time may not be an important factor in reducing this risk of acute stress as was suggested by O'Loughlin (1985) (see figure 1). Although some revegetation and stabilisation has taken place on banks adjacent to the New Road, there are still large areas of bare ground (Figures 17 and 18) and the road remains unsealed with gradients of up to 1 in 3. Cut bank sections continually slump and maintenance work frequently consists only of bulldozing landslips off the road and downslope, thus providing material for further enhanced sedimentation. The exact time at which an irreversible mortality of corals in the Cape Tribulation area takes place cannot be predicted. However, the exceptionally high rates along the New Road section in an area in which sedimentation rates are already high would suggest that the next major cyclone in the region could produce such a result. Whilst closing the road would appear to be an unacceptable solution to the problem, it is strongly recommended that a programme of sealing and associated engineering works, such as providing more effective culverts, stabilising of steep banks and provision of adequate drainage, be undertaken.

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APPENDIX

NEARSHORE HYDRODYNAMICS AND SEDIMENT DYNAMICS OF THE FRINGING REEF COAST IN THE CAPE TRIBULATION AREA

NEARSHORE HYDRODYNAMICS AND SEDIMENT DYNAMICS OF THE FRINGING REEF COAST IN THE CAPE TRIBULATION AREA

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Abstract

The hydrodynamics of fringing reefs and associated nearshore waters in the Cape Tribulation area are described within the context of an examination of the effect of disturbed rainforest catchments on adjacent fringing reefs. The theory of water and sediment dynamics is reviewed. Field data were collected during periods in January 1988 and July 1988, with moderate southeasterly wind conditions prevailing during both periods. Water velocity and direction data, suspended sediment concentration data, and surficial sediment data are used in conjunction with nearshore coastal process theory to examine local water circulation, and the relative importance of resuspended and river derived suspended sediments. The available evidence suggests that wind and wave generated circulation dominates in the nearshore, but is modified by local morphology. Offshore surficial sediments contain a high proportion of muds, and resuspension of these sediments occurs under modal wind and wave conditions. River derived sediments may add to offshore suspended sediment concentrations during extreme weather events, but are only significant in the near vicinity of the stream mouths, with sedimentation likely only in zones of very low velocity. Cape Tribulation fringing reefs are likely to have developed in conditions of high turbidity and high suspended sediment concentrations.

1. Introduction

Following the construction of a road linking Cape Tribulation and Bloomfield, the Great Barrier Reef Marine Park Authority initiated a research and monitoring programme to provide a sound basis for the management of the mainland fringing reefs in the area (Craik and Dutton, 1987). A component of this research is to examine the 'effects of disturbed rainforest catchments on adjacent fringing reefs in the Cape Tribulation area' (Craik and Dutton, 1987). This report details a study which contributes to this research.

Although the Cape Tribulation fringing reefs have developed and been maintained with high suspended sediment concentrations and turbidity (Johnson and Carter, 1987), it is clear that increased sedimentation and suspended sediment levels, resulting from catchment land use change, could cause the siltation tolerance of corals in the area to be exceeded. The literature relating to siltation effects on coral reefs is well summarised by Johnson (1987). Ayling and Ayling (1987) report early results of studies examining the effect of silt runoff on the Cape Tribulation reefs.

The research utilises nearshore coastal process theory tested by Lagrangian and Eulerian hydrodynamic techniques to examine the movement and redistribution of sediments which reach the reef flat and offshore areas from the numerous small streams which flow from the mainland, and which are resuspended from the offshore seabed. Fieldwork was undertaken during January 1988 and July 1988.

The research objectives were:

1. To describe nearshore water circulation under winter and summer wind conditions
2. To describe water circulation within bays under winter and summer wind conditions
3. To determine the conditions under which resuspension of offshore sediments will occur, and to examine the redistribution of these sediments
4. To examine the dispersion of sediments derived from streams flowing onto the reef flat.

2. The study area

The study area (Figure 1) extends approximately 19 km from Cape Tribulation in the south to approximately 3 km south of the Bloomfield River (Figure 2). The coastline consists of a series of headlands separating bays, containing sandy beaches and reef flats of various widths. The outer living coral zone is generally narrow, and variable in its occurrence. The offshore area can be divided into an inner shelf (to 20 m water depth), a flatter middle shelf (20 - 40 m water depth) and a mid-shelf reef tract some 15 km offshore (Johnson and Carter, 1987). The coastal ranges lie in close proximity to the coast with dense tropical rainforests growing to the coastline. The coastline falls within the Cairns Section of the Great Barrier Reef Marine Park, and is zoned Marine National Park 'B'.

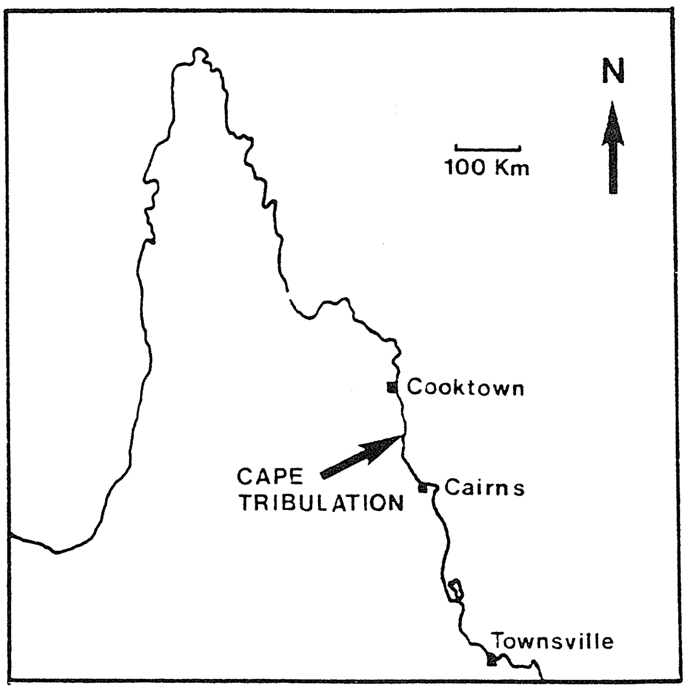

Figure 1: Location map of the Cape Tribulation area. Source: Johnson and Carter (1987)

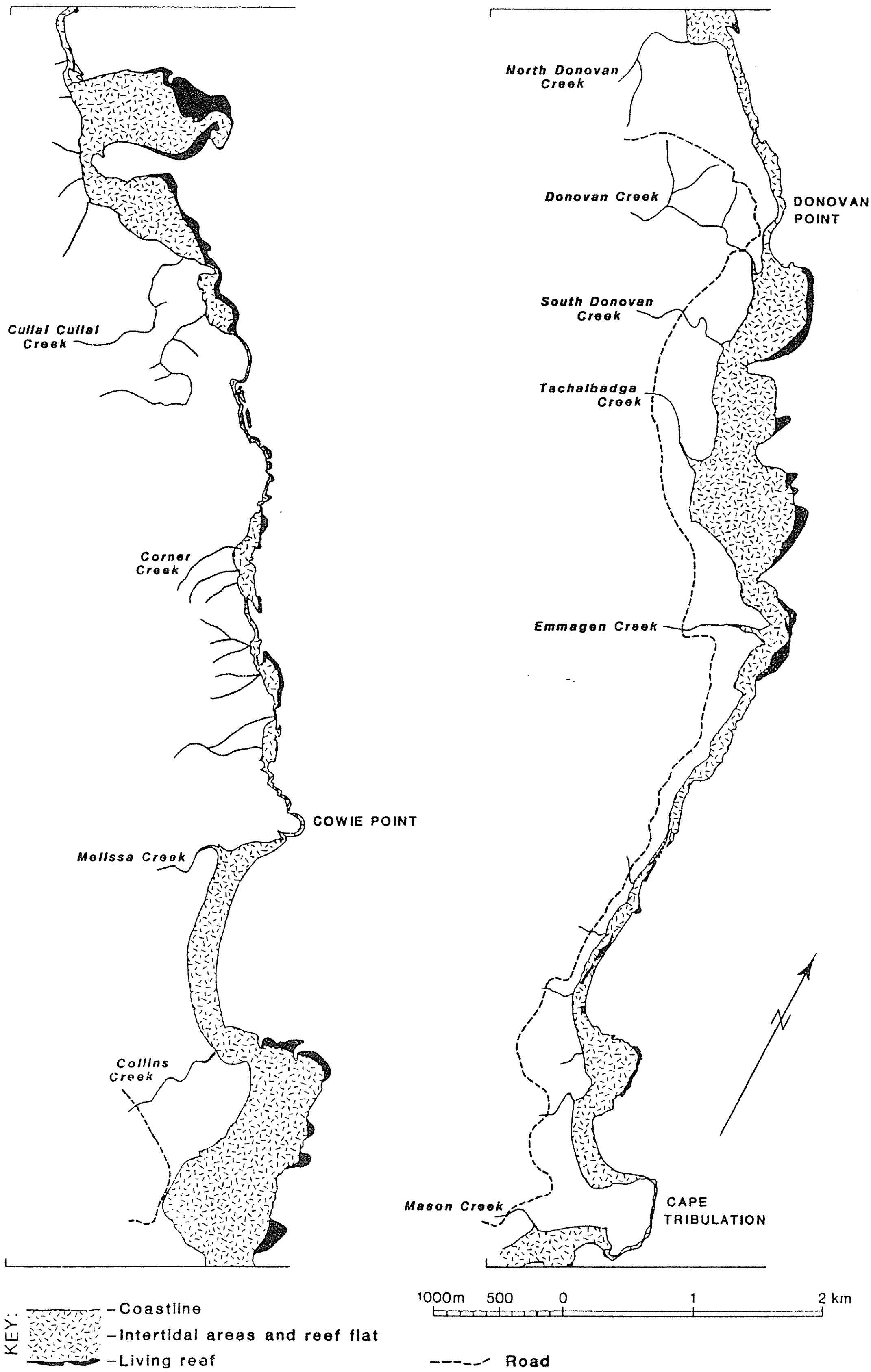

Figure 2: The study area, Cape Tribulation area.

The most noticeable climatic influences of the area are the persistent southeasterly trade winds and the marked seasonality of climate. The winter dry season is associated with anticyclones crossing the continent at about 30°S causing ridges of high pressure along the coast adjacent to the Great Barrier Reef. In summer, low pressure systems dominate although weaker ridges may persist. From December to March moist air masses move over northern Australia, with winds typically from the north or northwest. Tropical cyclones may occur during the months November to May. Pickard (1977) and Downey (1983) provide comprehensive accounts of the regional climatic features. Annual average rainfall is approximately 4000 mm at Cape Tribulation (Ayling and Ayling, 1987), with annual totals of 6000 mm being not unusual. Annual average evaporation is in the order of 1250 mm (Bureau of Meteorology, 1971).

Wind and wave data relevant to the study area are limited. Data from Cairns indicate modal wave heights in the order of 0.2-0.6 m (Beach Protection Authority, 1978), with cyclonic wave heights, limited by the short fetch, recording a maximum of 3.21 m (Hopley, 1982). Because the prevailing southeast winds blow obliquely up the inner mid shelf between the mainland and the inner reef tract, Johnson and Carter (1987) report the common formation of waves 1-2 m high reaching the coast in the Cape Tribulation area.

Tidal data for Cape Tribulation is based on the 'Secondary Place' table for Low Isles (Department of Harbours and Marine, 1988) (Table 1). Tides are semi diurnal with significant diurnal inequality.

Table 1: Tidal data, Low Isles (with respect to Standard Port, Cairns)

	HW	LW	MHWS	MHWN	MLWN	MLWS	ML	Rat	Con
Cairns	Standard Port		2.4	1.7	1.3	0.6	1.50		
Low Isles	0 00	0 00	2.3	1.6	1.3	0.6	1.46	0.92	+0.10

Circulation is a function of mean flows and oscillatory motions. It is expected that in the vicinity of Cape Tribulation flows will be a combination of currents set up by the wind, and tidal currents. In the vicinity of nearshore high islands, many studies have reported consistency in reversing tidal stream directions indicating minimal wind driven flow (Hamner and Hauri, 1977, 1981; Falconer et al., 1986; Parnell, 1987, 1988). In other areas wind driven flow dominates. Perhaps most significant for the Cape Tribulation area is a two and a half year data set for currents near Green Island (Wolanski, 1983;

Wolanski and Pickard, 1985). Time series data showed high correlation between current direction and wind direction, the result of wind driven low frequency barotropic shelf waves, but with large seasonal and interannual variations generated by fluctuations in circulation in the Coral Sea. In relation to the Cape Tribulation area the Hydrographic Chart (AUS 831) states that "from April to November the prevailing set is northerly with rates up to about 1.25 knots (0.64 m/s). From December to March the currents are irregular, but southerly sets may predominate with rates up to about 0.75 knots (0.38 m/s)". The available evidence suggests that for Cape Tribulation nearshore circulation should be dominated by wind driven currents, flowing north during periods of southeasterlies, and south during periods of summer northerlies, but with the possibility of some modification due to tidal reversals. Additionally in the nearshore zone, longshore currents will be established caused by the oblique angle of approach of waves (Pethick, 1984). Wave generated longshore currents increase with increased wave height and increased angle of approach.

The nature of the fringing reefs of the area has been described by Johnson and Carter (1987), with a description of the Myall Beach fringing reef, immediately south of Cape Tribulation:

> "At Myall Beach the fringing reef lies seaward of the sandflat and consists of three parts: 1) a dead emergent reef top, 2) a living reef crest and upper slope, and 3) a sediment covered lower slope which passes onto the inner shelf. The emergent reef forms an irregular, raised, wave resistant pavement at approximately -0.5 to -1.0 m (AHD), incised by gutters up to 1 m deep. This subfossil reef consists of branching and head corals heavily encrusted and cemented together by coralline algae, barnacles and oysters. Living corals only occur seaward and below the dead reef top, along a steep, indented outer margin approximately 3 m high, with deep gutters between patch reefs and individual coral columns. The upper limit of live growth has been leveled at ca -1.40 m (AHD). SCUBA observations show the lower slope, seaward of this cliff consists of sandy substrate with scattered coral heads up to 0.5 m high, coral rubble, seagrasses and taller columns close to the reef margin. Coral growth extends about 50 m seaward of the reef edge, down to ca 6 m below AHD at Cape Tribulation . . . This depth range is shallow compared to the mid shelf reefs

only 15 km offshore, where coral growth extends down to 30-40 m. Sediments of the lower slope becomes increasingly muddy seawards where they merge with those of the inner shelf."

Cape Tribulation fringing reefs are developed on coastal sediment bodies, with carbonate rich reefal deposits prograding seawards over finer grained, terrigenous sediments which are accumulating on the inner shelf seaward of the reef flat (Johnson and Carter, 1987).

A number of rivers of various sizes flow from the mainland catchments adjacent to the study area. Most of the rivers are ephemeral, with high discharge and rapid response during periods of heavy rainfall, due to the steep compact catchments they drain. Discharge measurement is almost impossible and movement between streams difficult during heavy rainfall events. In the lower reaches the stream beds consist of coarse gravels to small boulders and it is likely that there is significant subsurface baseflow. In all but the large rivers, water discharges into the backreef zone, often into entrapped pools and occasionally breached estuarine systems, and flows as a wide shallow wash across the intertidal zone. Within the study area, only Emmagen Creek retains a distinct estuarine channel mouth, approximately 50 m wide.

The nearshore waters of the Cape Tribulation area are characteristically turbid, even under light wind conditions (Johnson and Carter, 1987; Hoyal, 1986). Ayling and Ayling (1987) report that under prevailing southeasterly wind conditions sediments are resuspended causing a wide band of turbid water against the coast. Under these conditions water visibility ranges from 0.5 to 2 m. Following extended calm periods water visibility is usually only 2 to 6 m. With all sediments associated with the reef having a high (>50%) terrigenous component it is likely that the Cape Tribulation reefs have always grown under conditions of high terrigenous sediment inputs (Johnson and Carter, 1987).

A description of the geology of the mainland and an analysis of the sediments of the Cape Tribulation area can be found in Johnson and Carter (1987). They find that the inputs of modern terrigenous sediments likely to be transported in suspension are dominated by kaolinite/illite assemblages, while the modern marine assemblages are dominated by smectite and illite-smectite mixed layer clays, with the different assemblages probably being due to the rapid diagenesis of clays when they are immersed in the marine environment. Immediately north of Donovan Point, the inner shelf surficial sediments contain 25 to 71% muds. These are available for resuspension into the water column. Johnson and Carter (1987) conclude that it is not possible to use the clays as tracers of discharge from mainland catchment, or in the determination of the importance of resuspended sediment on suspended sediment concentrations.

Hoyal (1986), in a study of the effect of disturbed rainforest catchments on sedimentation in the Cape Tribulation area, used suspended sediment measurements and sediment traps to examine the nature of sedimentation across the reef flat and living reef zone. A number of his observations are relevant although it must be noted that standard deviations for groups of his samples are high and he concludes that "this large natural variability in sedimentation rates may mean that sedimentation rates are not significantly different over the whole study area:" (Hoyal, 1986, 78).

Hoyal (1986) concludes:

1. Low sedimentation rates accompanied periods of low rainfall and low wind velocities.
2. Highest sedimentation rates accompanied a period with a large number of days with winds greater than 15 knots.
3. Sedimentation rates for fine sediment on the living reef were found to be highest in the northern sector of the study area, and suggests that this may be the result of the northward current moving sediments from the south, or the generally shallower nature of the bathymetry to the north, ensuring more sediment above the fairweather wavebase allowing greater resuspension of sediments.
4. Intertidal fine sedimentation decreases from north to south.
5. Sedimentation rates for fine sediment are high inshore, low across the sand and reef flat and high on the living reef. This is explained in terms of the wave energy regime.
6. Sand deposition is related to proximity of source.
7. Sedimentation rates are related to rainfall and wind strength and direction, with temporal trends due to these factors being more important than spatial trends related to land use. A differentiation of the importance of rainfall and wave influence was not possible.

3. Methods

The examination of the physical processes on mainland fringing reefs requires the intermingling of the theory of sediment dynamics, with our knowledge of reef processes. The literature on the dynamics of the nearshore coastal zone is extremely large (Dyer, 1986), although there is still much not understood.

This study considers the Cape Tribulation coastal system in the context of an open coastal sediment transport system (with regional circulation and wave generated longshore currents dominating), but recognising particular features of the reef environment. The factors of most significance in this regard are the dramatic change in water depth at the reef front and the importance of grooves in directing flow. Basic hydrodynamic forces operating are determined from the literature and field observation, and field measurements are undertaken to confirm appropriate application of the theory. Time and budget did not allow long term measurements to be undertaken to enable a detailed description of regional hydrodynamics.

Water velocities and water movement directions were determined using either an Ott tethered current meter and hand held compass (with 2, 50 second sampling periods being averaged), or using dye as a visual tracer from a fixed marker (buoy), with distance traveled over three minutes being estimated and direction of travel being determined by hand held compass. It is realised that the method of velocity data collection has errors associated with it (see note in Tables 7 and 8) and the temporal coverage is short. Velocity and direction data are used only to confirm flow direction under the conditions sampled, and gain an approximate estimate of velocity. Wind velocity and direction was measured using a hand held cup anemometer and a hand held compass.

Larger quantities of dye were injected near the mouths of Emmagen Creek (2 occasions) and South Donovan Creek (1 occasion), and tracked over longer periods of time. The dye used was Rhodamine WT, a fluorescent tracer which has been used widely in marine environments. Parnell (1987) gives a detailed description of the properties and uses of Rhodamine WT.

Suspended sediment samples (1 litre) were collected using a hand operated pump, and analysed by filtration. Seabed sediments were collected using a grab sampling device, and analysed by wet sieve techniques.

4. Literature review

4.1 Fringing reef hydrodynamics

Studies of reef hydrodynamics have led to considerable advances in our understanding over the last decade (see Parnell, 1988, for a review), but mainland fringing reefs have not been examined. Parnell (1986, 1987, 1988) examined the hydrodynamics of island fringing reefs in the Great Barrier Reef Marine Park, and found that physical processes were dominated by tidal currents, with wave generated and other currents being of minor importance.

Processes on mainland fringing reefs are more likely to be dominated by wave generated currents (perhaps similar to the windward edge of mid shelf reefs). Additionally processes are likely to exhibit some similarity to Caribbean fringing reefs studied extensively by Suhayda and Roberts (1977), Roberts et al. (1975), Roberts and Suhayda (1983) and Roberts (1980), and Pacific Island reefs (for example, Guam, studied by Marsh et al., 1981) which showed wave generated currents dominating zones of landward movement of water, and narrower zones of seaward return. The results, however, are not directly comparable because of the different tidal ranges, and the different reef forms (in particular the presence of a back reef lagoon in the Caribbean situations, and the raised nature of the Cape Tribulation reefs).

4.2 Sediment dynamics

Currents in the nearshore zone are a combination of regional wind generated currents, wave generated longshore currents, wave generated oscillatory motions and tidal currents. These factors combine to give the 'measured' current at any particular time and place. Although research into the relationships between sediment and water movement in the sea has been extensive (Dyer, 1986), sediment transport mechanisms, particularly for fine sediments, is still relatively poorly understood. The early work of Hjulstrom with subsequent modifications and refinements such as Sundborg (1956) (Figures 3 and 4), provide the best basis from which to work. Empirical threshold relationships for the initiation and maintenance of sediment movement have been established. For example, for unconsolidated quartz sediments:

$$U_{100} = 122.6D^{0.29} \text{ for } D < 0.2 \text{ cm}$$

$$U_{100} = 122.6D^{0.45} \text{ for } D > 0.2 \text{ cm}$$

where U_{100} =velocity measured in cm/s,100 cm above the sediment bed and D is the diameter of the sediment grain in cm. This relationship, for a unidirectional flow, is particularly important in the determination of the ability of currents to resuspend material. For the generally recognised upper size boundary for silts and clays (D = 0.0064 cm), U_{100}=28.3 cm/s. For D<0.001 cm, the theory is not well developed, but U_{100} is likely to be not less than 15 cm/s. If there is any consolidation or binding (which is likely in most marine circumstances), U_{100} is likely to be much greater.

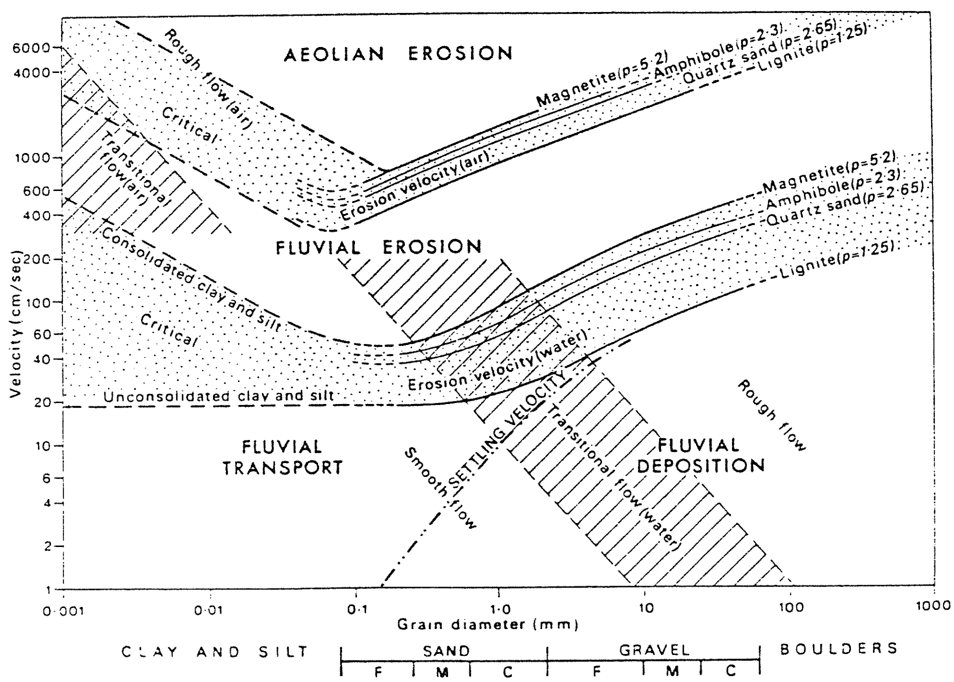

Figure 3: Curves showing relations of grain size to critical fluvial and aeolian erosion velocity for uniform materials of different density. The critical fluvial erosion velocity refers to a height of 1 m above the bed. Source: Chorley <u>et al.</u> (1984).

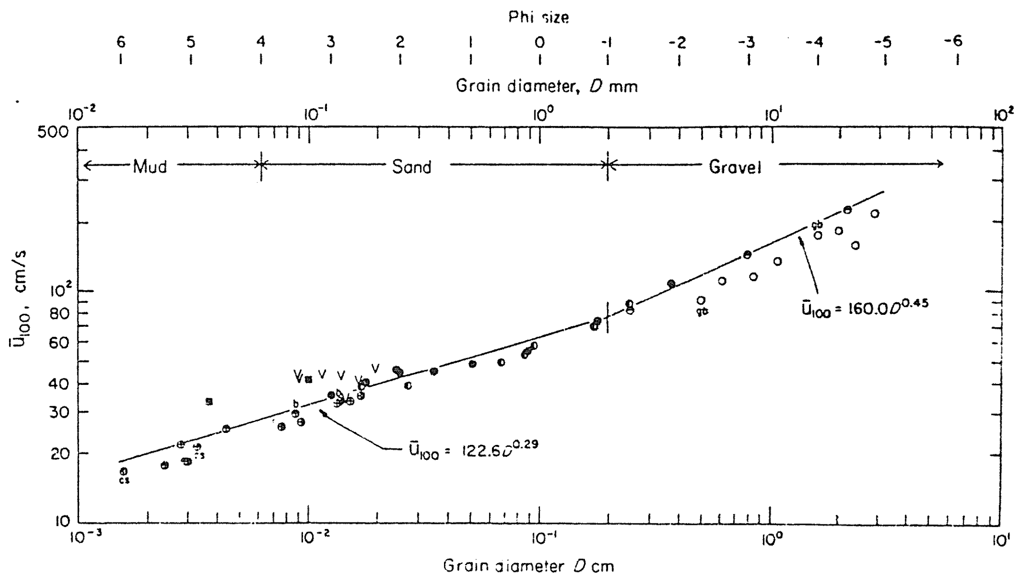

Figure 4: The grain diameter D versus the threshold flow velocity 100 cm above the bed (U_{100}) necessary for the movement of quartz density material in water of temperature 20°C. Source: Miller et al. (1977).

It has been shown that an essential element of sediment transport is the tendency for disturbance to occur in intermittent bursts, even when water velocities are below threshold levels. Such movement has been attributed to the penetration of turbulent eddies (Sutherland, 1967), and has been termed 'turbulent bursting'.

Oscillatory currents established under waves are also able to disturb sediment on the seabed. Using the theory developed by Komar and Miller (1975) and applying their computer simulation (Appendix A) to the modal waves occurring in the GBR lagoon (period T=4 sec (Wolanski et al., 1986), height H = 20 - 150 cm), Table 2 shows that oscillatory motions can cause sediment to be resuspended in water depths from 6.82 m to 15.1 m for sediment sizes D=0.001 cm, and Table 3 shows depths 3.63 m to 12.0 m for sediment size D=0.01 cm. For storm conditions eg T= 8 sec, H=250 cm, disturbance depths are in the order of 40-60 m for sediment sizes D = 0.01 cm - 0.001 cm. Again, for sediments consolidated in any way, thresholds are likely to be much greater.

Table 2: Output from Komar and Miller's (1975) computer programme (Appendix A) examining depth of disturbance from oscillatory currents under waves, for sediment size G=0.001 cm

GRAIN DIAMETER= 0.001 cm
WAVE PERIOD = 4 sec
THRESHOLD ORBITAL VELOCITY, UM= 5.27 cm/s

Wave height (cm)	Depth (cm)	H/L	H/Depth
20	682	0.00844	0.0293
30	854	0.01230	0.0351
40	973	0.01623	0.0410
50	1065	0.02019	0.0469
60	1140	0.02416	0.0526
70	1202	0.02815	0.0582
80	1256	0.03213	0.0636
90	1304	0.036128	0.0690
100	1346	0.040121	0.0742
110	1384	0.044115	0.0794
120	1419	0.048112	0.0845
130	1451	0.052109	0.0895
140	1481	0.056107	0.0945
150	1508	0.060105	0.0994

Table 3: Output from Komar and Miller's (1975) computer programme (Appendix A) examining depth of disturbance from oscillatory currents under waves, for sediment size G=0.01 cm

GRAIN DIAMETER= 0.01 cm
WAVE PERIOD = 4 sec
THRESHOLD ORBITAL VELOCITY, UM= 11.37 cm/s

Wave height (cm)	Depth (cm)	H/L	H/Depth
20	363	0.0099	0.0550
30	528	0.0133	0.0567
40	650	0.0170	0.0614
50	745	0.0208	0.0670
60	822	0.0247	0.0729
70	887	0.0286	0.0788
80	943	0.0325	0.0848
90	991	0.0364	0.0907
100	1035	0.0404	0.0966
110	1074	0.0444	0.1024
120	1109	0.0483	0.1081
130	1142	0.0523	0.1138
140	1172	0.0563	0.1194
150	1200	0.0603	0.1249

In summary, therefore, unidirectional currents >15 cm/s, or modal wave conditions in water depths to about 15 m have the ability to resuspend sediments of silt and clay sizes. However, as research into sediment movement on the seabed continues, it is becoming more obvious that poorly understood modes of current generation such as infragravity waves can cause sediment movement and bedform development in water depths far below that previously established in the literature (Boczar-Karakiewicz and Bona, 1986). It is likely that the estimates above are conservative.

Once in suspension, however, velocities need to fall dramatically before sedimentation occurs. For sediment with D<0.0064 cm, velocities need to fall to below 1 cm/s before it falls to the bottom. This is not likely to occur in any areas generally subjected to a regional, wind driven current. In the context of Cape Tribulation situation, areas of sedimentation are likely to be zones sheltered by reef (at either large or small scales), and very sheltered locations such as may be found in the shallow water of the intertidal areas on calm days. Sediment with D>0.0064 cm requires higher velocities to be maintained to keep it in suspension. This generally means that sand and gravel sediment is deposited close to source, and movement across the bed occurs as bedload or by saltation.

A number of studies in reef environments have shown that despite velocities being too small to initiate major sediment movement, sediment does move (Frith, 1983), this being attributed to bioturbation. Tudhope and Scoffin (1984), Suchanek (1985), Vaugelas (1985) and Parnell (1987) all illustrated the very important role of Callianassa shrimps in the process of sediment movement in reef areas. Other organisms, including Gastropod snails, Holothurians and basking fish perform the same task. The principal role of these organisms is to entrain sediment into the water column by ejecting it upwards. The sediment is then able to be carried in suspension or carried in the water current for a short distance before being redeposited (Figure 5).

The behaviour of sediment in suspension in freshwater streams which then flow into the sea needs to be examined. Freshwater is less dense than saltwater, and will flow in a layer on the surface when it meets the sea. Suspended sediment contained in this layer will remain in it and flow with the freshwater as a surface lens. Mixing will occur, however, and the freshwater lens will reduce in size as mixing progresses away from the stream inflow. In streams which reach the sea by flowing in a wide sheet across the intertidal zone, mixing will occur rapidly.

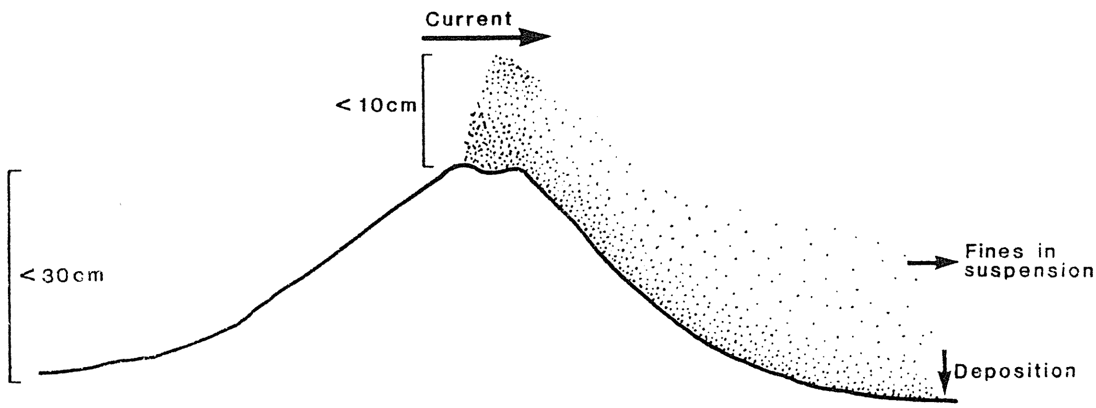

Figure 5: The process of sediment movement in low velocity currents caused by Callianassa burrowing.

When reaching salt water particles in suspension in the silt size range and coarser remain hydraulically independent. However, clays will flocculate (or clump) on contact with salt water, hydraulically behaving as particles of greater size. The degree of flocculation rises in proportion to the clay content of the sediment. The cause of flocculation in salt water is well described by Dyer (1986). The implication of this is that when clay particles in suspension in freshwater first come into contact with saline water (even at salt concentrations as small as 0.6 ppt (Krone, 1978)), they clump together and behave as would a larger particle. In very low velocities this may cause sediment to fall to the bottom.

Flocculation is demonstrated in an experiment by Swales (1988). A sediment sample was dispersed and made up to 15 g/l. Grainsize analysis (using pipette analysis) was undertaken on two subsamples of the dispersed sample (A and B). Further subsamples were then treated with salt at three concentrations (3 ppt, 15 ppt and 35 ppt), and grainsize analyses conducted. The results are reported in Table 4. Although the sediment concentration used in the experiment is greater than that likely in field situations, the results are clear. At salt concentration greater than 15 ppt, the clay sized material ($D>8\phi$ Wentworth or $D<3.9\mu m$) flocculates and behaves hydraulically as silt ($4\phi>D>8\phi$ Wentworth or $3.9\mu m<D<64\mu m$).

Table 4: Flocculation in salt water of sediment at 15 g/l

	Sample treatment				
	Dispersed A	Dispersed B	3 ppt NaCl	1 5 ppt NaCl	35 ppt NaCl
Mean (ϕ)	7.89	8.10	5.77	5.21	5.7
Sorting (ϕ)	2.78	2.84	1.74	0.71	0.45
% Sand	6.8	6.8	6.6	7.4	6.6
% Silt	50.0	47.4	78.7	92.6	93.4
% Clay	43.2	45.8	14.7	0.0	0.0

Importantly, this experiment shows that despite flocculation sediment remains in the silt size classification, probably at the finer end, and the conclusions reported above in relation to sediment movement and transport thresholds remain valid.

With respect to the potential for the deposition of fine sediments in reef environments, recent studies of reef hydrodynamics have assisted in identifying areas of the reef system where velocities are likely to be low, therefore allowing sedimentation to take place. In particular, velocities will be small within eddies shed by headlands or reef at a large scale (see Parnell, 1988 for a review), or eddies caused by individual coral heads (Wolanski and Jones, 1980) at a small scale. Also, velocities are likely to be small across reef flats and in the intertidal zone towards low tide when the water is shallow, with wave energy and associated longshore currents being interrupted by the reef front.

5. Field Results

5.1 Conditions during field studies

Field measurements were undertaken on two occasions, 28-29 January 1988 and 5-7 July 1988. Terrestrial suspended sediment samples were also collected on 30 January 1988. These data are included in Appendix B. It was intended that these field periods would cover winter (predominantly southeasterly winds) and summer conditions (winds from the northwest to east), which would exhibit northward and southward regional circulation in the nearshore zone respectively. However, as indicated in Table 5, southeasterly winds dominated during both sampling periods. During the field periods, there was little rain, with a maximum daily recording of 15 mm on one day during the July field period. Significant differences in stream discharge did not occur during the sampling periods. Tide data for the experimental periods are given in Table 6.

Table 5: Wind data during experimental periods

Date (1988)	Time (h)	Vel. (m/s)	Direction(°)
28 Jan	1015	7-8	115
28 Jan	1352	7-8	115
29 Jan	0846	5	115
5 Jul	1220	6	160
5 Jul	1515	6-7	150
6 Jul	1310	8-9 (Gust 12)	135
7 Jul	0840	6-8 (Gust 9)	135
7 Jul	1005	7-10	135
7 Jul	1150	6-12 (Av. 9)	135

Table 6: Tidal data during experimental period (Cairns:Standard Port)

Date	Time (h)	Height (m)	Date	Time (h)	Height (m)
28 Jan	0705	2.49	5 Jul	0135	2.39
	1314	1.18		0819	0.82
	1844	1.87		1418	1.66
				1944	0.96
29 Jan	0042	0.56	6 Jul	0240	2.19
	0742	2.68		0932	0.76
	1347	1.08		1551	1.76
	1927	1.92		2128	1.19
			7 Jul	0349	2.02
				1037	0.66
				1723	1.98
				2308	1.25

5.2 Cape Tribulation hydrodynamics

Water velocity and direction data collected 28-29 January 1988 are presented in Table 7, with the location of measurement sites and an indication of movement direction given in Figure 6. Data for the period 5-7 July 1988 are presented in Table 8 and Figure 7.

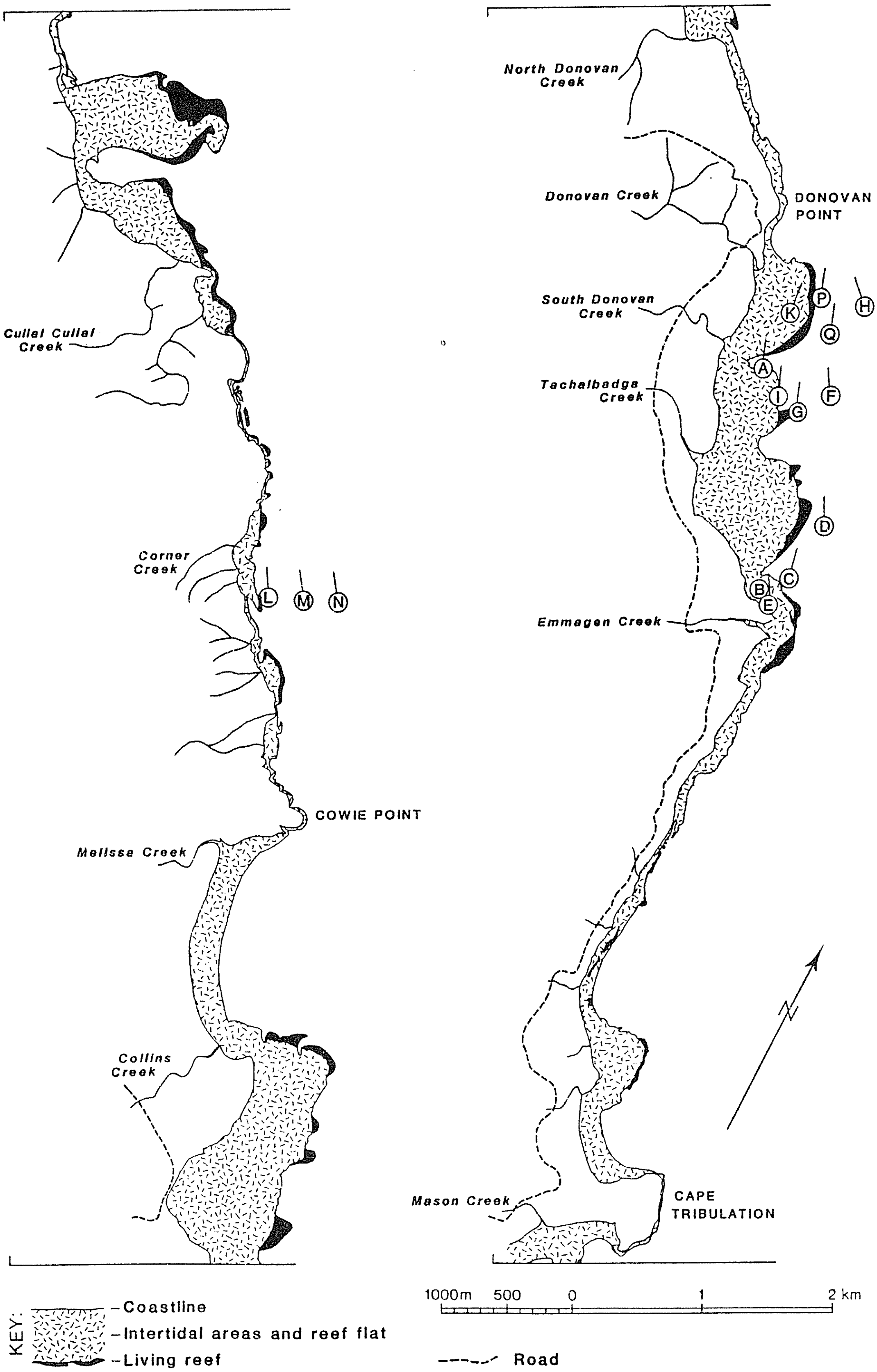

Figure 6: Water velocity and direction measurement sites, 28-29 January 1988.

Table 7: Water velocity and direction data 28-29 January 1988

Site#	Date	Time(h)	Depth (m)^	Vel.(m/s)	Dir (°)	Method*
A	28	1005	1	0.10	330	D
B	28	1015	1	0	---	D
C	28	1035	1	0.05	338	D
D	28	1038	1	0.25	325	D
E	28	1051	1	0.05	315	D
F	28	1100	1	0.17	310	D
G	28	1105	1	0.20	330	D
F	28	1125	1	0.31	320	C
F	28	1125	4	0.18	320	C
F	28	1134	1	0.25	320	D
H	28	1420	1	0.25	305	D
I	28	1430	1	0.10	315	D
K	28	1440	1	0.10	348	D
L	29	0915	5	0.10	320	C
L	29	0915	4	0.19	320	C
L	29	0915	1	0.21	320	C
L	29	0915	1	0.18	320	D
M	29	0935	5	0.10	314	C
M	29	0935	4	0.19	314	C
M	29	0935	1	0.21	314	C
M	29	0935	1	0.16	314	D
N	29	1006	5	0.14	315	C
N	29	1006	4	0.19	315	C
N	29	1006	1	0.27	315	C
N	29	1006	1	0.20	315	D
P	29	1104	5	0.13	335	C
P	29	1104	4	0.12	335	C
P	29	1104	1	0.27	335	C
Q	29	1200	5	0.14	330	C
Q	29	1200	4	0.24	330	C
Q	29	1200	1	0.32	330	C

Notes:
\# Site location, see Figure 6
^ Depth from surface. Due to the dye being slightly heavier than seawater, it tends to settle just below the surface.
* C= Ott current meter, D=Rhodamine WT dye.
The use of dye tends to underestimate true velocity, due to dye at subvisible concentration moving at the front of a dye cloud. Tethered current meters tend to overestimate true velocity due to vertical boat movement being reflected in the velocity reading.

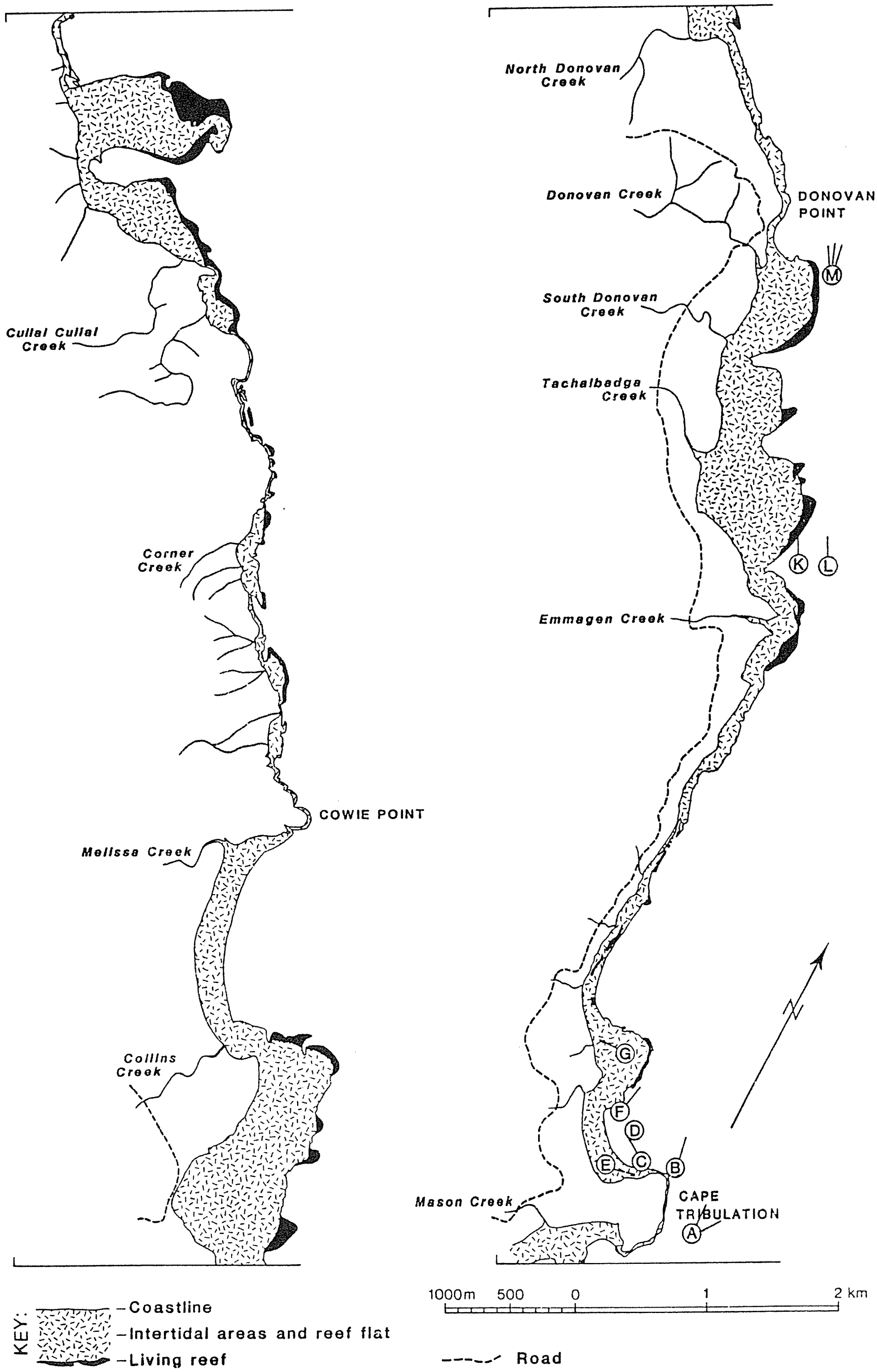

Figure 7: Water velocity and direction measurement sites, 5-7 July 1988.

Table 8: Water velocity and direction data 5-7 July 1988

Site#	Date	Time(h)	Depth (m)^	Vel.(m/s)	Dir (°)	Method*
A	5	1220	1	Fast	350	D
B	5	1235	1	0.33	340	D
C	5	1240	1	Very Slow	290	D
D	5	1250	1	0.0	---	D
E	5	1255	1	Very Slow	070	D
F	5	1300	1	Very Slow	360	D
G	5	1305	1	Slow	260	D
A	5	1630	1	0.25	025	D
K	6	1330	1	0.35	320	C
K	6	1330	4	0.31	320	C
L	6	1350	1	0.35	320	C
L	6	1350	4	0.28	320	C
M	7	0845	1	0.20	330	C
M	7	0845	4	0.17	330	C
M	7	0845	1	0.16	330	D
M	7	0905	1	0.23	336	C
M	7	0905	4	0.18	336	C
M	7	0925	1	0.20	320	C
M	7	0925	4	0.16	320	C
M	7	1005	1	0.24	320	C
M	7	1005	4	0.15	320	C
M	7	1030	1	0.24	330	C
M	7	1030	4	0.18	330	C
M	7	1030	1	0.18	330	D
M	7	1150	1	0.25	340	C
M	7	1150	4	0.18	340	C

Notes:
Site location, see Figure 7
^ Depth from surface. Due to the dye being slightly heavier than seawater, it tends to settle just below the surface.
* C= Ott current meter, D=Rhodamine WT dye.
The use of dye tends to underestimate true velocity, due to dye at subvisible concentration moving at the front of a dye cloud. Tethered current meters tend to overestimate true velocity due to vertical boat movement being reflected in the velocity reading.

Velocity and direction data indicate that circulation is driven by the wind, either locally or regionally. Flow directions out of the influence of eddies shed by headlands and fringing reefs are generally parallel to the coast, with velocities highest in the vicinity of headlands. Tidal influences under moderate wind conditions appear to be negligible, with no significant change in flow direction or velocity between ebb and flood tides (for example, site M in table 8). Across reef flats, and in the lee of reef framework and headlands, flows are disturbed, and generally slower than in undisturbed water. For example, there is a distinct eddy within the bay to the north of Cape Tribulation (Figure 7). Wave generated circulation becomes significant across reef flats. There does not appear to be significant direction of flow shoreward up discontinuities in the reef front. In undisturbed water (not immediately off a headland, across a reef flat or in an eddy), surface velocities tend to be in the order of 0.2-0.4 m/s, decreasing with depth. Within 1-3 m of the seabed, velocities are in the order 0.1-0.2 m/s.

At 1455h on 5 July 1988 (ebb tide) , 1 litre of Rhodamine WT was released in the mouth of Emmagen Creek. The behaviour of the dye patch is illustrated in Figure 8. Dye moved seaward until it reached the northward current at the reef front, then turned north. Its progress was mapped until 1534h, when it was approximately 600 m north of Emmagen Creek, and then observed continuing to move north. The dye cloud, once clear of the reef front moved north in deeper water, well seaward of the reef front.

The experiment was repeated on the flood tide on 6 July (injection at 1230h). Dye was injected at a location outside the mouth of the creek so that the flood current would not carry the dye into Emmagen Creek, thus simulating a situation during flood conditions where freshwater inflow flows seaward down the Emmagen Creek estuary even during flood tides (Figure 9). Dye again crossed the reef front just to the north of the creek entrance, and moved as a narrow patch, with a clear advection axis well clear of the reef front. The dye patch did not disperse as rapidly as in the earlier experiment due to the different injection location and strategy.

A similar experiment was conducted at the mouth of South Donovan Creek, with injection of dye in an indentation in the reef framework, into which river water appeared to flow after crossing the reef flat as a wide shallow sheet. Movement was very slow in the early stages (Figure 10), until the dye reached the dominant northward current, after which dispersion and movement was faster. The dye moved along the living reef zone, then moved seaward off the reef and progressed northward in deeper water.

5.3 Suspended sediment concentrations

Suspended sediment samples were collected at sites indicated in Figure 11, during both sample periods (January, sites A-J; July, sites 1-6). Results are given in Table 9.

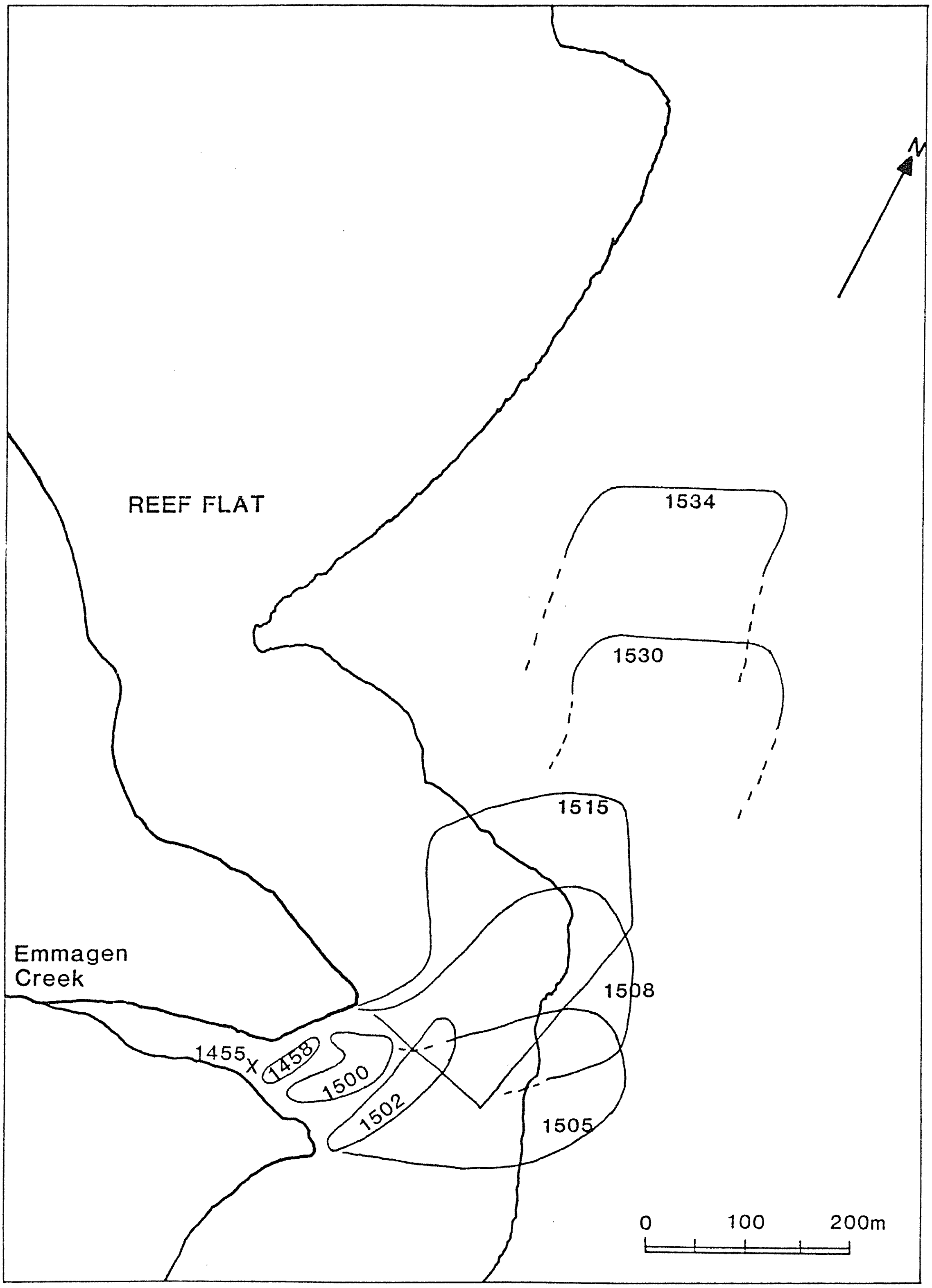

Figure 8: Movement of Rhodamine WT dye injected at site (x) at 1455h on 5 July 1988

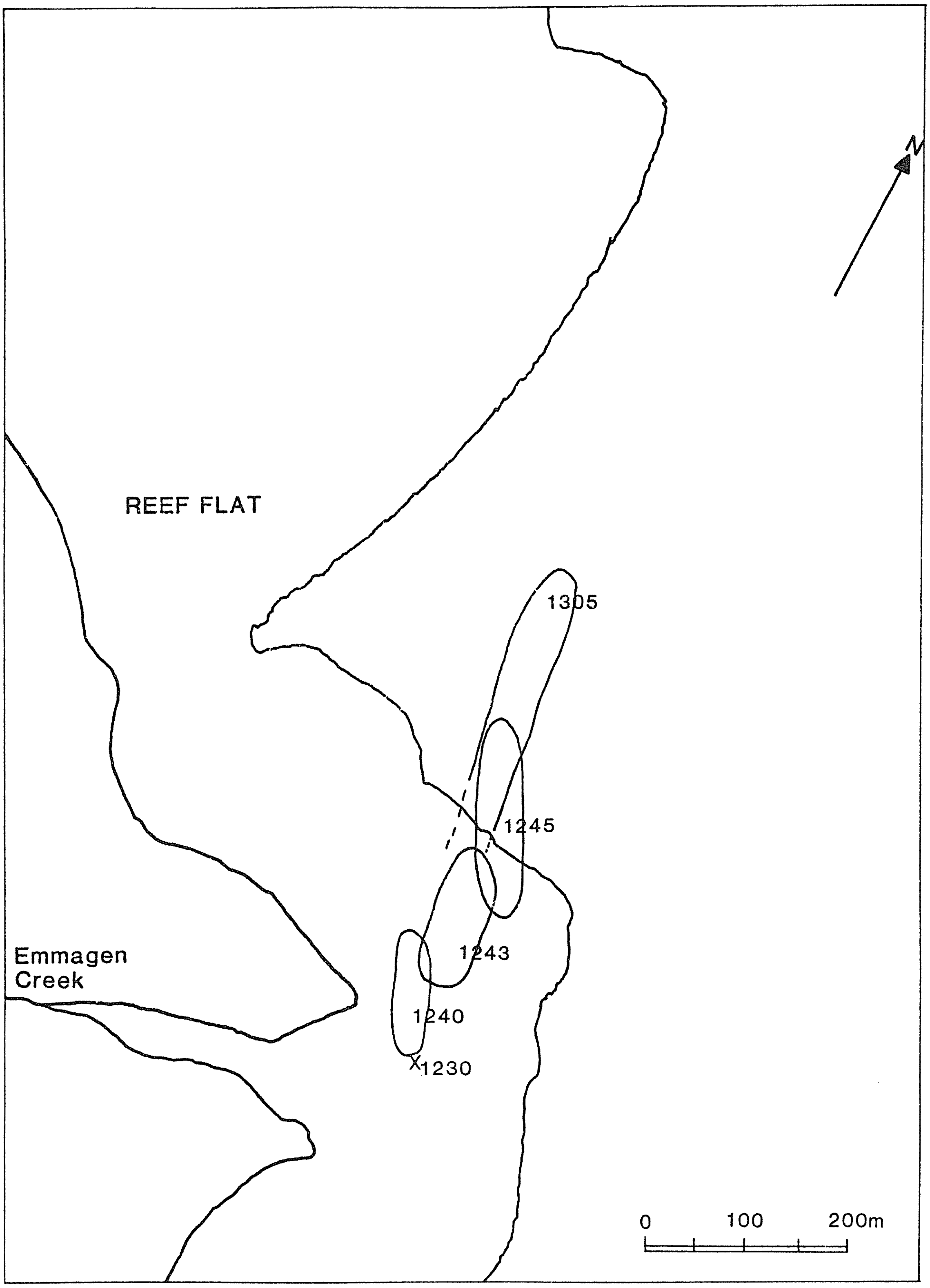

Figure 9: Movement of Rhodamine WT dye injected at site (x) at 1230h on 6 July 1988

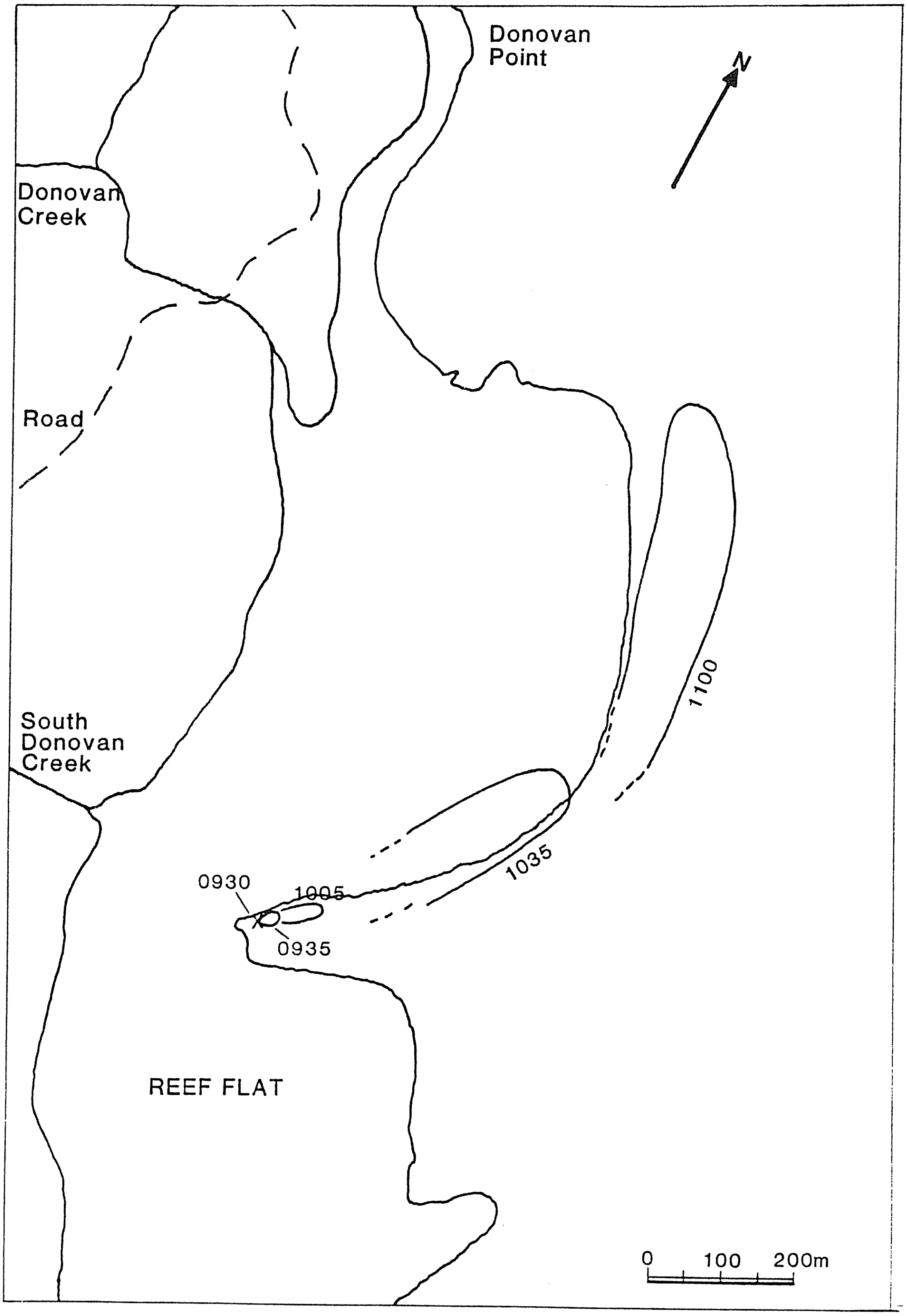

Figure 10: Movement of Rhodamine WT dye injected at site (x) at 0930h on 7 July 1988

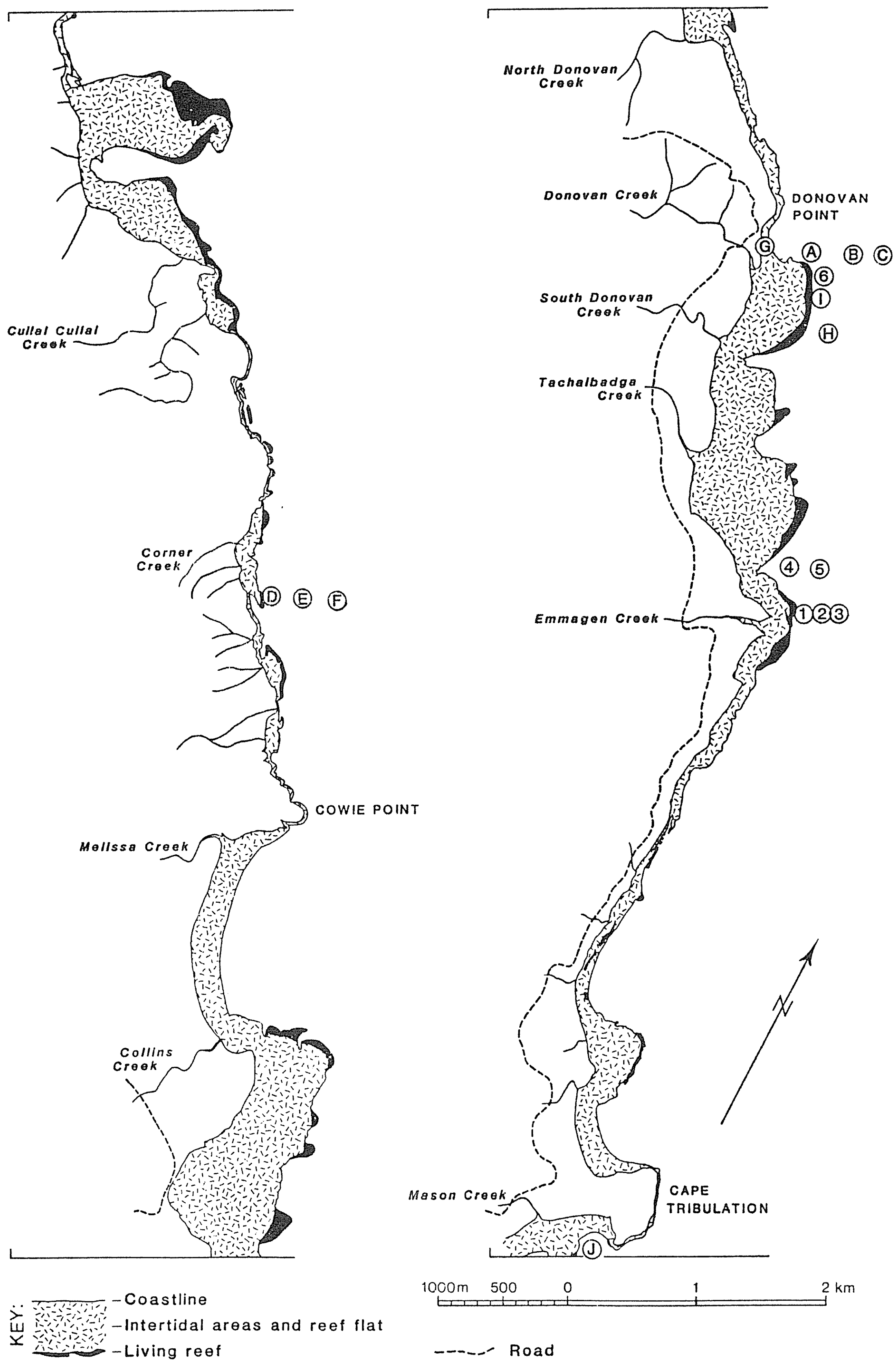

Figure 11: Suspended sediment concentration sampling sites in January 1988 (sites A-J) and July 1988 (sites 1-6).

Table 9: Suspended sediment concentrations

Site	Date	Time	Depth (m)	Sample depth (m)	Susp. sed. (mg/l)
A	28/1	1400	5	Surface	124.5
				4	112.1
				Bottom	186.4
B	28/1	1408	8	Surface	113.7
				4	84.1
				Bottom	210.1
C	28/1	1415	11	Surface	88.0
				4	97.9
				Bottom	104.9
D	29/1	0915	8	Surface	64.9
				4	110.9
				Bottom	113.9
E	29/1	0936	?	Surface	91.5
				4	90.3
				Bottom	166.1
F	29/1	1006	?	Surface	116.8
				4	116.9
				Bottom	172.3
G	29/1	1315	Surf zone		154.8
H	29/1	1145	7	Surface	92.6
				4	71.7
				Bottom	136.3
I	29/1	1104	5	Surface	97.6
				4	97.9
				Bottom	113.5
J	29/1	1500	?	Bottom	269.6
1	6/7	1250	?	Surface	50.3
2	6/7	1250	?	Surface	69.6
3	6/7	1250	?	Surface	50.3
4	6/7	1330	6	Surface	57.6
				5	54.3
				Bottom	66.9
5	6/7	1350	8	Surface	61.6
				7	53.3
				Bottom	74.6
6	7/7	0830	6	Surface	32.9
				5	51.6
				6	93.6
6	7/7	1037	6	Surface	47.6
				5	54.3
				Bottom	62.3

6	7/7	1150	6	Surface	59.9
				5	71.3
				Bottom	101.3

Note: Bottom samples were taken as close to the bottom as practical without disturbing seabed sediments. Samples were collected using a hand pump, and placed in 1 litre plastic containers. Concentrations were determined using filtration.

Suspended sediment concentrations were significantly higher during the January sampling period than during the July sampling period. The reason for this is not known, as wind conditions were approximately the same during both periods. Suspended sediment concentrations generally increase towards the seabed, typically by a factor of 1.5 to 2. There is no observable spatial pattern to the data.

During the July sampling period, samples were collected at site 6 over an ebb, slack water, flood tide sequence with no significant differences in suspended sediment concentrations being recorded.

5.4 Seabed sediments

Surficial sediment samples were collected at sites indicated in Figure 12, during the January 1988 sampling period. These were analysed for percentage mud (>4ϕ or <64μm) and %sand (<4ϕ or >64μm) using wet sieve techniques. Results are presented in Table 10.

Table 10: Sediment size analysis, seabed sediments

Site	Mud (%)	Sand (%)
N1	50.6	49.4
N2	39.4	60.6
N3	52.3	47.7
D1	37.8	62.2
D2	35.2	64.8
D3	50.8	49.2
M	0.2	99.8

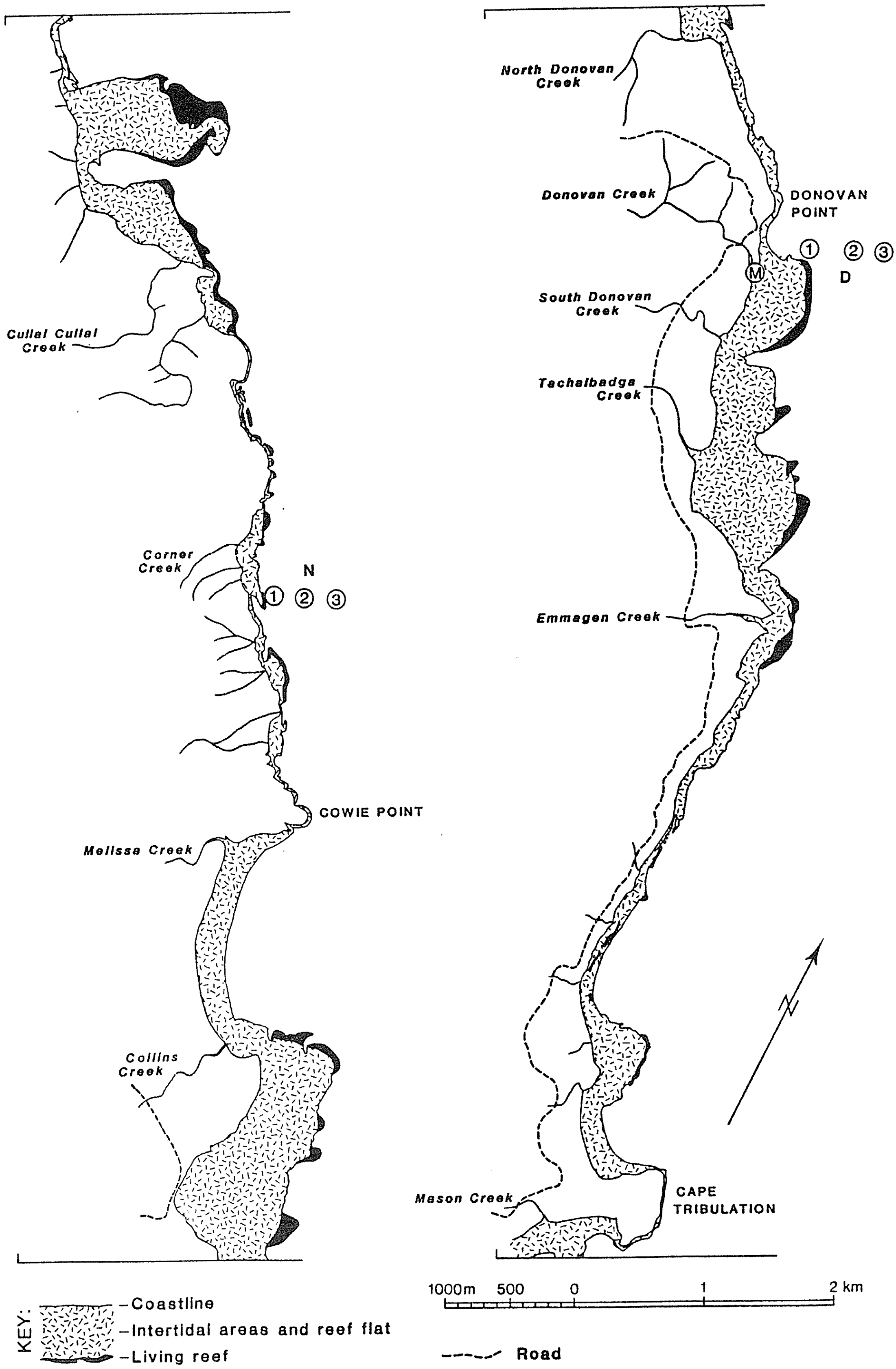

Figure 12: Surficial sediment sampling sites.

Although the sample is small, there is general agreement with the findings of Johnson and Carter (1987) who report sediments north of Donovan Point as comprising 25-71% muds. There is some suggestion from the data above of a fining of sediment away from the land, and higher mud percentages to the north of the study area. This is in general agreement with the findings of Hoyal (1986). However, at all sites, there is ample surficial sediment available for resuspension in the mud size range.

Sample M, taken from the sediment fan where the Donovan Creek estuary flows as a wide shallow sheet across the intertidal area, has a very low percentage of mud. This indicates that fine sediment deposited in this zone is resuspended rapidly. This supports Hoyal's (1986) finding that sedimentation rates across the sand and reef flat are low.

6. Discussion

It was unfortunate that typical 'summer' conditions were not present during the January 1988 sampling period. It was, therefore, not possible to confirm current reversals and any tidal modifications which are thought to occur during periods of northerly winds. However, it is reasonably certain from information available for nearby areas that flow reversal occurs but with lower associated velocities and wave heights (except during periods affected by cyclonic events). Freshwater inflow during these periods are likely to be high with greater quantities (but perhaps not concentrations) of suspended sediments being delivered to the reef flat via the rivers.

The narrow range of conditions sampled means that the conclusions based on application of the theory and field results to other than moderate southeasterly wind conditions (particularly calm conditions and northerly winds) are subject to higher errors. However, if there is a significant nearshore current from either direction, and/or wave action, sediments are likely to be disturbed and transported, with velocities needing to fall significantly before sedimentation will occur.

Nearshore water circulation in the Cape Tribulation area appears to be simple, being wind driven with negligible tidal influence although confirmation of this based on long tem observations would be helpful. In bays in the lee of headlands, across reef flats and in the vicinity of reef framework, water flows are disturbed, with velocities generally low and flow directions diverse (although generally predictable).

It is shown that the potential for resuspension of fine sediments from the nearshore zone to water depths of at least 15 m is high, even for modal wind and wave conditions. Bioturbation in the surface sediments will increase the likelihood of resuspension. It is clear that given the high proportion of fine particles in the surficial sediments in the nearshore zone, resuspension will result in turbid water, with high suspended sediment concentrations, almost all year round. It is likely that Cape Tribulation fringing reefs have always developed with high suspended sediment concentrations. During periods of high freshwater inflow, suspended sediments will be delivered from the mainland via the rivers, but except for periods of very high rainfall, resuspended sediments are likely to dominate. It is unfortunate that mineralogical tracing of suspended sediments is not possible to determine the relative proportions of resuspended and river derived particles.

Experiments in the South Donovan and Emmagen river mouths showed that mainland derived suspended sediments flowing in the rivers are likely to cross the living reef within a relatively short distance of their mouths, and then flow in the higher velocity areas seaward of the reef front. Suspended sediments are likely to flow for some distance in a lower density surface lens.

Sediments, once in suspension, are likely to remain in the water column for a considerable period, as velocities must fall to less than 1 cm/s before deposition will occur. Therefore, zones of potentially high sedimentation can be identified as areas of near stagnation. Such zones include areas of the reef flat when the water is shallow (although resuspension of this sediment is likely when the tide rises), crevices and small indentations in the reef framework, and in eddies behind headlands and in the vicinity of reef framework. The conclusion made by Hoyal (1986) that temporal trends in sedimentation caused by rainfall and wind conditions are more significant than spatial trends are supported by this study. Sand sized sediment is likely to be deposited close to source and moved by saltation.

Periods of heavy rainfall coinciding with calm conditions have the potential for significant sedimentation. This situation is the most speculative with respect to the theory and field data available. It is also the period for which relevant data is most difficult to obtain, because of the difficult access to Cape Tribulation during periods of heavy rainfall. Under this circumstance the following physical situation is likely to exist:

a. Low nearshore velocities, with the possibility of tidal reversals dominating
b. No wave generated longshore current
c. No resuspension of seabed sediment caused by wave oscillatory motions
d. High freshwater inputs, with high total loads of suspended sediments.

Because of the lower velocities the potential for sediment deposition is higher. However, given that the suspended sediment will be contained in a freshwater body which will retain some integrity in the vicinity of the reef due to reduced potential for mixing, and given that velocities would need to fall to below 1 cm/s before sedimentation occurs, it is likely that except for limited extremely sheltered areas, sediment deposition near the reef would not be significant. Much of the sediment deposited would then be resuspended following an increase in wind speed and wave energy.

7. Conclusions

1. This study is limited to some extent by the range of conditions (moderate southeasterly winds, low rainfall) present during the field periods. The conclusions, which are primarily based on nearshore coastal process theory and tested with simple field measurements, should be reliable for periods when wind and wave generated nearshore currents occur. Conclusions for calm periods, and to a lesser extent northerly wind conditions, are more speculative.

2. The hydrodynamics of the Cape Tribulation area are dominated by currents driven by winds, with a predominantly northward flow parallel to the coast during periods of southeasterly winds. Although not measured during the sampling periods, a southward flow is likely to dominate during periods of winds with a northerly component. Tidal influences on nearshore circulation during periods of moderate winds appear to be negligible, but may become significant during calm periods. Waves approaching the coast at

an oblique angle cause unidirectional longshore currents, which reinforce the current in the nearshore zone. Waves drive oscillatory motions in the nearshore zone.

3. Nearshore circulation is modified by local morphology with eddies within bays in the lee of headlands and in the lee of reef framework. When waves are present, wave action drives circulation across the reef flats, except towards low tide when the water is shallow, when tidal shore normal movement dominates. In intertidal areas with no seaward reef framework wave processes dominate.

4. Under modal wave conditions (H = 0.2-1.5 m), oscillatory motions caused by waves are sufficient to resuspend fine sediments from the seabed to water depths at least in the order of 6 to 15 m. Under storm conditions depths of disturbance are much greater. Under moderate southeasterly winds non-oscillatory currents near the seabed are at the lower end of the range able to resuspend sediments. Bioturbation and turbulent bursting, however, will assist resuspension. Surficial sediments contain high proportions of muds able to be resuspended. Once in suspension, velocities must fall below about 1 cm/s before sedimentation occurs. Waters in the Cape Tribulation area are, therefore, characteristically turbid under modal wind and wave conditions. During storm events, turbidity and suspended sediment concentrations will be higher. Areas susceptible to high sedimentation rates can be identified as areas of near zero velocity, such as in eddies, and in crevices and indentations in reef framework.

5. Sedimentation potential is greatest under high rainfall and low wind conditions. The results of this study are speculative for this combination of events. River derived suspended sediment will be contained within a freshwater body flowing over the reef flat. Velocities, once the freshwater reached deeper water, would need to fall below about 1 cm/s before significant sedimentation could occur, This is likely to occur infrequently. Much of the sediment deposited would be resuspended following an increase in wave energy.

6. Except in the case of Emmagen Creek, streams flowing into the sea in the Cape Tribulation area flow from occasionally breached estuarine systems as wide shallow bodies of water across the

intertidal areas and reef flats. For both small and large streams, the water will tend move as a less dense surface flow across the reef in a fairly narrow band before moving in the dominant current seaward of the fringing reef. Clay sized suspended sediment contained in the fresh water will flocculate as salinity increases with mixing, but will remain in suspension. The area potentially affected by increased sedimentation will be restricted to a narrow zone near the stream mouth. However, except in rare circumstances, most sediment should remain in suspension beyond the fringing reef. Fine material does not remain in the intertidal sediments.

7. The corals of the Cape Tribulation area are likely to developed with high suspended sediment concentrations in the water column, with suspended sediments primarily being derived from resuspension of seabed sediments. Sediments flowing in streams will add significantly to suspended sediment concentrations only during extreme events, with only localised increased sedimentation on the reef flat and in the zone of living reef.

8. References

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10. Appendices

Appendix A: Computer programme in Microsoft Basic adapted from the Fortran version by Komar and Miller (1975), to examine the depths of disturbance caused by oscillatory motion under waves

```
G=981!
PIE=3.1416
RHOW=1!
DIAM=.001
RHOS=2.65
IF DIAM<.05 THEN GOTO LAB5:
A=.463*PIE
B=.25
GOTO LAB7:
LAB5:A=.21
B=.5
LAB7:PWR=1!/(2!-B)
FAC = (A*(RHOS-RHOW)*G/(RHOW*PIE^B))^PWR
FAC1=FAC*DIAM^((1!-B)*PWR)
T=3!
INPUT "FILEOUT";FILEOUT$
OPEN "O",#3,FILEOUT$
FOR I=3 TO 10
LO=156.13*(T^2)
UM=FAC1*(T^(B*PWR))
PRINT #3,"GRAIN DIAMETER=",DIAM
PRINT #3, "WAVE PERIOD =",T
PRINT #3, "ORBITAL VELOCITY,UM=",UM
LAB9:
REM  INCR WAVE HGT, CAL DEPTH
H=10!
FOR K=1 TO 60
SING=PIE*H/(UM*T)
X=SING
IF X<1! THEN GOTO LAB30:
ASINH=LOG(2!*X)+
(.25/X^2!)-(.09375/X^4!)+(.05208/X^6!)-(.03418/X^8!)+(.02461 /X^10!)
GOTO LAB32:
 LAB30:ASINH=X-.16666*X^3!+.075*X^5!-.04464*X^7!+.03038*X^9!-
.02237*X^11!
LAB32:
F1= (EXP(ASINH)-EXP(-ASINH))/2
F2=(EXP(ASINH)+EXP(-ASINH))/2
LI=LO*(F1/F2)
DPTH=ASINH*LI/6.2832
REM CHECK WAVE STAB
RATIO=H/DPTH
IF RATIO>=.78 THEN GOTO LAB11:
STEEP=H/LI
TEST=.142*(F1/F2)
IF STEEP>=TEST THEN GOTO LAB11:
PRINT #3,H,DPTH,STEEP,RATIO
LAB10:
LAB11:H=H+10!
NEXT K
T=T+1!
NEXT I
CLOSE #3
END
```

Appendix B: Terrestrial suspended sediment data (1988)

Date	Time	Site	Susp Sed (mg/l)
30 Jan	0920	Emmagen Ck, above road	1.1
30 Jan	0920	Emmagen Ck, below road	5.5
30 Jan	0940	Donovan Ck, above road	31.6
30 Jan	0940	Donovan Ck, below road	29.9
30 Jan	0940	Donovan Ck, well above road	4.6
30 Jan	0930	Tachalbadga Ck, above road	14.2
30 Jan	0930	Tachalbadga Ck, below road	61.9
5 Jul	1040	Emmagen Ck, above road	0.3
5 Jul	1040	Emmagen Ck, below road	3.3
5 Jul	1020	Donovan Ck, above road	0.9
5 Jul	1020	Donovan Ck, below road	7.3
5 Jul	1000	North Donovan Ck A, above road #	5.3
5 Jul	1000	North Donovan Ck A, below road #	54.6
5 Jul	1000	North Donovan Ck B, above road #	11.9
5 Jul	1000	North Donovan Ck B, below road #	34.3
5 Jul	0945	Melissa Ck, above road	18.3
5 Jul	0945	Melissa Ck, below road	8.3
5 Jul	1030	Tachalbadga Ck, above road	12.6
5 Jul	1030	Tachalbadga Ck, below road	11.3
5 Jul	0915	Ditch by road above Donovan point	3607.6

North Donovan Creek has two tributaries, A to the north, B to the south. The southern tributary (B) receives obvious runoff from the road upstream of the road.

Appendix C : Wentworth size classification for sediment grains (Source: Leeder, 1982)

	US Standard sieve mesh	Millimeters		Phi (ϕ) units	Wentworth size class
GRAVEL	Use wire squares	4096		−12	
		1024		−10	boulder
		256	256	− 8	
		64	64	− 6	cobble
		16		− 4	pebble
	5	4	4	− 2	
	6	3.36		− 1.75	
	7	2.83		− 1.5	granule
	8	2.38		− 1.25	
	10	2.00	2	− 1.0	
SAND	12	1.68		− 0.75	
	14	1.41		− 0.5	very coarse sand
	16	1.19		− 0.25	
	18	1.00	1	0.0	
	20	0.84		0.25	
	25	0.71		0.5	coarse sand
	30	0.59		0.75	
	35	0.50	1/2	1.0	
	40	0.42		1.25	
	45	0.35		1.5	medium sand
	50	0.30		1.75	
	60	0.25	1/4	2.0	
	70	0.210		2.25	
	80	0.177		2.5	fine sand
	100	0.149		2.75	
	120	0.125	1/8	3.0	
	140	0.105		3.25	
	170	0.088		3.5	very fine sand
	200	0.074		3.75	
	230	0.0625	1/16	4.0	
SILT	270	0.053		4.25	
	325	0.044		4.5	coarse silt
		0.037		4.75	
		0.031	1/32	5.0	
		0.0156	1/64	6.0	medium silt
	Use	0.0078	1/128	7.0	fine silt
	pipette	0.0039	1/256	8.0	very fine silt
CLAY	or	0.0020		9.0	
	hydro-	0.00098		10.0	clay
	meter	0.00049		11.0	
		0.00024		12.0	
		0.00012		13.0	
		0.00006		14.0	