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.

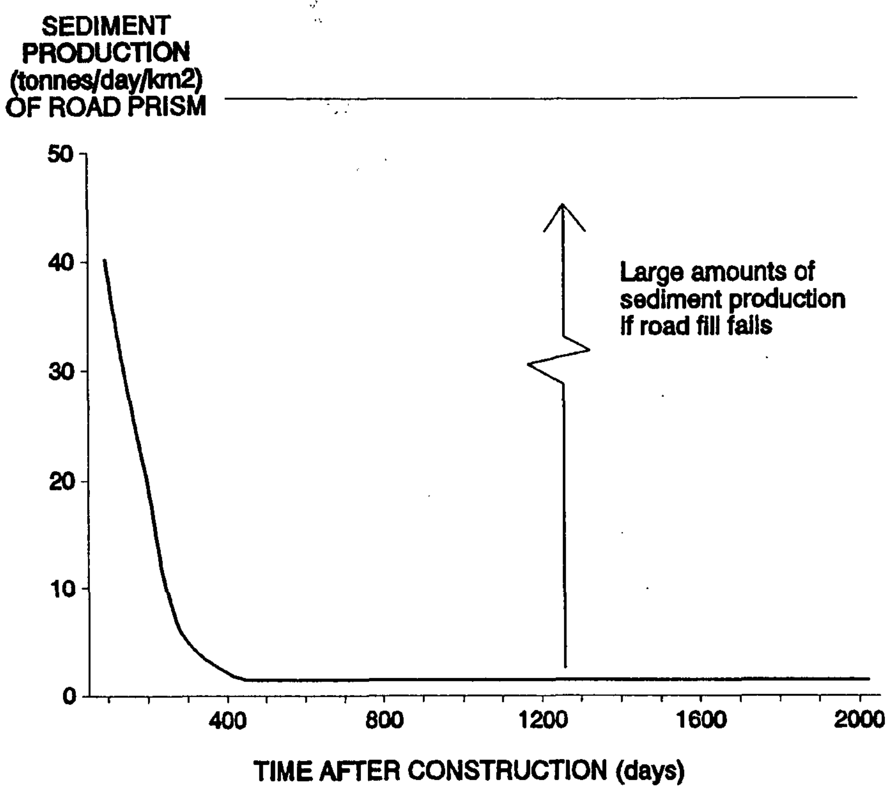

FIGURE 1. Response of rainforest catchments to road construction after O'Loughlin (1985).