South Pacific Regional Environment Programme

Transporting Sediments via Rivers to the Ocean, and the Role of Sediments as Pollutants in the South Pacific

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Foreword

Monitoring the Environment through research and studies is something quite new to the Pacific islands region. It remains somewhat unknown and unimportant until a tragic event happens to people through a change in the environment. If decision makers do know the importance of monitoring is to mankind, they normally do not highlight for fear that it would affect next year's national budget. Monitoring the environment to discover its natural equilibrium is not usually a priority for the budget of any country in the region. So, without outside financial commitment, monitoring is not feasible.

SPREP's Pollution Emergency and Management Programme area (SPREP-POL) focuses on research into pollution indicators, such as sediments and chemicals. This study is a preliminary regional review and assessment of different sediments transported by rivers into the ocean as possible pollutants.

This review provides useful baseline data for future studies in this area. This is an important area of research as sediment loads could be a pollution indicator for the marine environment in the South Pacific region.

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1. Introduction

1.1 General Introduction to the Study

In the South Pacific, pollution due to sedimentation has been identified as a major and potential problem (Phang et al, 1988; Kinsey, 1988; Tsuchiya et al, 1989). Suspended matter can have an extremely detrimental effect on coastal ecosystems (Holthus, 1991), particularly coral reefs, mangroves and marine nursery areas.

In addition to causing problems because of their particulate nature, sediments can also act as a vehicle for the transportation of pollutants including heavy metals, pesticides and other organic substances. Long term prediction of the quantities of the materials which are delivered to the ocean, or distributed in estuaries, coral reefs and other parts of the coastal zone, depend on the rates of storage and composition of the sediments delivered from within the catchment, and their storage, transport and mixing behaviour once in the coastal zone.

A knowledge of sediment dynamics both within the catchment and the coastal zone is of particular importance in establishing upstream-downstream conveyance relationships and for determining patterns of sediment distribution in and supply to the littoral environment.

The effects of sediment additions to the coastal environment in the South Pacific are not well understood. The ecological impact on mangroves, reefs and coastal fish breeding areas have been studied but not in any detail and there is virtually no information on the economic implications of such pollution. Where the impact of suspended sediment has been studied, determination of the source of the sediment is usually overlooked. It is widely believed (and there is supporting evidence) that changing land use patterns such as logging activities and intensifying agriculture are contributing to changes, such as alterations in the water balance, the runoff regime and increased sediment loads. Evidence that includes quantification of the linkage between cause and effect is, however, very rare.

As the South Pacific region is particularly active tectonically active and has both very intense and spatially/temporally highly variable rainfall, recent changes in land use and the rapid increase in coastal development plus mining activities have produced markedly increased sediment loads, it is important to determine the potential impact of these enhanced sediment loads.

1.2 Objectives

The objectives of this project were to:

- review the present state of knowledge on the amounts and the effects of suspended material transported to the oceans by rivers in the South Pacific;
- review the causes of higher anthropogenically-generated sediment loads in South Pacific rivers;
- review the effects of increased sediment loads on coasts and coastal ecosystems in the South Pacific.
- review the current state of knowledge and techniques regarding the assessment of the economic value of impact of increased sediment loads.
- estimate, the quantities of nutrients, metals and organic substances, entering the marine environment via sediment.
- investigate and review common procedures for representative sampling and quantitative assessment of river suspended solids; particularly techniques suitable for routine use in some of the more remote parts of the region.

1.3 Workplan and Methods

The project was carried out in four steps.

1. A survey of sediment loads carried by rivers to the coastal zone was made using available and published data. Data such as total and mean water discharge was available for a number of rivers and areas in the region, and these values were used to assess the accuracy and applicability of an empirical model used to estimate the load of rivers where no direct observations have been undertaken. This data was assimilated into an estimate of the total suspended sediment load transported by fluvial systems into the South Pacific Ocean.
2. A review of the causes of increased (anthropogenic) sedimentation was made in order to facilitate the preparation of recommendations for the mitigation of the impacts of increased sedimentation. The review includes the effects of changing land use, land management techniques and development activities. The impact of the increased sediment loads on coastal ecosystems has also been reviewed with particular reference to mangroves and coral reef systems.

   This section also contains a study of the flux and fate of sediment once in the coastal zone. A special case study is presented regarding the Torres Strait and Gulf of Papua as a representation of the largest area of continental shelf area in the South Pacific. This review has facilitated the determination of what information is currently available and identification of problems requiring further study.
3. Soil nutrient data has been collected to facilitate the calculation (in conjunction with the total suspended load calculation) of a nutrient movement load value for the whole region.
4. A review and evaluation of various methods used to determine sediment loads has been made in an attempt to locate a method, of sufficient accuracy and technical simplicity, to be used widely in the South Pacific region for extending the data base of suspended sediment transport.

2. Regional Sediment Yield Value for the South Pacific

2.1 Data Availability and Approaches to the Problem

One of the primary aims of this investigation was to estimate the total suspended sediment load of rivers carried to the coast for the South Pacific region. As extended or detailed sampling programmes were impractical given the resources available, and the existing primary data base was minimal, it was decided that the estimate be made by an empirical model. An estimate made by such a model, although unsubstantiated by extensive field testing, could be compared with existing data to assess the validity of the estimate and the plausibility of the model. This chapter presents a rationale for the selected method, tests and executes that method, presents the results of the regional calculation, discusses the findings and draws some tentative conclusions.

2.1.1 Rationale and Methodology for an Empirical Procedure

The calculation of a regional sediment yield estimate using an empirical model had to be made under a number of limiting assumptions (outlined below). It must, therefore, be expounded that the estimate was made in the absence of any known comprehensive regional calculation of sediment yield. The resulting estimate, while largely unsubstantiated by measured sediment yield data, provides a useful tool for the prediction of sediment yield magnitude and patterns on a regional and sub-regional scale. It does this while encouraging future researchers to accumulate field data for comparison to, and calibration of the model, to explain the spatial patterns and magnitudes predicted by the model.

There is a vast amount of literature pertaining to the empirical modelling of erosion rates and, to a lesser extent, suspended sediment. As much of this literature, and most of the research, especially that concerning the erosion modelling has been undertaken in mid-latitude agricultural areas, much of it bears little relevance to tropical steeplands, and thus is of minimal use in this study.

In this section, a coverage of the relevant literature on measurement and modelling of erosion and sediment transport rates at a regional scale is presented. In order to be succinct, detail is restricted to that which is relevant to the context of this study.

The context of this study therefore needs to be defined. It is most simply described as: A preliminary calculation of transported sediment, at a regional scale, over a largely geomorphically homogeneous area. This is done in a region where even standard data sets of routinely monitored variables can be severely limited or clustered in their spatial or temporal coverage. More specific (with regards to this investigation) and less common data sets, such as suspended sediment load, rainfall erosivity and intensity, and soil erodability, are in many places absent, and the long-term monitoring or regional mapping of these variables is non-existent for the South Pacific.

Climatological variables, and many of the variables and controlling factors of suspended sediment mobilisation and transportation, (such as soil erodability, vegetative cover, relief, rainfall magnitude, intensity and erosivity, etc.) are spatially and temporally highly variable. If data were available for the South Pacific, analysis would require a resolution at or below the sub-catchment scale. Such a resolution was far beyond the resources of this study.

An approach was therefore undertaken that sought to eliminate these temporal and spatial variations in the controlling physical factors and thus decrease the resolution of the analysis to greater than catchment scale. This approach sought to incorporate mean values of standard climatic data, thereby utilising some of the most spatially and temporally representative, and most complete, data sets available in the region.

2.1.2 Climatic Geomorphology and Utilisation of Data

It was considered desirable that the empirical method selected to estimate the total sediment load of the South Pacific, be based on a standard set of data. The reasoning for this is the lack of the available resources to enable the collection of meaningful primary data. Peart (1990) states that short-term data sets of climatic, hydrological and geomorphic processes of three to five years, have a less than one in two chance of coming within 10% of the mean. Day (1988) suggests that data sets of ten years duration show little improvement.

Available standard data consists of such data sets as those routinely collected at meteorological stations, hydrological stations, and ports, following common, accurate and well established, usually internationally standardised procedures. These data sets are of a higher quality and coverage than any that could be collected even if resources were available within this investigation. The high quality and standardisation is particularly apparent in climatic data, which is much under-utilised. As Barry and Perry (1973) point out; "despite the vast quantities of (climatic) data in existence, especially in the mid- latitudes, very little has ever been applied to geomorphic analysis." The utilisation of this data source in the lower latitudes is particularly attractive in the great absence of alternative or more specialised high quality primary data sets.

As sediment yield and mobilisation is inextricably linked to climate through rainfall and runoff (Day, 1988; Peart, 1990), the exclusion of long-term climatic data and the reliance on short-term primary data sets would increase the subjectivity of an empirical method by a lack of replicability and comparability of the data set and the subsequent calculation. This is particularly likely in an area such as the South Pacific where a high temporal variability of climatic conditions dictates the predominant physical and ecological conditions. The South Pacific is an area that is dominated by, and highly adapted to, high magnitude events, such as monsoons, cyclones and tropical storms.

Mean values of precipitation and discharge may be regarded as useful surrogate measures for long-term sediment yields. Lam (1974) rationalised this by providing evidence from Hong Kong that high magnitude events govern long-term sediment production and yield. Lam (1974) also provided evidence that long-term estimates of sediment production made from short-term monitoring of erosion processes may not give comparable results to sediment yields derived from long-term mean values, as the governing high magnitude events may not appear within the shorter time scale.

Geomorphic analysis based on standard climatic (or any other) data, at a local or regional scale, enables new or unproven techniques to be replicated, tested and compared with results from other regions, or compared with results from the same area calculated or measured using other methods.

Climatic geomorphology as such has received little popularity in recent years (Stoddart, 1969; Derbyshire, 1976). There are, however, some notable exceptions; and explanations of regional geomorphic processes using standard climatic data (as proposed in this study) have met with a varying degree of success. Peltier (1950, as reported in Derbyshire (1976)) used mean annual temperature and precipitation to delineate global weathering regimes, and Leopold (1964, as reported in Derbyshire (1976)) and Wilson (1973) used these same parameters to delineate and classify the dominant geomorphic process on a regional scale. Corbel (1966) distinguished erosional provinces of the basis of temperature, moisture and relief.

Langbein and Schumm (1958) established the relationship between mean annual rainfall and sediment yield. Fournier (1960) found significant correlations between a function of rainfall means and suspended sediment yield. This he used for the basis of a world map of erosion, as did Strakov (1967). Both Strakov and Fournier noted the deficiency in the work of Langbein and Schumm (1958) in that the relationship they proposed only seemed to hold for arid areas. This was because rainfall (manifest as moisture availability) is also an erosion mitigating factor due to its influence on vegetation.

The relationship between rainfall and sediment load holds true for arid areas due to the lack of the erosion mitigating forces of vegetation. Rogers and Schumm (1991) point out that "less than 15% vegetative cover is ineffective at retarding erosion." They do, however, qualify that statement by saying that rates of sediment yield continue to increase at under 15% vegetative cover (in erosion flume experiments), to a maximum attained in the total absence of vegetative cover. Thus, Rogers and Schumm (1991) discovered that at low vegetative coverage, sediment mobilisation rates are less sensitive to changes in the area of vegetative cover than the rates of re-deposition of the eroded material.

Low vegetative cover fails to prevent erosion, but it does discourage the entrainment, and encourage the re-deposition of the eroded material. Rogers and Schumm proved that erosion and sediment transport are two different processes and operate by different mechanisms. This finding, however, is further confused by DePloy et al (1976, as reported in Morgan (1986)) and Morgan (1986) who reported slight increases in sediment yield from zero vegetative coverage, to a maximum at some low percentage of vegetative cover (possibly due to the physical loosening of the soil structure by the roots). Bruijnzeel (1991) concluded that "It is not how great the coverage is, but rather whether there is coverage at all."

Wilson (1973) concluded that fluvial erosion rates were higher in seasonal than in non-seasonal environments. As Fournier (1960), Carson and Kirkby (1971), Hudson (1971), Roose (1977) have all pointed out, rainfall frequency and magnitude are the "most effective elements" (Derbyshire, 1973) of fluvial erosion and suspended sediment transport. Turner et al (1984) stated that "rainfall is the major cause of soil erosion" while Starkel (1976) noted that "climatic seasonality is also of equal importance" and he used the example of snow melt (regarded as a seasonality of effective precipitation) to illustrate this point.

It is important to note at this point that Dunne (1979) defined land use as the most important factor in sediment transport rates. This conclusion came from his work in over sixty Kenyan catchments, of which, over half receive less than 500 mm of rain a year, while over 75% receive less than 1000 mm. While this finding corroborates that of Schumm etc, it is unlikely to hold true for areas like the South Pacific that can receive up to 1000 mm of precipitation in one month.

Dunne (1979) compared a number of different methods, including those of Langbein and Schumm (1958), Douglas (1967) and Fournier (1960) and concluded as did Wilson (1973) that no single relationship is valid on a worldwide basis.

2.1.3 Hydrometeorological Variables and Sediment Yield

There is general agreement in the literature that rainfall seasonality and magnitude (or moisture availability and resultant vegetative cover) are two of the most influential, causal differences in sediment yield on catchments of geological and topographical homogeneity. It should therefore be possible to determine with a certain degree of accuracy sediment transport or erosion rates from rainfall data.

Modelling erosion, suspended sediment yield or any geomorphic process, however, requires calibration if any comparative analysis is to follow. Gregory and Walling (1973) stated that even model estimates calculated from high quality climatic data need backup from instrumentation. Thus, figures from empirical models, not accompanied or supported by instrumented data should be treated with some caution.

Rainfall as the main factor of erosive precipitation has three features: Magnitude, frequency and intensity. Magnitude is the total volume of precipitation over a given time, often given in daily, monthly or annual increments. Intensity is a measurement of the rate of precipitation and is often used as a surrogate measurement of erosive energy or erosivity of a rainfall event. Frequency is a measure of the predominance or regularity of precipitative events and can be measured on short (daily or hourly) timescales, or over longer intervals such as months to give a measure of rainfall seasonality. Of these features, intensity has been the most widely studied and discussed in the literature with reference to soil erosion and entrainment.

The relationship between rainfall and sediment yield is complex. Rainfall is translated into sediment yield (via runoff) as a pulse of hydrological discharge. This discharge can take the form of overland flow, through-flow or even return flow. Suspended sediment is derived from either soil particles that are detached by raindrop impact and then transported to the stream by overland flow or by the mechanical action of turbulent overland or channel flow. The rate of erosion or sediment entrainment is governed by the transport power of the flow or by the volume of available material, whichever is smaller (Horton, 1945)

Unfortunately, the analysis of flood events and their effects on sediment yield has not yet been taken far enough for regional or worldwide comparisons to be made. Despite a greater understanding of sediment transport processes, prediction of rates is still dependent on models using broad climatic parameters. Few models are more satisfactory than that of Fournier (1960) and his parameter for rainfall seasonality and magnitude (Douglas, 1976; Stoddart, 1969).

Fournier, in attempting to demonstrate a relationship between suspended sediment yield and climate plotted the graphs of yield against a number of climate parameters. The plots obtained showed that, while sediment yield was related to climate, some allowance must be made for relief.

Using the climate parameter:

$$p^2 / P$$

where p is the maximum mean monthly rainfall, and P is the mean annual rainfall in mm, the sediment yield data for almost 80 catchments displayed curves which yielded four separate regression equations depending on very general relief and climate groupings.

Fournier developed an index of relief (C_m)

$$C_m = H.\tan\theta$$

where H = mean height in m of the catchment above its base, θ = mean slope angle, and using this formulated a sediment yield (S_y) equation:

$$\log S_y = 2.65 \text{ Log } p^2/P + 0.46 \log H.\tan\theta - 1.56$$

which gave a good fit of measured against calculated erosion for the catchments tested. The term $H.\tan\theta$ was cumbersome to use in large catchments, so Fournier utilised the regression equations derived from the original graphs for estimation of erosion on a global scale. The regression equation for high relief - humid climate catchments:

$$S_y = 52.49\, p^2/P - 513.21$$

was used in this study.

Fournier, and subsequently Jansen and Painter (1974), developed equations for different physiographic and climatic regions. Those of Jansen and Painter are more complex, as they include the factors temperature and rock hardness. Both Fournier and Jansen and Painter pointed out the anomaly of arid climates (that restricted Langbein and Schumm's (1958) relationship to those areas) and the inverse relationship between catchment size and sediment yield. In general, this latter feature can be overlooked in the South Pacific where catchments and drainage networks are small with the exception of a few in Papua New Guinea.

2.1.4 Rainfall as a Surrogate for Geomorphic Process Data

As noted above, of the three rainfall features, magnitude, frequency and intensity, intensity has received far more attention in the literature with reference to soil erosion and sediment transport. Wischmeier and Smith (1978) developed the EI_{30} index, which quantifies over a thirty minute interval a rainfall events maximum rate of intensity. This value is combined with a value of magnitude to create a index of erosivity (Wischmeier, 1962).

Although the EI_{30} index has been used extensively around the world, Vuillhaume (1969) argued it has "No scientific basis. A twenty minute interval is, in fact, far more appropriate." Vuillhaume used a twenty minute interval for his Sahelian study because a thirty minute interval often exceeded the total length of the rainfall event and led to considerable inaccuracies in the erosivity values calculated.

The spatial generalisation of rainfall intensity data can also cause major inaccuracies. Equations, such as the Universal Soil Loss Equation (USLE), designed for plot sized experiments, are not necessarily suitable for application to larger areas. The reliability of point source rainfall intensity data on catchments larger than a few square kilometres has rarely, if ever, been tested (Vice and Heidle, 1972). This makes the use of rainfall intensity data less attractive than other measures such as seasonality for large catchment or regional scale investigations.

Douglas (1976) noted that strong seasonality in the tropics is often manifest in the form of increased occurrence of tropical cyclones or of extreme erosive events and intensification of the monsoon climate. The timing of incidence and spacing of tropical cyclones and such events were noted by Guy and Clayton (1973) to have great influence on the magnitude of the erosion and sediment transport caused. Starkel (1976), whose work was predominantly at higher latitudes, pointed out the analogy of tropical cyclones and intense monsoonal events with that of snow-melt in their erosive impact (although he acknowledged that the processes involved differ greatly).

Rainfall erosivity data that emphasises seasonality rather than intensity is thus likely to be of considerable value in the study of erosion rates (Douglas, 1969; 1976). Douglas illustrated this feature with his comparison of the sediment mobilisation rates in Malaysia and Australia.

2.1.5 Spatial Scale and Erosion Rates

While investigating the dynamics of non-point source erosion or sediment transport rates, aspects of spatial scale need to be considered. The catchment and basin scale represents the order of 1 km^2 to 10^4 km^2 and is thus within the meso-scale domain as defined by Delcourt and Delcourt (1988).

The primary problem encountered in extrapolating soil erosion or sediment yield rates to the meso-scale (drainage basin size or larger), is that of physical heterogeneity. Individual plots may be established so that variance in causal parameters (rainfall intensity and soil erodability, etc.) are minimised, but the land surface and climate over a larger area is typically heterogenous which prevents many of the spatially variant factors from being incorporated effectively into single indices. Also, spatial variability of environmental and land-use factors is most pronounced in environments of high relief and land-use fragmentation (Harden, 1990).

The variability of relief and land-use more important in the South Pacific where patterns of variability are less understood and documented than the agricultural land of the mid-latitudes. This knowledge-base situation in the tropics has evolved because of the predominance of developing and recently developed countries where economic resources and priorities have so far not permitted large scale research.

Harden (1990) proposed an approach to viewing an area as a mosaic of smaller units, which has some advantages. The most obvious advantage is that of overcoming the problems of spatial heterogeneity of the causal factors of erosion and sediment transport. The size of the units or cells will reflect the spatial resolution of the data available and the output required. As pointed out by Meentemeyer and Box (1987) the minimum size of the cell is constrained only by the resolution of the data. The maximum size is constrained by the required accuracy of the analysis.

For this study, the required output is a sediment load estimate on a macro-scale (that of the whole South Pacific), so the cell size must be at the meso-scale or smaller. This means that the input data required would ideally be that of an island or catchment size. To introduce data of a greater resolution would contribute little (other than a level of significance disproportionate to the accuracy of the method) and could complicate matters considerably.

Harden (1990) found relief to be far more spatially variable than precipitation over small areas than; Fournier's (1960) regression, however, accounted for this variation by including relief in two broad classes; high relief and low relief, thus greatly diminishing the spatial variability of the relief factor. Relief in this study is restricted to the single class of high relief. This means that "cell size" (Harden, 1990) or the spatial resolution of data represented by a single value, is controlled entirely by the spatial resolution and distribution of rainfall data, thus optimising the utilisation of that data.

2.1.6 Standard Data and this Study

The strategy employed in this investigation was to collect the data (past and present) from as many rainfall stations in the South Pacific region as practical (since rainfall data was the major parameter required in the Fournier equation), and to utilise as many of them as possible. All known rainfall data sets for a given island or area were located on a map. Those that spatially replicated one another by clustering were disregarded. Unfortunately, clustering of rainfall stations is common in the South Pacific where piecemeal demographics and the absence of development in some areas prohibit routine collection of meteorological data.

The elimination of spatially clustered, and assimilation of temporally replicated data (rainfall stations), reduced the total number of data points for the region from over a thousand to about three hundred and sixty. This gave a mean cell size (see Harden, 1990; and above) of 1600 km^2, or a 40 x 40 km cell. This mean cell size was, however, rather misleading as the density of rainfall stations was highly variable. From Fiji, for example, over seventy data sets were collected . These covered an area of 118,300 km^2, giving a spatial resolution of 260 km^2, or a cell size of 16 x 16 km. By comparison, Papua New Guinea with an area of 380,000 km^2, only 136 useable data sets were located, giving a resolution of 2800 km^2, or a cell size of 52 x 52 km. For two P.N.G. provinces (Gulf and Western), only five data sets were available. With a combined land area of over 133,800 km^2, this represented a resolution of 67,000 km^2, or a cell size of 365 x 365 km. This figure was clearly unacceptable and a different approach was taken for those two particular provinces.

The differences in the resolution and the cell size between PNG and Fiji were difficult to interpret. While showing a smaller cell size (thus greater resolution) for Fiji, if cell size was compared to the drainage basin area the reverse might be indicated. PNG, having drainage basins which are orders of magnitude larger than those in Fiji, might actually show a greater number of data points per catchment and thus greater resolution than Fiji. Conjecture on the resolution of the data, however, adds nothing to its resolution, and the strategy employed in this study was to utilise all appropriate available data, thus optimising the spatial resolution of that data. The resultant resolution of the model is, therefore, variable throughout the region, depending on the availability of data.

2.1.7 Application of the Fournier Method for Sediment Yield Determination to the South Pacific

The application of the Fournier method of sediment yield estimation to the South Pacific was undertaken in two stages:

Initially, a preliminary investigation was undertaken to assess the accuracy and viability of the method. This assessment considered three catchments on Viti Levu, Fiji. These catchments were chosen for the good coverage of quality rainfall data and the physical differences including area, climate, geomorphology, vegetative type. These catchments also had the advantage of having a number of previous estimates of sediment yield by various researchers using a variety of methods.

The results of this assessment (which appears in Annex 1) was favourable and the yield estimates for all three catchments by the Fournier procedure fell well within the range of the other estimates and measurements. The method was considered valid within the limitations of the data and the assumptions made.

It was therefore decided to proceed with the evaluation of the sediment yield of the entire South Pacific region using the Fournier method. This was done on a country/territory, island group and an island by island basis. Areas where data were limited or inadequate, were included if possible. In a number of cases where virtually no data were available, information from neighbouring islands was utilised. The details of the calculations are given in appendix B. The results and the conclusions drawn from the exercise are presented below.

2.2 The Study Area.

The area covered by this study is that of the South Pacific Commission (with the exception of Australia and New Zealand) which extends from a line at 100°E to 123°W and from 8°N to about 22°S. The area includes a total of twenty two island states or territories and covers some 29,000,000 km^2 - "Roughly the size of Africa" (Makensen and Hinrechsen, 1984); the land area, however, is restricted to 550,000 km^2, of which 462,200 km^2 occurs in Papua New Guinea.

The fifteen island nations that have land areas of less than 1000 km^2, have a total land area of less than 5000 km^2 and an average land area of less than 300 km^2. Although the small land area of the region may appear to contribute little to global terrestrial human impact, the 90,000 km^2 outside PNG supports over two million people or about twenty three people per square kilometre. In real terms this value is misleading as much of the land is uninhabited or uninhabitable for a variety of reasons. The demographic patterns show that much of the population is found in relatively highly concentrated areas, and human impact on the environment tends to increase exponentially. Thus there are areas within the region that suffer from unusually high levels of human impact.

2.2.1 Surface Drainage in the South Pacific

With reference to the movement of suspended sediment, significant areas of Oceania can be disregarded. In many of the island groups there is no established drainage network in which sediment can be mobilised and transported. A brief assessment of the twenty two island nations in the region, with reference to land area, the number of main islands, the presence of surface drainage, the availability of rainfall data, the number of rainfall sets and their use, inclusion or exclusion in this study, is given below.

2.2.2 The Islands

AMERICAN SAMOA

(197 km^2)

Five main islands make up American Samoa, of which only Tutuila, Ofu and Olosega sustain any drainage development. The lack of drainage on the high island of T'au appears to be due to the highly permeable nature of its Tertiary volcanic geology. Drainage that appears on the islands of Ofu and Olosega is severely restricted spatially, and is thought to be ephemeral; these islands have thus been disregarded in this study. There are only two rainfall data sets available for American Samoa and these are both on Tutuila.

COOK ISLANDS

(240 km^2)

There are fifteen main islands in the Cooks group, of which only three, Rarotonga, Atiu and Mangaia are not atolls or raised limestone islands. In the case of Atiu and Mangaia, however, although both are high volcanic islands, they have large uplifted pleistocene fringing reefs forming a limestone pediment to the volcanic island. This prevents any of the drainage developed on the relatively impermeable volcanic soils from reaching the sea. Thus the effective drainage of these islands in terms of suspended sediment reaching the sea is zero. Rarotonga (64 km2) is the only Cook Island that is included in this study, and the only data for the island is a single rainfall data-set for Avarua.

FEDERATED STATES OF MICRONESIA

(591 km^2)

The Federated States of Micronesia cover a vast area of the Pacific. The four states of Yap, Chuk, Pohnpei and Kosrae all sustain some permanent drainage, although on some islands it is limited by various geological constraints. The hydrological and climatological data for this area is more comprehensive than other areas, due to the long influence of at least three occupying military forces. The eight islands that support surface drainage, have a total of thirteen useable rainfall data sets.

FIJI ISLANDS

(18,272 km^2)

Fiji has seven main islands with developed drainage systems supporting permanent surface drainage. There are many other smaller islands which support surfacial drainage, especially in the Lau (Eastern) and Yasawa (Western) groups. Due to their diminutive size and the scarcity of data, however, it was impractical and of minimal benefit to include them in this study. Those that were included in the study are the islands of Vanua Levu, Viti Levu, Taveuni, Ovalau, Koro, Gau and Kadavu. Fiji has one of the best coverages of rainfall data, and this study was able to utilise over seventy different data sets, although there were more than twice that number available.

FRENCH POLYNESIA

(3,265 km^2)

French Polynesia contains over 130 islands in four island groups. Of these only Tahiti and Moorea, Raiatea, Tahaa, Nukuhiva, Uapou and Tahuata have any significant surface drainage. The rest, mostly atolls, were excluded from this study. The rainfall data availability for French Polynesia was found to be relatively poor, and the calculation of the sediment load for the area was undertaken from just four rainfall data sets. This coverage is not considered adequate for great confidence to be put in the results; however, the mitigating factors are that there is a data set for each of the main groups, and the islands themselves are small.

GUAM

(541 km^2)

Guam has two distinctive geological districts, roughly dividing the island in two; the northern half is an uplifted limestone plateau which supports no surface drainage, while the volcanic southern half has a well developed drainage network and is included in this study. There are only two rainfall data sets available for Guam. One is in the very northern part of the island, and thus not representative of the southern area where the drainage development is. The second data set is on the Western side of the island, and is thought to be in a rain-shadow from the southern high section of the island. The calculation of sediment yield for the island of Guam, should therefore be treated with caution.

KIRIBATI

(690 km^2)

The Kiribati group is composed entirely of atolls and is thus not included in this study.

MARSHALL ISLANDS

(180 km^2)

The Marshall Islands are all atolls and are thus not included in this study.

NAURU

(21 km^2)

Nauru is an uplifted, phosphate capped limestone plateau which sustains no significant surface drainage and is thus not included in this study.

NEW CALEDONIA

($19{,}103 \text{ km}^2$)

The main island of New Caledonia supports a highly developed drainage network. The three uplifted limestone islands of the Loyalty group support no surface drainage and were not included There is a good rainfall data base and thirty data sets were included in this study.

NIUE

(259 km^2)

While Niue is hydrologically significant due to its intriguing groundwater doughnut, it sustains no surface drainage and was not included in this study

NORTHERN MARIANAS

(471 km^2)

The only member of this group that sustains drainage significant enough for inclusion in this study is the island of Saipan. While there are a number of reliable sets of data for the island the total drainage area of the island is restricted to only 5 km2 where denudation has removed the limestone cap and a less permeable geology has been encountered. Thus only one of the rainfall data sets has been utilised as it is the only one that falls within the area of surface drainage.

PALAU

(460 km^2)

The island of Babelthuap is the only island in this group to sustain surface drainage significant enough to be included in this study. There are three rainfall data sets that are suitable for use in the calculation.

PAPUA NEW GUINEA

($262{,}243 \text{ km}^2$)

For reasons of simplicity, in this study, Papua New Guinea has been divided into two sections: the provinces on the eastern half of the mainland of New Guinea, and island territories which include New Britain, New Ireland, Bougainville, Manus, Lorengau and Tanguila. All these islands and the New Guinea mainland are extensive in both land area and drainage network development. Thus as they comprise such a large part of the land mass in the South Pacific region, they play a significant and very important part in this study.

In the island provinces over thirty five data sets were found to be suitable and included in this study. In the New Guinea provinces, data from over three hundred rainfall stations were available. Data was used from only 137 as the patchy demographic development means that many are spatially clustered. The Gulf and Western provinces, however, require special attention. Only five rainfall stations were found for these two provinces, which have a combined land area is slightly over $130\ 000 \text{ km}^2$. This was considered an insufficient density of data and an alternative method of calculating the sediment yield of the area was required.

PITCAIRN

(5 km^2)

There is a developed drainage network on the island of Pitcairn, but its total area is less than 1 km^2. Pitcairn was not included in this study.

SOLOMON ISLANDS

(27,556 km^2)

There are twelve main islands in the Solomon Group. All support extensive surface drainage. The islands of Choiseul, Santa Isabel, Malatia, Guadalcanal and San Cristobal were all treated on an individual basis, while the slightly smaller islands of Vella Lavella, Kolombangara, Ranongga, Rendova, Tetepare, New Georgia and Vangunu were treated as one geomorphic entity (referred to from here on as the New Georgia group) due to their high spatial clustering and the homogenous nature of their geology. The Solomon Islands were found to have limited rainfall data, with only 33 rainfall data sets for the whole country. Santa Isabel and San Christobal, for instance, had only two data sets each, Choiseul had only three and Malatia just four. The New Georgia group has a total of thirteen data sets, and displayed the best data coverage in the group.

TOKELAU

(10 km^2)

Tokelau consists of three low atolls and was not included in this study.

TONGA

(699 km^2)

Tonga includes over 150 islands, but most are either atolls or uplifted limestone plateaux. The only islands in the group to sustain permanent drainage are 'Eua, Tofua and Kao. No rainfall data could be found for the island of 'Eua, so data from the island of Tongatapu which is nearby was used. Data also could not be found for the islands of Tofua and Kao, so data from the island of Hivaoa some twenty kilometres to the east was utilised. These substitute data were compared to the general pattern of rainfall throughout the Tonga group, and found to be consistent.

TUVALU

(26 km^2)

Tuvalu is comprised entirely of atolls and was not included in this study.

VANUATU

(11,880 km^2)

Vanuatu is a group of large high volcanic islands. Thirteen main islands sustain surface drainage. These include: Espirito Santo, Malekula, Tanna, Aneityum, Ambrym, Epi, Erromanga, Efate, Pentecost, Aoba, Maewo, Vanua Lava and Gaua. Of the 57 minor islands in the Vanuatu group, none were considered significant enough to include in this study. The rainfall data for the islands of Vanuatu was severely limited with a total of only seventeen rainfall stations for the whole group. For most of the islands data was considered to be insufficient to provide a reliable calculation. For the island of Gaua, there was no data at all. Calculation for the Vanuatu group was undertaken using all available data, but particular caution must be used when interpreting the values.

WALLIS AND FUTUNA

(225 km^2)

Of the three islands in this group (Wallis, Futuna and Alofi), only the island of Futuna has any developed drainage system. This is very small and ephemeral and was not considered further.

WESTERN SAMOA

(2935 km^2)

Of the four islands that make up Western Samoa only two (Upolu and Savai'i) support surface drainage. Extensive upper Tertiary and Quaternary volcanic geological sequences mean that much of both islands have a permeability that precludes surface drainage. This means that the effective drainage area of the group is less than half the land area. On Upolu there was a good coverage of rainfall data with a total of eight suitable data sets. For Savai'i a total of five rainfall data sets was available; however. as the drainage development is restricted to only specific areas, only two of those data sets were used.

2.3 Results of a Regional Sediment Yield Calculation

2.3.1 Results

The results of the sediment yield calculations for the whole of the South Pacific are given in Table 1. Details of the calculations are included in Appendix B.

2.3.2 Data Overview

Two major points were noted from the sediment yield estimate calculations for the South Pacific:

The first point is that the construction of a regional sediment yield estimate is possible from mean monthly rainfall and basic mapping data alone. The estimate was, however, made in the light of a number of assumptions, and a deficiency of sediment transport data with which to compare the estimates. Geomorphic homogeneity was also assumed. Arguably this is not proven; however, in the context of Fournier's classification of relief into two classes (high and low relief) the high islands of the South Pacific are geomorphically homogeneous.

The second point is that there is an almost total absence of published data on suspended sediment loads or sediment transport for the South Pacific region. This lack of data applies also to other relevant physical influencing factors such as rainfall erosivity, vegetative cover, relief, length of slope, soil erodability, etc. This lack of data is one of the justifications for the use of the Fournier method and the fact that some estimates of sediment yield can be obtained would appear to be one of the advantages of this procedure.

These two points are further discussed below in conjunction with a more detailed assessment of the validity of the sediment yield calculation in general.

2.3.3 Discussion

As parts of the South Pacific region lack even good quality rainfall data, the assessment of the sediment yield using commonly monitored variables such as rainfall, as a surrogate, remains difficult. One island group in particular, Vanuatu, has little published rainfall data. Correspondence with the Vanuatu Meteorological Office yielded little more than the published data sources. The data that was located was often the result of three years or less of monitoring. These short data sets have mean values which are unlikely to be representative of the rainfall over longer periods. Where data is scarce or have only short time frames, there is a need for validation of the estimates by other methods including direct measurement. Where validation is not possible, the estimates must be treated with caution. Detailed information regarding the raw data has not been included in the calculations. Most of the rainfall information was obtained from Brookfield and Hart (1966), Taylor (1973) and Ash, Wall and Hansell (1974), or from national meteorlogical services. The length and representativeness of the data sets used and the resultant calculations are discussed below.

Of all the South Pacific nations, Vânuatu has the most incomplete and probably least representative rainfall data base. This makes the validity of the suspended sediment estimates of that group the most tentative. French Polynesia is similarly lacking in data, and because the islands are generally smaller some have no data sets at all. Where this occurs data from neighbouring islands was used.

Countries such as Fiji and Western Samoa have good rainfall data coverage, although in Western Samoa the exact area of perennial drainage is debatable and rainfall data tends to come from only around the coast. Anecdotal evidence from Upolu indicates that rainfall in the interior is considerably higher than that around the coast. This is thought to reach seven meters in some areas, while the maximum published (but unsubstantiated) estimate for the interior is about 5000 mm per annum (Kammer, 1978).

The data coverage of Papua New Guinea is variable and was discussed earlier in this chapter. Some provinces such as Milne Bay, Enga and some of the highland provinces have excellent coverage, while other areas such as Central and Western provinces were so lacking in data that the application of the Fournier method was not possible. In case of Western and Central provinces, it was fortunate that documented sediment yield data for two very large rivers (the Fly and Purari), could be extrapolated to facilitate sediment yield estimates for the whole provinces.

The Solomon Islands was adequately documented with regards to rainfall, as was the Federated States of Micronesia, the Northern Marianas, Palau and Guam. Rainfall data for New Caledonia was derived from a large selection of long-term data sets; like Western Samoa, however, they tended to be located on the coast and may be unrepresentative of the highland rainfall.

In general it has not been possible to validate the sediment yield estimates. The Fournier method has been criticised in the literature for overestimating the sediment load in mid-latitudes. In Walling and Webb's (1987) comparison of thirteen global sediment budgets the Fournier procedure gave the highest values. Other methods of sediment yield and erosion estimation have, however, been criticised for underestimating the sediment yield in humid tropical regions.

Meybeck (1984) noted that while measured values of sediment yields in Oceania appear very high, when the relative sizes of the catchments are taken into account, measured sediment yield values for Oceania exceed those of Africa by an order of magnitude. Keeping this in mind, some of the sediment yields in the South Pacific seem extraordinarily high, e.g., New Britain, where yields of $65m^3$/ha/yr or 157t/ha/yr were estimated. New Britain has mean rainfall values of over 6000 mm per year, and over 1000 mm can fall in one month. Given its geological youth, such an area would be expected to have a very high sediment yield. A similar situation occurs in the interior of Viti Levu in Fiji where there are some areas that receive up to 1400 mm of rain in a month yet only get 4000 mm of rain in a year. Such magnitude, variability and seasonality of rainfall are conducive to very high erosion and sediment transportation rates. Thus while the estimates may seem high, when taken in the context of the local physical environment they are likely to prove more reasonable than they may first appear.

The validity of the total calculated sediment yield value is less certain, as it is effectively a sum of all the individual island and island group calculations with their individual errors and limitations. Verification of the regional value would require a sampling programmeme of a magnitude unlikely to be seen in the foreseeable future, unless some new technology becomes available. Some degree of verification could be achieved with piecemeal monitoring and research from the individual island nations.

The sediment yield value of $2.3x10^9$ - $2.5x10^9$ tonnes per annum is not unrealistic in the light of the global sediment budgets/flux calculations of Walling and Webb (1987), Milliman and Mead (1983) and Milliman (1990a,b). Milliman (1990b) noted that global fluvial sediment flux estimated by the Fournier method was $32x10^9$ to $51x10^9$ t/yr. While this estimate is probably high (current opinion puts the value at more like $15x10^9$ t/yr), there is a general consensus in the literature that the contribution from Oceania represents a considerable proportion of the global value. Milliman (1990b) noted that Southern Asia and Oceania contribute over 70% of the worlds sediment flux with Oceania (which includes Australia and New Zealand) discharging $3x10^9$ t/yr of sediment to the ocean. This is close to the value obtained independently in this study.

Milliman's value is slightly higher as the inputs from Australia (although that is estimated to be less than that from the Fly River alone) and New Zealand are included. Comparison of the results of this study with those in the benchmark paper of Milliman and Mead (1983) provides verification that the estimate resulting from this study is probably as accurate as any presently available.

A further topic requiring discussion is that of the karst areas in Papua New Guinea. Karsts, or areas where the underlying geology is predominantly carbonate or soluble rocks, often sustain little surface drainage. This fact was taken into account in the selection of the islands included in this calculation, and was one of the reasons for disregarding all the atolls.

The areas of karst that appear in Papua New Guinea, however, were not discussed in this context. This was not an oversight, rather, it is rationalised by noting that while small (atoll size) karst can have the total lack of developed drainage, and intercepted precipitation flows exclusively as ground water, in continental and massive karst, this is rarely the case. In areas that have massive karst, tertiary porosity develops, and epiphreatic drainage, while subterranean, is effectively identical with regards to sediment transport as surface drainage. Thus the areas of massive, cockpit and uplifted reef plateau karst that occur if PNG were treated as though they sustained surface drainage.

Table 1. The Results of the Regional Sediment Yield Calculations for the South Pacific, using the Fournier (1960) Method.

Islands and Island Groups	Drainage Area, km2	Calculated Sediment Yield				
		Volume m^3/km^2	Minimum $t/km^2/yr$	Maximum $t/km^2/yr$	Total Min. t/yr	Total Max. t/yr
AMERICAN SAMOA						
TUTUILA	145	1741	3657	4428	530265	656596
OFU	0					
OLOSENGA	0					
TAU	0					
COOK ISLANDS						
ATIU	0					
MANGAIA	0					
RAROTONGA	67	1425	2992	3705	201096	248972
FED. STATES OF MICRONESIA						
KOSRAE	108	2951	6197	7672	669276	828576
POHNPEI	334	2330	4894	6058	1634429	2023372
CHUK	61	1166	2449	3932	149389	184928
YAP	98	2111	4437	5489	436660	540627
FIJI						
VITI LEVU	10389	3434	7211	8928	74915079	92758174
VANUA LEVU	5538	2731	5734	7099	31754892	39314262
TAVEUNI	435	2268	4764	5898	2072300	2565600
OVALAU	125	1953	4103	5079	410300	507900
KORO	108	1953	4103	5079	443124	548532
GAU	100	1953	4103	5079	512875	634875
KADAVU	408	1833	3851	3768	1571208	1945443
FRENCH POLYNESIA						
TAHITI & MOOREA	1052	3056	6417	7945	6750680	8358140
TAHAA	88	1376	2889	3577	254232	314776
RAIATEA	194	1376	2889	3577	560466	694054
RURUTU	28					
NUKUHIVA & UAPOU	435	508	1068	1322	446580	575070
HIVAOA & TAUHATA	370	954	2003	2480	741110	917600

Islands and Island Groups	Drainage Area, km2	Calculated Sediment Yield				
		Volume m^3/km^2	Minimum $t/km^2/yr$	Maximum $t/km^2/yr$	Total Min. t/yr	Total Max. t/yr
MARSHALL ISLANDS	0					
NAURU	0					
NEW CALEDONIA	17130	1694	3557	4404	61274010	75440520
NIUE	0					
NORTHERN MARIANAS						
SAIPAN	5	2426	5094	6308	25470	31540
PALAU						
BABELTHUAP	396	2268	4762	5898	1886068	2337200
PAPUA NEW GUINEA						
Mainland Provinces						
ORO	22800	2556	5368	6647	122390400	151551600
MILNE BAY	14000	1901	3994	4945	55916000	69230000
CENTRAL & N.CAPITAL	29740	1801	3783	4684	112506420	139302160
MOROBE	34500	1196	2511	3109	86629500	107260500
E.SEPIC & SANDUAN	79100	1299	2728	3348	215784800	267152340
MANDANG	29000	2438	5102	6339	147958000	183831000
W.HIGHLANDS & ENGA	21300	1507	3165	3919	67414500	83474700
S.HIGHLANDS	23800	1472	3091	3827	73565800	91082600
E.HIGHLANDS & SIMBU	17380	1539	3237	4003	56259060	6924280
GULF	34500		1727		59581500	
WESTERN	99300		1058		105124463	
Island Provinces						
NEW BRITAIN	39807	6055	12715	15743	506146005	626681601
NEW IRELAND	9974	2304	4839	5991	48264186	59754234
BOUGANVILLE	9300	1899	3988	4938	37088400	45923400
LORENGAU/ MANUS	1943	1654	3473	4300	6748039	8354900
PITCAIRN	0					

Islands and Island Groups	Drainage Area, km2	Calculated Sediment Yield				
		Volume m^3/km^2	Minimum $t/km^2/yr$	Maximum $t/km^2/yr$	Total Min. t/yr	Total Max. t/yr
SOLOMON ISLANDS						
CHOISEUL	2590	1323	2780	3442	7200200	8914780
SANTA ISABEL	4122	2452	5150	6376	21228300	26281872
MALAITA & MARIMASIKE	4900	3489	7327	9071	35902300	44447900
SAN CRISTOBAL	3125	2268	4764	5898	14887500	18431250
GUADAL-CANAL	6400	2478	5202	6444	33292800	41241600
NEW GEORGIA GROUP	4250	2710	5691	7046	24186750	29945500
TOKELAU	0					
TONGA						
EUA	15	1061	2229	2759	33435	41398
TOFUA	28	1995	4106	5083	114968	142345
KAO	1	1995	4106	5083	4106	5083
TUVALU	0					
VANUATU						
ESPIRITO SANTO	3680	1638	3439	4258	12655520	15669440
MALEKULA	2023	2111	4433	5488	8967959	11102224
TANNA	549	1954	4103	5085	2252547	2791665
ANEITYUM	65	2373	4984	6171	323900	401162
AMBRYM	665	3108	6526	8080	4339790	5373732
EPI	444	1533	3219	3985	1429236	1763405
ERROMANGA	975	1953	4101	5077	3998767	4950075
EFATE	915	2426	5094	6307	461010	5770905
PENTECOST	438	3699	7768	9618	3402617	4212764
AOBA	339	3039	6383	7902	2163709	2678878
MAEWO	269	2504	5258	6510	1414619	1751433
VANUA LAVA	308	2111	4433	5488	1365364	1690304
WESTERN SAMOA						
SAVAI'I	503	2609	5480	6785	2756440	3412855
UPOLU	708	2898	6087	7536	4309596	5335488

Calculated Sediment Yield:

	VOLm^3/ km^2	MIN t/km^2/yr	MAX t/km^2/yr	TOTAL MIN. t/yr	TOTAL MAX. t/yr
REGIONAL MEAN	2331	4631	5762		
REGIONAL TOTAL				2015,673,053	2486,186,626

2.4 Nutrient Delivery via Sediments to the Coastal Zone

2.4.1 Particulate Sediment as a Pollutant and a Vehicle for Pollution Transport

The importance of sediments to ocean-water chemistry is great. The chemical composition of the oceans is a direct result of the interactions between sediments and water. As a transporting medium for both suspended and dissolved loads, rivers play an important role in the addition of organic and inorganic substances from terrestrial sources to the oceans.

This process is part of a greater natural cycling of nutrients and minerals which has continued over geological time. Perturbations to the process can occur which change the rate or nature of chemical delivery to the oceans in the short term. The persistence of the effects of such changes is poorly understood as there is often a lag period involved and as a result the causal relationship is often difficult to establish. The changes impressed on the process of cycling may be natural and/or, more increasingly, anthropogenically induced. Natural sources include volcanic dust, marine aerosols, geochemical fractionation, river transport and weathering (Martin and Meybeck, 1979).

The relative importance of natural or manmade inputs via rivers is highly variable. For example, approximately eighty percent of the dissolved load of the Rio Tete, an Amazon tributary, is derived from the atmosphere (Gibbs, 1970); by contrast, the majority of solutes in many urban streams is derived from pollutant discharges by man (Turman et al, 1989). It is important therefore, in the context of this study, to establish some idea of the flux of nutrients via rivers through the sediments they transport that can be expected to occur naturally. Utilising this information a better understanding of the sources and amounts delivered as a result of human activity may be made.

To this point this study has placed emphasis on the aspect of terrestrially derived sediments as a pollutant in the coastal zone in their own right. Sediments, because of their chemistry and/or their ability to carry other chemical compounds which become adhered to individual particles have the potential to pollute or at least disturb natural processes of chemical delivery to the oceans. In recent years concern has been raised over the potential for sediment to deliver anthropogenically derived pollutants to aquatic ecosystems because of the increasing use of potentially harmful chemicals on land and also the increasing sediment yield which may carry these pollutants along with them. Examination of these pollutants in both solid, adhered and dissolved form is outside the scope of this study.

The investigation of nutrients carried out here is restricted to that which is derived ultimately from the parent bedrock but which enters aquatic systems once weathering has taken place and the material is subsequently taken away during erosion. Nutrients derived in this way are in both solid and dissolved forms. Dissolved load is highly variable and specific data is required for such investigations. This section of the report, therefore, concentrates on the nutrient budget delivered in a solid form, i.e., the chemical constituents of the eroded sediment itself. Ideally, sampling and analysis of river sediments would provide the best data for such calculations. In the absence of such published data and/or the resources to obtain the necessary data on sediments, it was decided that soil data be used as a surrogate using the assumption that the amounts and characteristics of the nutrients eventually delivered to the coastal zone via river sediments is reflected in the type of soil found at the place of origin. Since in most cases the material eroded is the top soil the data utilised for the purpose of this exercise was for soil found in the first 25 cm of the pedon or less.

2.4.2 Method

Soil analytical data was collected from both published and unpublished (e.g., consultancy reports) sources for as many islands as possible. More specific and extensive data is probably held by the various ministries and departments of the respective countries so the nutrient budget presented here does not incorporate all the available data but is likely to reflect the overall situation

In the majority of cases where data was available the coverage was limited to major islands. Where this occurred data was extrapolated from the major areas/islands and applied to the other islands making up the country. Where data was totally absent information from geologically / geomorpho-logically similar islands was substituted. Such situations are indicated in Table 2.

A comparison of soil data with data for parent materials was carried out so that where soil data was lacking, data for constituent elements of the bedrock could be substituted. However, the comparison revealed that the soil chemistry and that of the bedrock from which it was derived varied significantly so that utilisation of the two data sets side by side in the same nutrient budget would have little practical value.

The number of data sets used to calculate averages varied greatly from 30-40 to 2-3 for areas with poor data availability. Only those elements which were reported more frequently in the literature were considered. Average values (usually as percentages of the element) for each island or island group were calculated and converted to a tonnes per square kilometer per annum figure based on the suspended sediment values reported in Table 1.

2.4.3 Nutrient Transport Results and Discussion

The amounts of organic matter (estimated using carbon and nitrogen) and other elements which are delivered to the South Pacific Ocean in the form of suspended sediments are indicated in Table 2. Considerable caution must be taken when drawing conclusions from these figures as they are highly generalised and have been collated from a variety of different sources using different analytical and reporting procedures.

Few data exist for the South Pacific tropical environments with which to compare these results for river inputs of nutrients. It does appear that these figures represent a reasonably high rate of delivery of nutrients via sediments in this way to the coastal environment. A nutrient budget for the Rewa River, Fiji was calculated by Morrison et al (1992) which concluded that the amounts of nutrients being exported were substantial. The results of that investigation, for purposes of comparison with the data summarised here, are shown in Table 3.

The figures calculated in this report are comparable to those reported by Morrison et al (1992). In general, it appears, however, that the values from Table 2 are significantly higher. This is the case for all elements reported by Morrison et al (1992). It is clear that further measurement is required in order to obtain an accurate picture of the total input of nutrients by rivers.

Table 3. Nutrient flux from the Rewa River, Fiji.

Element	Particulate flux (t/yr)	Particulate flux (t/km^2/yr)
C	5×10^5	166.70
N	4×10^4	13.30
P	2×10^3	0.67
K	2×10^4	6.67
Ca	7×10^4	23.30
Mg	1.1×10^5	36.70
Si	7.5×10^5	250.00

(Adapted from Morrison et al, 1992)

Table 2: Nutrient Movement via Sediments entering the South Pacific Coastal Environment.

	Organics			**Other Elements**			
Islands Countries	C	N	C/N Ratio	Ca	Mg	K	Na
American Samoa*	420	34	13	62	58	20	37
Cook Islands	197	14	14	52	48	17	31
Fed. St. Micronesia:							
Kosrae	498	-	-	-	-	-	-
Pohnpei	476	-	-	-	-	-	-
Chuuk	146	18	8	-	-	-	-
Yap	148	-	-	-	-	-	-
Fiji							
Viti Levu	303	23	13	125	116	41	74
Vanua Levu	322	15	27	89	92	33	59
Others	209	12	17	74	69	24	44
French Polynesia	252	59	17	33	60	4.9	10
Guam	250	19	13	-	-	-	-
New Caledonia	129	45	3	21	24	3.5	2.9
Northern Marianas*	281	21	13	-	-	-	-
Palau	103	-	-	-	-	-	-
Papua New Guinea	204	17	12	-	16	5.6	-
Solomon Islands	683	53	13	149	53	5.9	89
Tonga*	407	33	13	60	56	20	36
Vanuatu	163	23	7	-	-	-	-
Western Samoa	685	55	13	101	94	33	60
Average	326	21	16	77	61	19	44

Table 2: Nutrient Movement via Sediments entering the South Pacific Coastal Environment (continued)

Islands	Other Elements t/km^2/yr									
	Si	Al	Fe	Ti	Mn	Ni	Cr	Co	Cu	P
American Samoa*	-	465	490	48	12	0.31	1.4	0.13	0.34	*10.6*
Cook Islands	-	25	56	40	10	0.25	1.1	0.10	0.28	10.9
Fed. St. Micronesia:										
Kosrae	-	-	-	-	-	-	-	-	-	-
Pohnpei	-	109	782	-	9.1	-	-	-	-	-
Chuk	-	28	153	-	5.9	-	-	-	-	-
Yap	-	37	260	-	14	-	-	-	-	-
Fiji:										
Viti Levu	605	-	-	97	24	0.62	2.8	0.27	0.69	*9.4*
Vanua Levu	481	-	-	77	19	0.50	2.2	0.21	0.55	*1.2*
Others	344	-	-	57	14	0.37	1.6	0.16	0.41	*5.5*
French Polynesia	395	534	978	170	8.8	-	-	-	-	17.8
Guam	-	56	532	-	14	-	-	-	-	-
New Caledonia	407	366	658	17	5.0	14	57	0.35	0.34	*3.1*
Northern Marianas	-	63	596	-	16	-	-	-	-	-
Palau	-	89	437	-	-	-	-	-	-	-
Papua New Guinea	664	286	208	22	7.3	0.75	4.9	0.72	0.94	3.9
Solomon Islands	-	1121	1035	116	30	1.7	80	0.96	1.2	5.3
Tonga*	-	451	475	47	11	0.30	1.3	0.14	0.34	*10.3*
Vanuatu	-	-	2.2	-	2.8	-	-	-	0.96	-
Western Samoa	-	786	800	78	19	2.5	2.2	0.22	0.56	*17.3*

Note 1: All calculations based on top soil nutrient data and suspended sediment load data indicated in Table 1.

Note 2: Where data for a country was absent data from a geologically/geomorphologically country was substituted in the following way:

Data absent for:	*Substituted data from:*
American Samoa*	Western Samoa
Northern Marianas*	Guam
Tonga*	Western Samoa

Data Sources:

Cook Islands (Rarotonga only)-	Leslie, 1980
Federated States of Micronesia-	Soil Conservation Service, USDA, 1984a
Fiji-	Morrison et al, 1987
French Polynesia-	Jamet, 1983
Guam-	Soil Conservation Service, USDA, 1984b
ew Caledonia-	Latham et al, 1978
Palau-	Soil Conservation Service, USDA, 1984b
Papua New Guinea-	Bleeker, 1983
Solomons-	Wall et al, 1979
Vanuatu-	Stevens, 1987
Western Samoa-	Scroth, 1970

Data indicated in *italics* was obtained using unpublished information.

These preliminary results indicate that substantial quantities of certain elements are being exported from the Pacific Islands to the sea. Average losses (in t/km^2/yr) of carbon (326), nitrogen (21), phosphorus (7), calcium (77), magnesium (61), potassium (19) and silicon (480) represent major removals of plant nutrients. Replacement of carbon and nitrogen by plant activities may occur, but elements like phosphorus cannot be replaced easily except by fertilizer application. These losses cannot be good for agricultural production in the region since the material being lost is often in plant available forms.

When these nutrient elements reach the coastal zone they may become available to organisms there, contributing to eutrophication and related problems such as algal blooms. One issue that appears to need investigation is the extent and rate at which the nutrient elements in particulate material transported to the oceans via rivers are released in forms available to marine organisms.

One issue that was also considered is the movement of heavy metals, particularly those that may create toxicity problems. Apart form the nickel and chromium losses form New Caledonia and the copper and chromium from PNG there is no evidence of particular problems. This assessment was also hampered by the lack of data on the trace element composition of suspended sediment.

In the original planning of the study it had been hoped to make an assessment of the movement of organic contaminants via sediment transport. Virtually no data could be located on the concentrations of organic contaminants (e.g., polycyclic aomatic hydrocarbons, organochlorine compounds) in suspended sediments in the South Pacific region. It was, therefore, impossible to obtain any values of the transport of organic contaminants.

3. Sediments as Pollutants

3.1 Sediments in Coastal Systems and the Fate of Sediments in the Coastal Zone

The main emphasis in this chapter is on the fate of sediments in the South Pacific, and the impact of suspended sediment on the two main coastal biotic communities in the South Pacific region - mangroves and coral reefs. A third community type, seagrass beds, is not covered in detail.

This first section covers the issues of sediment flux to and from the coastal zone in the South Pacific. The fate of sediment is of great importance to:

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- the persistence of pollutants transported by it;
- the amount of sediment that remains in the coastal zone; and,
- some more obscure impacts as coastal lithosflexture, localised isostacy and continental shelf loading.

The near-shore zone in the South Pacific is somewhat unusual due to the general absence of any significant area of continental shelf.

Special consideration was given to the one exception, the largest continental shelf area in the region, which occurs in the Torres Strait and the Gulf of Papua. The area is also of special interest because of the presence of the Ok Tedi mine which is having major environmental impacts, mainly due to the enhancement of the suspended sediment transport rates and the chemical load of that sediment.

An overview of the literature concerning the Ok Tedi mine is presented along with an assessment of the possible long-term fates and effects of the sediment and chemical load introduced into the environment via the discharge of tailings into the Fly River. While these assessments are largely hypothetical, they present a number of possible alternatives that require further investigation.

This first section is followed by a general assessment of the literature on the impact of sediments on mangroves. An outline of the ecological and physical environment in which mangroves exist including a discussion of the value of mangroves from a ecological, physical and human resources perspective. The third section considers the coral reef ecosystem and includes a general coverage of the environmental factors influencing coral growth, as well as a discussion of the direct impact of sediment on the coral reef environment and the adaptations of the ecosystem to that sediment.

The fate of terrigenous sediments in the coastal zone is determined by the nature of the coastal environment, whether mangroves, rocky cliffed, presence of coral reefs, etc. Sediment once in the coastal zone, is subject to a number of fates, on a number of different time scales:

1. Sediment can be stored over short periods, for up to a century or more, as an active, dynamic sediment, in beaches, harbours, estuaries and lagoons, regularly being reworked from time to time.

2. Sediment can also be stored in more major, longer term sediment traps around the coast. These sediment traps include the same prograding harbours estuaries, beaches and lagoons as in the temporary stores, but they also include the major back-shore dune systems, mangrove swamps and coral cays.

   Sediment enters these stores, settles and is fixed for periods from decades up to thousands of years, until such time that long-term changes like minor eustacy or isostacy cause the sediment to be either re-mobilised or removed from the system altogether.

3. Probably the most globally significant fate of sediment in the coastal zone is that of continental shelf deposition (Milliman, 1990). Sediment is exported from the coastal zone and settles on the continental slope and shelf, where it remains until major eustatic and isostatic sea-level changes, over tens to hundreds of thousands of years, prompt it to re-enter the active coastal zone, or be exported to the oceanic abyss.

   Where this is the case, the sediment effectively ceases to exist as a part of the active system as it can only be recycled over a period over many millions of years when it reaches a Benihoff or subduction zone, by which time it is likely to have undergone lithogenisis and require substantial energy inputs for reworking.

It becomes clear, when considering the possible fates of sediment in the coastal zone, that factors controlling the dynamics of sediment within that zone are more far reaching than the immediate concerns of short term fluctuations of terrestrial supply.

3.1.1 Continental Shelf Deposition of Sediment in the South Pacific

The South Pacific is, perhaps, somewhat anomalous with regard to the predominance of continental shelf deposition. This is due, not to any difference in the dynamics of the sediment, rather, to the absence of a continental shelf over much of the region. Islands in the South Pacific are almost exclusively volcanic in origin (including atolls), which unlike the continents, rise directly from the oceanic plateau. In this way the region differs from much of the rest of the world where, since the end of the Holocene, the majority of terrestrial sediment has been deposited on the continental shelves.

Globally, terrestrial sediment only escapes to the abyssal plateau from the continental shelf during times of sea level low (Milliman and Mead, 1983), or in the presence of major rivers where sediment supply exceeds the dispersive capacity of the shelf currents. Where this happens, sediment spills over the shelf and onto the abyssal plains (Southam and Hay, 1981).

In the South Pacific, sediment that elsewhere would be destined for (long-term) storage on the continental shelf (and available for re-working) is constantly being irretrievably lost from the system to the deep ocean. In light of this loss, the question arises of how such a large sediment sink affects the dynamics and supply of sediment in the coastal zone, and is there a great sediment deficit in the region?

There seems to be no answer to how the loss of the sediment effects the area as quantitative assessment of the problem would be a formidable task. The lack of any significant apparent sediment deficit, however, can probably be attributed to the potential to supply vast amounts of carbonate sediments, fixed directly from seawater by Hermatypic corals. These corals thrive throughout the South Pacific.

Although there is a general absence of extensive continental shelf area in the South Pacific region, there is one notable exception - Papua New Guinea and the Torres Strait, which lies between Australia and PNG and is the largest single area of continental shelf in the region. It also has the added distinction of having a number of large rivers flowing into it including the Fly and Purari rivers, which are among the world's major tropical rivers in terms of both discharge and sediment yield (Milliman and Mead, 1983).

The area of the Torres Strait and the Gulf of Papua has been the subject of increasing scientific investigation, particularly in light of some recent very significant resource development projects. A large hydro-electric scheme was developed on the Purari around Wabo, while on the Fly river, there has been the development of one of the world's largest copper/gold mines (Ok Tedi), which is a continuing international and political issue.

With this background in mind, a closer look was taken at the Torres Strait, the Fly river and the Ok Tedi mine, the interactions between them and the area as a representation of a major component of the continental shelf area in the South Pacific.

This investigation was undertaken in the hope that understanding of the dynamics of sediment flux in this area, (by monitoring its accumulation on, and dynamics to and from the continental shelf), will provide information on the proportion of sediment lost to the abyssal plateau in areas of the South Pacific where the continental shelf is absent.

3.1.2 Sedimentation in the Torres Strait and the Gulf of Papua

Torres Strait is a rimmed continental shelf environment of mixed siliclastic and carbonate sedimentation (Harris, 1988). The area is influenced tremendously by the freshwater and sediment input of the large rivers that enter it. The freshwater input to the Gulf of Papua alone is over 13000 cumecs (Wolanski et al, 1984).

Sediments are supplied in vast quantities by the rivers (Dent, 1986) and by biogenic inputs (Maxwell 1968) and moved in equally large volumes by powerful tidally generated currents (Harris, 1988). Harris (1988) discussed the major advances of oceanography that have lead to a greater understanding of the processes operating in the Torres Strait area, including the use of large scale remote sensing to disprove the net easterly current proposed by Wyrtki (1960), Admiralty (1973) and Johnston et al (1982)

Fluvial derived sediment is dominant in the Gulf of Papua and the northern end of the Great North East Channel. Sediment cores show a dark estuarine mud interbedded with thin sand and organic layers, which include some limestone clasts that may be interpreted as being extensions of, or reworked material from, Pleistocene lacustrine deposits. The presence of woody organic material suggests that this area was raised to or above sea level at some time during the Pleistocene.

At the southern end of the Great North East Passage, the sediments show a distinct stratification with the top 60 to 100 mm being a non-cohesive muddy, gravely, sand, comprised of over 85% carbonate sediment (Harris, 1988). Harris interpreted this layer as a Holocene deposit of biogenic origin.

Below this layer lies strongly cohesive, dark terrigenous clay, containing up to 45% weathered (reworked) limestone clasts. This layer is also probably an extension of, or reworked, Lake Murray Pleistocene beds that supply much of the sediment to the Fly River today.

These sediment cores indicate a simple depositional sequence of the Torres Strait shelf, including three distinct phases. Firstly, there is Pleistocene terrigenous flood-plain and deltaic deposition which occurred during low sea level stands. This is covered by cohesive estuarine and deltaic sequences that occurred during the Holocene sea level transgression, finally topped by the biogenically derived carbonate sediment of the present depositional environment.

Such a depositional sequence follows the general rule proposed by Milliman and Mead (1983), that periods of sea level high are periods of sediment accumulation on continental shelf environments. The accumulation of sediment on the Torres Strait shelf during the sea level lows of the Pleistocene as described by Harris (1988, and other references therein), can be discounted from this statement as they appear to be terrestrial flood-plain lacustrine and deltaic deposits. It is assumed that during the low sea level stands of the Pleistocene, much sediment was directly transported (by sub-aerial erosion), or spilled over the edge of the continental shelf onto the abyssal plateau of the Coral Sea or the Gulf of Carpentaria (Harris, 1988).

Torres Strait is thus, at present, undergoing a period of sediment accumulation. The Holocene sea level transgression has created a geomorphically anomalous situation of a vast sediment sink on the recently submerged shelf area.

The efficacy of the transport of sediment to and from the coastal zone, the continental shelf, and to the abyssal plateau, is entirely dependant on the tectonic situation and whether sea level is rising, falling or stable (Southam and Hay, 1981). The sediment dynamics of Torres Strait and the Gulf of Papua are thus unlikely to be transporting much of their sediment load to the abyssal plateau, rather, retaining it on the continental shelf and in the coastal zone where it may undergo further reworking under certain conditions. Such reworking may be similar to that proposed by Harris (1988) as happening in and around the Warrior reefs.

There has been discussion in the shelf science literature regarding the phenomena of shelf loading and continental shelf lithosflexure. The vast amounts of sediment being supplied to and probably retained on the Torres Strait and the Gulf of Papua continental shelf make this highly possible.

If this phenomenon was occurring, it would be expected that areas of the Fly River delta and the Gulf of Papua would be undergoing subsidence, while other areas, possibly further inland would be experiencing some form of uplift. As yet there seems to be little reference to any detailed studies of this phenomenon in the region, other than descriptions of the area as tectonically active. The possibility that additional sediment, supplied from anthropogenic sources such as the Ok Tedi mine site, is contributing to this effect requires further investigation.

3.1.3 Marine Management and Environmental Concern in Torres Strait

As Torres Strait lies between Australia and Papua New Guinea, (one nation a member of the developed world economy, the other a nation struggling to prevent development destroying its rich cultural, physical and environmental resources) the area is not covered by any comprehensive marine management plan (Lawrence, 1991).

Some protection is received as the eastern end comes under the jurisdiction of the Great Barrier Reef Marine Park Authority, and the western end is included in the Torres Strait protected zone.

Torres Strait Islanders have expressed major concern over the impacts of increased sediment, originating from the Ok Tedi mine site, discharge from the Fly River. They have been concerned at the increasing inertia and lack of the environmental safeguards they demanded and which were promised by both the government of Papua New Guinea and the Ok Tedi mining company. There is increasing concern about the impacts of the Ok Tedi mine on the Gulf of Papua, Torres Strait and even as far south as the Great Barrier Reef and Northern Queensland.

This unease has, however, only slowly been translated into scientific investigation of the actual and potential impacts. As a result, this study included a review of the Ok Tedi mine and the literature concerning it has been included in this chapter.

3.1.4 The Ok Tedi Mine and the Sediment Problem

In 1984 one of the world's largest copper mines was opened in the Star mountains in the remote western corner of Papua New Guinea. Development was, and still is, surrounded with controversy due to the measured and predicted impacts of the mine on this relatively untouched area of the world, and the possibility that impacts may extend across international boundaries.

The mine itself consists effectively of Mount Fubilan, which comprises the ore body; at the end of the thirty year expected life of the mine, this mountain will cease to exist (Pernetta, 1988). The site of the mine is virtually on the watershed between the Sepik and the Fly Rivers which are two of the largest tropical rivers in the world in addition to being the two largest rivers in Papua New Guinea. The Sepik River will, however, be virtually unaffected by the development of the mine. Tailings that are discharged into the Fly River (via the Ok Tedi and other tributaries) have an impact in Papua New Guinea, in Irian Jaya and in Australia (Torres strait, Northern territories, Queensland and the Great Barrier Reef).

The mine environment itself is very humid, receiving up to 13000 mm of rain per year (Viner, 1984) in the upland tropical rainforest zone, decreasing to 6000 mm in the foothills where the Ok Tedi river meet the Fly, and 2000 mm in the lowland savanna where the Fly enters the sea. The high relief and rainfall of this region mean that the Ok Tedi and Fly rivers have very high natural sediment loads.

The mining process at Ok Tedi was to involve the grinding of thirty million tonnes of gold and silver ore, followed by some three hundred million tonnes of copper ore. The gold was to be extracted from the ore using ferrocyanides. The mining company proposed a 50 m high oxidation weir over which the tailings were to flow, rendering the cyanide into relatively innocuous compounds (Pernetta, 1988). The PNG government pushed for increased processing of the contaminated waste to reduce the cyanide levels. The fine sediment and tailings (known as the slimes and fines) were to be confined within a tailings dam, maintained by the company in perpetuity (clause 9.1 of the 1980 governmental mining agreement).

cycle in the mangrove environment, then the figure would be far higher.

reclaimed in the early 1900s for the production of sugarcane by the Colonial Sugar Refining Company.

The reclamation can be successful, but requires careful management, e.g. if insufficient fresh water is available following the reclamation salt water inundation of the soils can occur rendering the land unproductive. Other chemical changes can occur in reclaimed mangrove soils, including the development of acid sulphate soils, and ironpan layers. Such chemical changes in the soil make agricultural use of the land non-viable.

3.2.2 Mangroves from Geomorphic Perspective

The mangrove community, or Mangal, consists of a variety of plants, adapted to inundation by salt water, or: "Angiosperms restricted to the intertidal zone" (Pillai, 1990).

Swarup (1983) describes their habitat thus: "Mangroves require land that is covered by salt water at least once a month and uncovered at least once a day". This means that mangroves are restricted to the zone between the mean high water spring (HWS) tide mark, and mean low water neap tide mark (LWN).

The vague definition of what exactly constitutes a mangrove means that many species and a number of genera are contained within the mangrove community. Each species performs different ecological and geomorphic functions. Some, as pioneer species (e.g., *Rhizophera spp.*) are less tolerant of shade and low salinity, but are more tolerant of higher energy conditions, sediment movements and salt water inundation.

These species inaugurate the habitat and create a landform suitable for other mangrove species. This landform is commonly known as a mangrove swamp, but from a geomorphic perspective can be more accurately described as a depositional plateau. Once this landform is created and sediment stabilised, secondary species (such as *Bruguiera spp.*) can out-compete the pioneers on it. Sediment entrapment continues and more organic matter is added, until site modification is such that the mangrove terrace is prograded to a supra-tidal condition outside the mangrove habitat (Galloway, 1979).

3.2.3 Mangroves and Sedimentation

"Mangroves encourage sedimentation" (Bird and Barson, 1979). They do this primarily by decreasing water velocities by up to 50% (Wolanski et al, 1980).

Bird (1971) studied the vertical changes of substrate level in Australia by using vertical wooden pegs placed in a similar pattern to the radial roots and pneumatophores of *Avicennia marinara*. The pegs were set in the upper part of the tidal range (mean high water neap) and showed an additional accretion of 16 mm per year over a five year period.

Elsewhere, such as adjacent and uncolonised mudflats, the sediment remains mobile. It is assumed (although no documented evidence has been found in the course of this study) that the rates of pneumatophore growth would equal or exceed the maximum natural rate of accretion that could be expected in the normal mangrove habitat. This is a safe assumption as it would be highly ecologically unsound to evolve a root system that alters the physical environment and processes around the plant, to levels outside the plants tolerance. The rate of accretion found in normal mangrove ecosystems are likely to reflect the results of Bird (1971).

The sediment stabilising role of mangroves is confined to low energy conditions (Savage, 1972). Where mangroves are found to be colonising in front of an established beach profile, it can be assumed that there has been a lowering of the ambient energy conditions. The energy dissipating landform commonly referred to as a beach, is highly attuned to absorbing and dissipating large amounts of wave energy through the high mobility and the abundant supply of a, usually coarse, sediment.

Proof of this is that beaches are rarely found in the absence of significant wave energy. The higher wave energy and water velocities prohibit the precipitation of the fine sediments and materials that favour mangrove colonisation. Care must be taken, however, not to mistake mangrove colonisation in front of beach profile, with instances where extreme events have caused the deposition of sand, shell or gravel storm ridges within or even near the most landward boundary of the already established mangrove community.

Under high energy conditions, mangrove seedlings are inundated with sediment or uprooted by sediment mobilisation caused by high water velocities. McNae (1968) noted that in such areas, even where numerous seedlings may take root, they suffer a high mortality. He suggested that even minor depositional events can have high impacts on seedlings. Where a thin layer of sediment covers the photosynthetic surfaces of the seedlings, the effect can be exactly the same as being in deep shade, thus killing the seedling.

Bird and Barson (1975) documented a mangrove seedling dieback after just such a depositional event in Australia. Established mangroves in contrast, seem to be able to cope with higher rates of sediment deposition as their photosynthetic surfaces tend to be above water and not subject to shading by deposited sediment.

Strong winds, however, can cause deep penetration of mangrove areas by waves, thus causing significant sediment deposition in or beyond the mangrove fringe (Oliver, 1979). Jennings and Coventry (1982) found mangroves that had survived being inundated by over 1 m of gravel. Inundation, however, to that depth of a finer sediment may have more serious effects. The void spaces between the particles of large particle size sediment such as gravel or shell may still permit respiration and gas exchange by inundated pneumatophores where fine sediments create anaerobic conditions which can drown pneumatophores (Oliver, 1979).

Little is known about the actual accretion rates of sediment across transverse profiles in the intertidal zone in the presence of mangroves. Partially contributing to this problem is the complex ecological response of mangroves, not only to circadian and seasonal rhythms, but also to lunar and tidal cycles. This complexity manifests itself in *Avicennia* (Gill, 1971) as non-annual growth rings, which thwart dendro-chronology and impede the dating of mangroves and the calculation of sediment accretion rates by this method.

Increased or increasing rates of sediment deposition may not always have negative impacts. Blacker (1977) examined changes to the mangrove distribution in Sydney harbour and found an increase in overall mangrove extent. This was due to sustained, higher sediment yields related to bushland burning, increasing urbanisation and other human activities in the hinterlands of greater Sydney. The increased sediment yield created a depositional environment that accreted at a rate favourable for the continued succession of mangroves. It may be that areas previously uninhabitable to mangroves, due to being subjected to increased sediment yields and long-term deposition, underwent a raising of the depositional terrace above the lower limit of mangrove survival. Hutching and Retcher (1977) independently drew the same conclusion about the condition of Sydney's mangroves. They related the overall reduction of mangrove area in the harbour entirely to mangrove clearance and land reclamation, and found no evidence of mangrove loss due to physiological or environmental stress.

Mature mangroves thus appear to be highly adaptable to (and possibly even benefiting from) high sediment loads, being vulnerable only at the seedling stage. High magnitude events, while causing high mortality among seedlings, can create areas for further colonisation after the event. Sustained high sediment loads, while creating environments suitable for further mangrove colonisation, however, can prevent colonisation by inhibiting the survival of colonising seedlings. Mature mangroves appear to be restricted by high sediment loads only when the rates of deposition exceed the maximum rate of pneumatophore growth. Little work appears to have been done in the quantification of these growth rates.

It is important to note that the conclusions drawn from the literature regarding the response of mangroves to increased and increasing sediment loads are not necessarily the same as those that should be drawn about the benthic and other biotic communities residing within or utilising the mangrove community. It is possible that organisms ecologically reliant or adapted to mangrove systems have similar tolerances to ecological and environmental stresses. This cannot be assumed, however, and any assumptions made about overall environmental stability from the consideration of mangrove stability must not be mistaken for an assessment of ecological stability or well being.

The study of ecological stability must include comprehensive data from the whole ecosystem. An illustration of this point is the impact of increased sedimentation on the fish species of the mangrove community. It has been proposed that increased sedimentation may greatly encourage the growth of algal communities, especially when that sedimentation is linked to agriculture and fertiliser runoff.

While this may have little impact on mangroves themselves, it may have drastic effects on the Biological Oxygen Demand (BOD), or the occurrence of toxic dinoflagellates. There has been little published research relating the ecological response to the nutrient input of suspended sediment. This is due mainly to the difficulties of proving the linkages between cause and effect.

3.2.4 Mangrove Stability as an Indicator of Environmental Change

A mangrove system can be considered stable if it continues to occupy the same area of tidal land (Bird and Barson, 1979), and unstable if its boundaries are advancing or retreating. Evidence from prograding coasts, such as that outlined above, and from submerging coasts (like Florida where landward migration has been documented), signifies that mangroves can be highly sensitive indicators of, and rapid in their response to, environmental changes such as coastal progradation or minor eustatic or isostatic fluctuations in sea level. Chapman (1976) noted, however, that few attempts have been made to measure the changes to or the stability of mangroves or to relate them to environmental stability.

The sensitivity and ability to respond rapidly to vertical and horizontal changes of habitat by the mangrove ecosystem is highlighted by the fact that mangroves have only occupied their present position since the end of the Holocene sea level transgression (Thom and Chappell, 1973; Bird and Barson, 1979). At the beginning of the Holocene, they were located up to a hundred and forty metres lower and in some cases many tens or even hundreds of kilometres from their present position. Thus the ability of the mangrove, and presumably all the species that reside within the mangrove community, to cope with long term environmental change is substantial.

Due to their sensitivity to environmental change, have the potential, if monitored properly, the potential to render some very valuable information. This is particularly appropriate in the light of the present uncertainty regarding the magnitude and impacts of the greenhouse effect.

3.3 Sediments and Seagrass Beds

Seagrasses are found in near shore localities where a number of environmental factors are conducive to settlement and development. Seagrass beds are areas of high biologocal productivity which support a large number of organisms which, among other things, feed into the life cycles of reef fish. In addition, nitrogen fixation takes place in seagrass beds and this represents an important source of fixed nitrogen in nutrient deficient tropical waters. Seagrasses have the ability to reduce water velovity, encourage sedimentation and stabilise sediments, thus making a significant contribution to the protection of coasts in tropical areas.

Increased sediment loads can affect seagrass beds in a number of ways. Very large sediment inputs can bury the seagrasses completely leading to death of the community. Smaller additions of sediment lead to increased turbidity which in turn reduces the photosynthetic activity and limits the productivity of the whole system. Thus for seagrasses we have an unusual situation in that they aid the sedimentation process in the near shore area, but too much sediment can overwhelm these communities removing their potential to retain further sediment.

3.4 The Impacts of Increased Suspended Sediment Loads on Corals

3.4.1 Coral Reef Ecosystems

A coral reef ecosystem is made up of many communities linked together by a complex web of interactions. Several distinct community types exist on coral reefs and their distribution is characterised by spatial zonation. This spatial banding or zonation is an ecological response to sharp environmental gradients and changes in physical conditions.

This creates many varied micro-habitats, and one of the most diverse ecosystems on Earth (Holthus, 1991).

The major physical factors controlling community composition of coral reefs are light availability, wave action and ambient energy, sediment regime, salinity and tidal range, availability of food and inorganic nutrients, temperature and bathymetry. The relationships between these physical factors are highly complex, and there are many causal inter-relationships between them, e.g., wave action affects turbidity which affects light intensity, which affects algal growth, etc.

3.4.2 Non-Biological Factors in the Coral Reef Ecosystem

Light

A major cause of variation in reef community structures is light intensity. Both intensity and composition changes with depth and water clarity.

There are two types of corals - hermatypic and ahermatypic. Hermatypic corals live symbiotically with algae commonly called zooxanthellae. These algae live within the cells of the coral polyp. In the presence of light, zooxanthellae produce fixed carbon via photosynthesis. They release about 95% of all organic carbon they produce and this is used as a food source by the coral polyp. The algae also take up CO_2 in the water which would otherwise form carbonic acid which attacks the calcareous skeletons of the coral polyp and hinders reef development. In the presence of algae the corals calcify at a rate that may be 2-3 times faster than in darkness where the zooxanthellae cannot grow. Ahermatypic corals do not have zooxanthellae, are not reef building corals and are therefore not restricted to sunlit waters. They can grow at any depth and are dependent upon plankton for their nutrition rather than the algae.

Because reef building corals and coral reefs are dependent on light for their existence, water turbidity is a governing factor to their growth. The range of light intensity in the water column controls the zonation seen in reef communities. A decrease in light availability will decrease photosynthetic production by the zooxanthellae and thus decrease coral growth.

Wave Action

The breaking of waves on the reef flat, especially during heavy storms, causes the destruction of many corals. Few hermatypic corals survive the conditions found in the high energy littoral zone on the reef crest (Veron, 1986) and corals are found in decreasing abundance and diversity in this area.

Sedimentation

There are two major types of sediment to be found on coral reefs:

- Autochthonous sediments, derived from the coral reef system, are primarily carbonates.
- Allochthonous sediments derived from terrigenous sources and are transported to the system via rivers. These are predominantly non-carbonate. The presence and predominance of the different sediment types changes in a gradient across many reef profiles due to a variety of factors.

Marine sediments, produced from the break down of coral skeletal structures and coralline algae by mechanical and biological action, are easily transported but have little effect on water clarity (Veron, 1986).

The different types of reefs - barrier, lagoon patch reef and fringing - have different susceptibilities to environmental stresses such as sedimentation (Holthus, 1991). Fringing reefs around high islands, because of their proximity to the source of sediments, have a greater potential to receive that sediment and they will be most influenced by and adapted to terrestrial sediments.

The magnitude of the impact will depend on the associated coastal features, the presence, absence or size of a lagoon and or barrier reef, as these influence the fluvial dynamics of the environment. A common source of sediments deposited within lagoons is from barrier reefs which produce large quantities of the calcium carbonate materials. The amounts produced may have little or no noticeable effect on the corals associated with the reef/lagoon system, but the combined effects of sediment delivery from the barrier reef and terrestrial sources may be great (Loya, 1976). The spatial distribution of sediment deposition depends on the lagoonal bathymetry and current patterns.

Coral reef ecosystems have, however, persisted over geological time. Adaptations to stresses have occurred, including response to regular cyclones which must be viewed as among the most destructive of all environmental events. Not only do cyclones cause destructive wave action along the coast, they are also accompanied by large erosive and transportation events, far exceeding regular levels. The persistence of coral reefs is the result of adaptation to the nature of South Pacific coastal zones.

The size and source of sediment and suspended sediment is a determining factor in the effect that the sediment has on the coral reef ecosystem. While this has been touched on earlier, further clarification of the relationship between sediment characteristics and impact is required here.

Sediment Size

Fine sediments remain in suspension for long time periods and are easily transported. These materials act as dense fluids, flowing on and off reefs, creating turbidity plumes which reduce light penetration. Fine sediment has less potential to cause damage through abrasion, but a higher potential to cause smothering. Coarse sediments are less likely to be transported or deposited on corals. They either roll off or settle on the coral surface and are unlikely to be re-suspended once settled. The ability of corals to physically eject sediment particles is markedly affected by the particle size.

Sediment Source

The source of the sediment (terrigenous, autochthonous or shelf) influences on the impact of that sediment through factors such as size.

Autochthonous sediment derived from the coral reef itself, often consists of large carbonate clasts (or pieces of coral) broken off during high energy events such as storms. The large particles can abrade and badly damage other corals through physical impact, but such material is, however, difficult to transport requiring high water velocities and is rapidly broken down into smaller sized sediment.

A notable and highly productive exception to this is the sediment flakes from the coralline algae *Halmeda*.. These flakes, because of their high surface area, are transported easily and have a higher rate of re-suspension than other types of sediment (Holthus, 1991). Smothering of corals by allochthonous sediment is less common than burial of corals from the accumulation of allochthanous sediment from the bottom up. Such burial commonplace in lagoonal areas and there is little defence from it other than upward growth.

Terrigenous sediment is usually finer in size than the autochthonous sediment and is, therefore, more likely to remain in suspension and is easily re-suspended. Fine sediment is less likely to cause abrasion or breakage of the corals but is more likely to cause smothering. Finer particles, such as those from terrigenous sources are easier for the corals to reject in small quantities. In larger quantities, however, fine particles are more cohesive than larger particles and likely to cause a more uniform coverage during a depositional event.

3.4.5 Adaption of Corals to Sediment Stress

Marine organisms utilise two main strategies of adaptation to environmental stress, such as sedimentation. These are morphological adaptation, or spatial (re)location by selection of habitat. The strategy of stress avoidance by relocation is unavailable to corals (Holthus, 1991).

The main morphological differences between sediment tolerant corals and those vulnerable to sediment are those of surface area, colony morphology, growth rates and cleaning behaviour. The fast growing branching corals with high surface area per unit volume are more vulnerable to sediment than are the slow growing massive corals. This is partially due to their high horizontal surface area.

The massive corals found in the lagoonal and back-slope areas of the reef have less horizontal surface area, and their vertical sides are less conducive to sediment accumulation. Adaptations such as growth rates and horizontal surface area, however, do not occur as a response to environmental conditions, rather they exist due to preferential colonisation of species with those physical attributes. There is difficulty in trying to separate the two types of adaptation strategy towards sediment available to corals. There are distinct zonations which include coral types more adapted to higher levels of suspended sediment.

There are, therefore, areas on coral reefs that are more vulnerable to increased sedimentation rates as the inhabitants are less adapted to the higher levels. If high rates of sedimentation occur where the predominant species are branching or platy corals, then the impact is likely to be greater than if the same sedimentation event occurs in an area where there is a predominance of massive corals. Because of the different preferred environments of these corals, a sedimentation event is more likely to occur in the area of the massive corals than in the areas where platy and branching corals are found. Lower water velocities and less sediment drainage prevail in the areas where massive corals are found, in comparison to the preferred environment of the more vulnerable branching and platy corals, where sediment drainage and water velocities are higher (Stoddart, 1969b).

Coral biology and ecology regarding sediment cleansing is well covered in the literature (e.g., Veron, 1986). Cleaning behaviour can be found in most corals and is a function of a number of methods; ciliary action, tentacular action, by polyp distension through water uptake or by mucus production (Loya, 1976; Holthus, 1991). Cleaning is done on an individual basis except for mucus production which operates on a colonial basis.

3.4.6 Documented Effects of Sediments on Corals

There is a long history of investigation into the effects of sediment and turbidity on coral reefs. Some of the findings are summarised below.

One example of a coral reefs response to a high sedimentation event was studied at French Frigate Reef, a natural wildlife refuge in the Hawaiian group. In April 1980, a freighter ran aground on the reef and 2,200,000 kg of kaolin clay cargo was dumped to facilitate refloating. The kaolin, being a particularly fine natural sediment, created a large sediment plume that gained created widespread public attention.

Investigation by Dollar and Grigg (1981) found that the sediment, being virtually inert, had no toxic effects on the corals. Although the event appeared severe, there were no lasting effects on the corals except for the areas where physical crushing by the ship or by bags of clay falling from the ship had occurred. Within an area of 50 m from the site there was some coral bleaching (loss of zooxanthellae), presumably in response to burial by up to 50 cm of clay for fourteen days or more. No plume was identifiable from a LANDSAT image twenty two days after the event, and an attempt to relocate the site of the grounding by a landing party less than five months after the event, failed.

Dollar and Grigg attributed the low impact of what was feared to be a serious event to a number of reasons:

- The sediment was of a nature that could be actively removed from the corals by mucus entanglement, it had a particle size requiring only low velocities for entrainment. Once suspended, the velocities required for deposition were almost zero, and as such velocities are uncommon on ocean reef situations re-deposition was unlikely.
- The coral community structure was predominantly of lobate and sturdy branching corals. Flat platy, or cup shaped colonies were absent from the site, presumably due to high wave energy.

Bak (1978) found in a similar case in the Carribean (following a spill of dredging materials) that mortality was concentrated on the plate like colonies of *Piorities spp.* The coral community structure of French Frigate Reef was also likely to be influenced by its high latitude of 20°N, putting it near the latitudinal extreme of coral reef development, almost certainly reducing the number of more specialised species.

An investigation was undertaken into the effects of longer term sedimentation stress on a coral reef in Malaysia. Phang (1988) measured the algal biomass production of a reef as a measure of impact. The causes of increased sedimentation stress were inland and coastal development, removal of mangroves, the use of explosives by fishermen and from heavy maritime traffic.

Phang (1988) found that high levels of suspended sediment caused mortality of both algae and corals, but total productivity soon returned to normal after cessation of the stress. Phang noted that while the total productivity soon returned to normal, and there was no noticeable change in the species diversity, the site was one that was adapted to and had suffered from high sediment loads for long periods. He concluded that the outcome would be different if the sediment were to encounter an ecosystem adapted to cleaner waters.

Loya (1976) also noted that long -term impact of sedimentation on a Puerto Rican coral reef had a detrimental effect on coral species diversity. Through experimental work, Kolehmainen (1973) found that corals were able to survive long -term sedimentation as long as the rate of sediment deposition did not exceed the capacity of the corals ability to remove it. Where this occurred, mortality and a reduction in species diversity followed.

3.5 Impact of Anthropologically Increased Sedimentation on South Pacific Aquatic Ecosystems

Pacific aquatic ecosystems appear to have a great resilience to high levels of environmental impact, and an ability to tolerate wide fluctuations in environmental conditions for short periods. Exactly how wide this tolerance range is, remains an unanswered question. The question of how ecosystems recover from a catastrophic event while under continued prolonged impacts, is also unanswered, but remains among the most important issues regarding human impacts including increased sedimentation, on the South Pacific environment.

3.6 Erosion and Sedimentation Costs in Monetary Terms

The costs of increased sedimentation and erosion can be incurred either directly or indirectly, upstream at the point of source, or downstream at great distances from the origin. Costs, as outlined above, include losses in productivity, decreasing crop yields, hillslope instability, damage to irrigation schemes, harbours and ports, impact on mangroves, coral reefs and fish productivity, impaired water quality, the sedimentation of reservoirs and increased flood control problems.

3.6.1 Cause and Effect Linkages

In many cases, the costs of rectifying the damage caused by upstream land use is far higher than the benefits from the land use. The reason that the downstream impacts are not prevented at source, is the difficulty of quantitatively linking the effects to the causes. Where direct linkages are unproven, money will not normally be spent in prevention. Thus the resultant costs are far higher than if the lower prevention costs were incurred.

The problem of the uncertainty between the causes and effects of both the detrimental impacts and the prevention or conservation measures regarding sedimentation, increases with the size of the catchment. This is because the time lag between the cause and impact can be quite substantial.

Even where quite simple cause-effect relationships occur (like increased erosion resulting in increased downstream sedimentation), there is a sufficient lack of evidence to quantitatively link the cause with the effect. Thus the economic benefits of prevention rather than symptomatic cure can be dismissed in favour of solutions that politically expedient.

The linkages between increased sedimentation and less direct impacts such as decreased biodiversity or biological productivity (Cordone, 1956; Greynoth, 1979; Newbold et al, 1980; Erman and Mahoney, 1985) are even more vulnerable to subjective interpretation. Even though tropical watersheds are highly complex systems, under pressure from a number of conflicting users, the causes and effects from different parts of the same system are usually managed separately. This piecemeal management leads to symptomatic resource management, correcting the impact and not the causes. The problems therefore are recurring.

Although the linkages between watershed erosion, silt-laden rivers and siltation impacts in the marine environment appear obvious, terrestrial ecologists rarely look beyond the freshwater environment, and marine ecologists who have studied the effects of siltation stress on tropical coastal regimes have rarely documented the source of siltation (Dixon, 1990). Thus the problems of linking terrestrial erosion and sediment yield with marine impacts are similar to those of linking the impacts within the catchment, only greatly magnified.

3.6.2 Problems associated with putting Monetary Values on Environmental Processes

Putting a monetary value or the assessment of impacts of increased sedimentation and erosion due to human mismanagement of the land is fraught with problems:

The most difficult of these problems is that of assessing intangibles. This has been, and still is, one of the major weaknesses in environmental impact assessment to date.

The problem of evaluating something that has no definable monetary value creates room for great subjectivity. If a coral reef, for instance, has no market value (as no one buys or sells them), then to be incorporate it into a cost-benefit analysis, a value must be assigned. This may be an assessment of the market value of the seafood taken from it, or the income earned from tourists who visit it.

Secondly there are the problems of unquantified linkages and off-site impacts. Brock (1985) used the example of tuna stocks that feed on planktonic larvae of coral reef fish, in which case the lag between cause and effect might take a number of years (while the cohort of tuna matures or fails to mature). This makes the cause effect-relationship very difficult to prove (Jones, 1982).

Dixon (1990) attempted to quantify and monetise the effects of increased sedimentation from a logging operations in the Philippines by comparing the revenue from the logging with the revenue from fishing and a growing tourism/diving industry. Estimation of the ecological impacts of the increased sedimentation was completed as part of a separate study (Hodgson, 1989), which quantified linkages through direct measurement. A ten percent per annum reduction in coral biodiversity was recorded and translated into a predicted ten year interval before the total destruction of the reef.

This was incorporated into a traditional economic analysis, with the predictable outcome that the potential revenue from the sustainable fisheries and tourism industries far outweighed the potential revenue of the unsustainable extraction of a stock resource.

The crux of this analysis is still based, however, on the subjective assignation of monetary values to the environment. If a similar site where there was no fishing or diving industry were investigated by the same method, then the marine environment would be assigned no value, even if the reef had exactly the same ecological structure.

Although widely practiced, placing a monetary value on environmental intangibles is fraught with subjectivity. This brings into question the value of the practice. While there is a recognised need for assessing the relative value of various environmental factors, the use of an capricious and abstract value such as that supplied through currency is hotly debated in the resource management literature.

Alternatives coming into favour include energy equivalents and other forms of energy analysis. This is because through these it is possible to incorporate the true costs of production of environmental intangibles within both stock and sustainable resources.

4. The Causes of Increased Sedimentation

4.1 Changes in Land Use

Changing land use is one of the primary causes of erosion and increased sedimentation in the South Pacific. This is because preceding any change in land use, is usually a concommitant change in the vegetative cover of the land. The change in vegetative cover alters the climate-soil relationships that tend to be in some form of equilibrium, and the hydrological and sedimentological regimes are also thus affected. These changes are then manifest in changes in erosion and sediment transport.

Considering land use, it is useful to distinguish between the different erosion types that can result in an increased sediment load, i.e., sheet or wash erosion, gully erosion, and mass movement, since the ability of vegetation and land use to influence them vary greatly (Bruijnzeel, 1991).

- Sheet or wash erosion is caused by the transportation by overland flow of material detached by raindrop impact. This is probably one of the dominant methods of erosion in the South Pacific.
- Gully erosion is relatively rare under natural conditions in the tropics, and is more usually associated with high intensity land-use and improper agricultural methods (FAO, 1985). It is manifest as ruts or gullies which undergo headword growth. This form of erosion can transport large amounts of material from an area.
- Mass movement is where for reasons to be discussed, a threshold value is exceeded, and a large mass of material moves downslope under the force of gravity.

Changes in vegetative cover are often related to the dynamics of mass movement. Ramsay (1987) stated that climatic and geological factors are more dominant controls and that deep seated mass movements are not affected by vegetative factors. Work by Liedtke (1989) in Fiji, however, proved a distinct relationship between the removal of forest cover and the number of mass movements.

To further complicate matters, Bruijnzeel and Bremmer (1990) emphasise that road construction exerts a more important influence on slope stability in tropical steeplands than do either vegetation or land use.

This confusion is likely caused by a lack of distinction between shallow and deep seated mass movement. Zeimer (1981) stated that the presence of tree cover is the most dominant control of shallow (less than one metre) landslides and mass movements, the major controlling factor being mechanical reinforcement by tree roots. Deep seated movements (greater than three metres) are not influenced by vegetation. This explains the discrepancy caused by Liedtke's (1989) findings as his analysis was done using aerial photographs and did not distinguish between movements at different depths.

The erosional and sedimentary effect of any change in landuse, however, will depend entirely on the processes and conditions supplying and removing sediment to and from the river network under natural conditions (Bruijnzeel, 1991). Areas adapted to very high levels of suspended sediment or erosion will suffer little from impacts from human activities. Systems adapted to low loads and high water quality will suffer more from even minor increases.

The direct impacts of changes in the sediment regime become less recognisable the larger the catchment is, and the further downstream one precedes. This is due to an often overlooked and underestimated factor; hysteresis, or time lag between cause and related impact of sediment flux. Sedimentary hysteresis or flowthrough time in larger catchments can be decades or even centuries, thus explaining the lack of its quantification. Pierce and Nichols (1986) stated that hysteresis increases with catchment size as the number of storage opportunities tend to be greater with catchment size. Hysteresis, however, can be far less in smaller catchments.

For ecological and agricultural land use, the carrying capacity of the land is vast. It is only where inappropriate technology or techniques are applied to its use or management does land degradation occur. If energy and nutrient inputs equal energy and nutrient outputs (or extraction) then the system is sustained.

4.2 Tropical Forest Conversion

Tropical forest conversion can best be defined as a change in land use. Large tracts of tropical forest land are being converted to other uses such as subsistence and market-based agriculture, livestock farming, extractive silviculture and tree plantation (rubber, oil palm, tea, coffee and cocoa), and to a lesser extent to mining (Bruijnzeel, 1991).

Such land use changes are usually accompanied by dramatic changes in the hydrological and sedimentological regimes. Erosion following land use changes such as logging, when forest cover is removed and soil disturbed (Lal, 1986), causes high sediment yields and is a great problem in many parts of the world, especially in tropical steeplands (Sundbourg, 1956).

Many people believe that all tropical forest conversion or deforestation causes major flooding, lower water yields, higher sediment yields, detrimental impacts on coral reefs and mangrove environments, changes in evapotranspiration and rainfall, and will eventually lead to desertification. Others who have attempted to be objective with what can be an emotive and political issue, by the presentation of scientifically established results have been accused of selling out to the enemy (Nooteboom, 1987; Smeit, 1987; Bruijnzeel, 1991).

4.2.1 Logging and its Role in Tropical Forest Conversion

Logging is seen by many as the primary process whereby tropical forest is converted to areas of non-forest. Although logging may be a major process, it must be pointed out that it is not the only method of forest conversion. Although the removal of tree cover usually involved in tropical forest conversion, the term logging is sometimes inappropriately used as a generic definition for that removal of trees. In the context of this discussion, logging will be considered under the heading of commercial timber extraction, as the methods, area and impacts of tree removal by commercial timber extraction are very different from those of other methods.

The two main methods or strategies of commercial timber extraction in the tropics are clear felling, and selective logging. The term selective logging is misleading in ecological terms as the ecosystem is usually altered beyond any capacity to restore itself to its previous state.

In this context selective logging and clearfell logging, which generally involves an almost complete destruction of the vegetation (Saulei, 1984), can be considered identical. Whitmore (1990) states that "in selective logging even where the greatest care is taken, for every tree extracted, a second is destroyed and a third is damaged." Selective logging therefore must not be confused with logging in a sustainable manner or silviculture.

In the context of hydrological and sedimentological impact, there is some difference in the effect of selective and clearfell logging, and they should be considered separately.

4.2.2 The Impacts of Commercial Timber Extraction

The increase in sediment yield from forested areas following logging is well documented (Deitrich et al, 1982; Dunne, 1979, 1984). Research into erosion under virgin forest in East Kalimantan by Besler (1987) showed that weathering and erosion are usually in a dynamic equilibrium. The equilibrium is altered, however, if the protective layer of vegetation or litter is removed. Denudation and sedimentation rates increase sharply due to increased rainsplash detachment and transport processes. This is the fundamental reason for increased rates of erosion and sedimentation in converted tropical forest land.

The impacts of commercial timber extraction arise from the changes in the equilibrium between the physical properties, processes and interactions of soil, climate and vegetation. Vegetation and organic litter is removed, which due to the methods of extraction, often involving heavy machinery and burning (Stadtmueller, 1990), has an impacts on the soil profile and structure. This change in soil profile and structure when faced with a change in ground-level microclimate (usually involving higher soil and air temperatures, greatly increased rainfall erosivity, insolation rates and evaporation rates) impacts significantly on the hydrological and sedimentological regimes. Malmer (1990) noted that prior to logging, most undisturbed forest streams show steady and low concentration of suspended sediment, with an absence of any distinct peak in sediment discharge.

In contrast, sediment load peaks are dramatic after logging and usually slightly precede the peak in hydrological discharge. Catchment sediment yields are changed as they are a direct result of physical variables and interactions between them. In this way, sediment yield can be used as an index of many hydrological and sedimentological variables.

To extract the timber from a forest, access must first be gained to the area. The creation of this access can have the greatest impact on the sediment yield (and all its encompassed processes and variables). Between 24% (Abdulhadi et al, 1981; Malmer, 1990), and 60% (Abdul-Rahim, 1989) of the soil surface may be damaged by the construction of roads, log landings and skid trails even in selectively logged areas. Dixon (1990) states that although roads can account for as little as 3% of the area they can account for as much as 80% of the erosion. This is primarily due to the compaction of the soil structure by heavy machinery.

Stadtmeuller (1990) described the effects of using heavy machinery in log extraction as profound. Soil that has undergone compaction by heavy machinery, in contrast to undisturbed soil, have very low infiltration rates. Malmer (1990) quoted an example of where post-impact rates were 0.28 mm/hr while adjacent, undisturbed areas retained a pre-impact rate of 158 mm/hr. This generates more overland flow and thus contributes to higher peak discharges, flow velocities and sediment loads.

This impact is long term and can have slow recovery times. A return to natural levels may take 5 to 9 years (Lal, 1990). Bruijnzeel (1991) documents areas of skid trails and logging yards that still have significantly lower infiltration rates and are unrecovered twelve years after use. Douglas (1969) warns however that even short term stabilisation of sedimentation rates may be misleading as this often fails to account for extreme events such as mass movement.

Damage patterns differ greatly between extraction methods. For example the high head method of extraction which utilises cables an winches rather than tractors, although having a higher impact on the vegetation, has a lower impact on the soil structure and protective litter covering.

As Bruijnzeel (1991) states; "surface erosion is rarely a problem where the soil surface is protected from the direct impact of the elements, be it by vegetative interception or by a litter layer". Some methods of log extraction have a greater effect on the protective covering of the soil or the ability of the soils to restore themselves.

Thus if forests are to continue to supply timber, log extraction will have to be limited and follow strict impact mitigating procedures and specifications (Whitmore, 1990). Abdul-Rahim (1989) stated that damage to both canopy and forest floor can be reduced enormously through the careful planning of extraction roads, and high sediment yields prevented by the provision of adequate buffer strips around water courses.

Post-extraction efforts to reduce the long-term effects, such as the raking or ploughing of compacted soil, may also be highly effective. Bruijnzeel (1991) noted ample evidence that strict enforcement of logging prescriptions and environmental legislation would reduce most adverse on site and off site effects. Although many tropical countries have developed such specifications and legislation, Poore et al (1989) estimate that less than 1% of tropical rainforest is being managed in a sustainable manner. "A sad indication of the discrepancy between theory and practice" (Bruijnzeel, 1991).

4.2.3 Natural Regeneration and Reafforestation of Converted Forest Land

Forests left alone for long enough have very high regenerative capacities and may recover to their previous state from such high impact events as fire, cyclones or even selective logging (Saldarriaga 1987). Clearly this is not the case when land is converted to agriculture or plantation forestry where impacts are sustained and high in intensity (Bruijnzeel, 1991).

Some work has even been done on the regenerative capacity of clearfelled forest (Saulei, 1984). Saulei noted that on areas that had undergone clearfell logging in Papua New Guinea, vegetative coverage had returned to 90% of the area after only six months. The areas left uncovered were not surprisingly those heavily compacted areas of the logging yards and major skid trails. He also pointed out that most of the regenerating seedlings tended to stem from the coppice around large tree stumps. It is presumed that these areas represent the seed banks or saplings in the less disturbed soil, protected from the heavy machinery by the presence of the large stump.

Seed dispersal is presumed to also occur due to the disturbances during the logging operation. Investigation of areas ten years after logging had ceased, showed 97% of species were composed of larger secondary or primary species. This work supports assurance (Bruijnzeels, 1991) of disturbed forests regenerative capacity, if left undisturbed.

Areas that have suffered heavy impact by commercial timber extraction are often susceptible to changes in the chemical composition of the soil. Low lying areas for example are subject to acidification due to the anaerobic decomposition of organic material. Deforestation of mangrove areas for agriculture can have profound impacts on the soil, including the possibility of acid-sulphate soils and the creation of ironpans.

There are a number of other problems caused by, and possible benefits from, the large amount of organic material generated by the removal of timber from tropical land. One of these problems relates to the nutrients contained within the biomass. It is a commonly recognised feature of tropical rainforests that the majority of the ecosystems nutrients, are contained in the biota, not the soil.

This is because the capacity for storage of nutrients is greater in plants than in soil. Surplus nutrients in the soil not extracted by plants, are leached out by abundant rainfall relatively rapidly. Thus when large amounts of the biota are removed, what appeared to be a very fertile environment due to its high biodiversity and biological productivity, soon proves to be a very infertile one as the productivity was due to efficient nutrient uptake and cycling, not the total abundance of nutrients in the soil.

Although the commercial extraction of timber implies the removal of trees, experiment has shown that far more organic matter remains behind than is physically removed. The reason for the change in the overall nutrient status of the ecosystem, is that the nutrients, once stored in living plant matter, are more available for release from dead plant matter. This release can occur in two ways. Burning of the slash (organic matter remaining after forest clearance), or through decomposition of the slash. Burning rapidly releases the nutrients, largely into the atmosphere in the form of smoke, the rest into suspended sediment in the form of readily transportable ash. Contrary to the belief of many swidden agriculturalists, that burning releases nutrients into the soil, most leaves the area. Decomposition in contrast releases a far higher proportion of the nutrients into the soil.

4.2.4 Forests and Fire

The effects of a natural forest fire may be felt as increased runoff and peakflows. Shimokawa (1988) found erosion rates under burned forests were significantly higher than under unburnt forests, and an enhanced streamflow for up to two years was measured by Nakane et al (1983) due to the decreased water requirements of damaged and regenerating vegetation.

Malmer (1990) noted that undisturbed forest had a lower sediment yield than forest that had suffered fire damage. The magnitude of the enhanced erosion and downstream sedimentation is directly related to the area burned, the severity of the fire Anderson et al 1976). In uncleared forest the severity of the effects of fire are the frequency of or interval since the last fire, and adaptation of the ecosystem to fire.

Increased runoff and peak flows in burned forests can be attributed to the decreased porosity of the soil and the creation of a hydrophobic layer or non-wetable condition due to the exposure to high temperatures (Stadmueller, 1990). The infiltration rates and soil porosity of burned land are less than that of unburnt land (Shimokawa, 1988; Dano, 1990), which is directly related to the exposure of the soil layer to raindrop impact and the clogging of soil pores with fine ash and organic material (Penafiel, 1980). Increased runoff and peak flows are translated into increased sediment yield through slope wash, channel erosion and reduced re-deposition of entrained material.

Quantitative sediment load and hydrological data immediately following forest fires tends to be scarce, as gauging stations are invariably destroyed in the fire and take longer to re-establish than the vegetation (Brown, 1972).

Leitch et al (1983) and Malmer (1990), however, have documented increased sediment yield from areas that have suffered burning, and relate that as fire destroys the litter layer and renders the soil water repellent, peakflows increase significantly and large amounts of soil can be washed away before vegetative cover can re-establish itself and stabilise the process. In some cases, vegetative cover will be permanently altered as the damage made directly after its removal will be of a magnitude that precludes its return.

Hardjono (1980) directly relates reafforestation of burned areas with decreasing sediment yields, and this tends to agree with the literature in general (Malingerau et al, 1985); however, Leighton and Wirawan (1986) suggest that even vigorous regrowth has little real influence on erosion rates, as the root systems of the pioneer plants are too shallow to prevent widespread erosion. This would certainly apply in areas where the erosion is primarily caused by large events rather than at lower continuous rates.

4.2.5 Alternative Resource Extraction Techniques

The two main areas of impact occurring by commercial timber extraction, are extraction impacts, and post-extraction impacts.

Extraction impacts are primarily those of roadbuilding, which is well known to cause great increases in sediment yield (Douglas et al, 1990), and the impacts of heavy machinery used in the physical removal of the vegetation (in this case the trees) from the land. Post extraction impacts are those that result from any post-logging land use, any impact mitigation or land rehabilitation efforts made, or other serious changes or catastrophic event occurring in the system, unrelated to the direct removal of the vegetation.

The impact of road building and the use of heavy machinery in the extraction of timber has been discussed above and need not be reiterated. These impacts are well documented, and recognised even in legislation of many countries. The only reason for the continuation of major problems, is that there is a lack of enforcement or compliance with the legislation. Compacted earth, as mentioned, can easily be ripped up by the very machinery that compacted it, which is probably one of the most efficient and cost effective ways of reducing their impact.

It has been shown, in light of experience in the Gogol valley in PNG, that buffer strips of mature vegetation retained around not only water courses, but also roads and areas that suffer from the impacts of heavy machinery, have an enormous capacity to reduce the amount of mobilised sediment from reaching the watercourses.

Post-extraction impacts, due to the various treatments and impact mitigation efforts made during and at the cessation of the extraction process, are highly variable, and depend on the individuals and organisations involved. They do include treatments of the compacted earth, the treatment of the logging slash, modification of certain hydrological features and the creation of sediment traps, etc.

The treatment of logging slash has long-term effects on the environment of the logged area. Because of the magnitude and variety of those effects, there has been much discussion regarding them. One possible option is burning, and as that is discussed above, and with reference to shifting agriculture, it will not be covered here.

A second option is that of mulching. In reality, mulching is often as simple as leaving it where it falls, however as much slash is created through the trimming and paring of logs in log yards, significant amounts of slash has to be dragged away to keep the yards clear. Douglas et al (1990) discuss the creation of artificial dams of vegetative debris as sediment traps. These occur commonly in natural systems and have great influence in the sediment load of rainforested areas (Spencer et al, 1990).

There is some debate as to the importance of the discarded slash with regards to the long-term effects of burning versus non burning. There seems no doubt in light of the evidence discussed above, that the burning of clearance slash significantly decreases the regenerative capacity of a cleared area, by causing short-term land degradation, often seriously enough to pre-empt the regeneration of the original vegetation.

It has been suggested (Malmer, 1990), however, that while protecting the soil from raindrop impact in the early stages of regeneration, mulching of slash, or the creation of windrows, can have serious long-term, negative effects on the sediment load of a regenerating area.

Malmer pointed out that while protecting the soil from erosion during the vulnerable stage prior to the establishment of canopy protection, the slash also inhibits the growth of understorey and sub-canopy species after the primary canopy is established, resulting in a one tier canopy. This, following the eventual decomposition of the slash, leaves the soil bare and vulnerable to erosion by overland flow and sheetwash.

It is presumed that the relative advantage of using slash as a protective soil coverage would be less in areas undergoing a concerted planting programme, as the re-establishment of a protective canopy is likely to be more rapid than that in areas left to regenerate naturally. Further work is required, however, to quantitatively assess this relative advantage and the negative effects of discarded slash with regards to naturally regenerating areas.

A further issue regarding clearance slash is the nutrients contained in the large amounts of organic material. The question arises as to whether the nutrients supplied to the soil by the decomposition of the slash can exceed the capacity of the regenerating vegetation to retrieve it. If this is the case, then any excess nutrients are likely to be leached from the soil resulting in a net loss, and a reduction of overall productivity.

Although nutrients are clearly lost, and a net decline in productivity found where slash is burned, little work has been done to assess the impacts of the slower addition of nutrients the environment through the decomposition of slash, studies in both Surinam and Malaysia suggest that the nutrients lost through the decomposition of slash can be as little as the equivalent nutrient input of one to four years rainfall input (Poels, 1987; Zulkitli, 1989), and that nutrient losses are due to problems with storage rather than supply.

4.2.6 Alternative Resource Utilisation Strategies

Large scale logging is unsustainable (Poore et al, 1989), and thus detrimental to the environment and economy of the South Pacific.

The occurrence of large scale timber extraction is common and probably increasing in the region. This is because to traditional landowners incurring costs for education, health and foodstuffs, the gathering of timber royalties is seen as a easy way of meeting these financial outgoings.

By its very nature, large scale logging is inaccessible to small communities. In tropical countries, concession fees are regularly set below the cost of the forestry services provided by the governments (Yu, 1992). Where low royalties are paid to the land owners, large areas of land need to be leased in order to realise any substantial revenue.

Where the sale of timber rights is made to meet financial outgoings of the land owner, any alternative source of revenue has the same net result with a different impact on the future productivity of the land. Destruction of the land excludes further and minimises future revenue from the land.

Community investment in small scale logging is one such alternative. Small scale community based logging can reap higher returns than the sale of logging concessions. In Fiji, the royalty value of the hardwood *dakua* (*Agathis*) is F$25 per m^3, while its retail value is F$500-600 per m^3 (S Weaver, pers. comm., 1992).

Yu (1992) noted that if the real value of the resource (or higher concession prices) were realised by the land owner, less resource would have to be extracted for the same net economic gain. If the Fijian landowners extracted the timber themselves, only five percent of the area would have to be cleared.

Realistic valuation of stock resources such as primary forest requires production costs to be incorporated into economic analyses. Failure to do so allows unsustainable industries to pass on the costs of production to landowners through pollution and a depleted resource base (Lang, 1992). This is in the form of a deforested hillside or drained wetland.

Higher royalty prices for timber mean, not only smaller areas logged and an increase in the potential resource through the increased efficiency of the user. Increased cost to the end users increases efficiency by leading to less wastage and more recycling of wood products in the consumer countries (Yu, 1992). This is a well known economic phenomenon exemplified by the response of the global economy to the OPEC oil cartel price hike of the late 1970's.

Legislative preservation of the resource works only in the short term, if at all. Legislation only preserves a desirable and marketable resource until its realisable value proves too much of a temptation and the protective legislation is ignored or changed. Protection of areas from environmental exploitation and degradation by default grants permission for the exploitation of non protected areas.

4.3 Shifting Agriculture

The term shifting agriculture encompasses a number of different landuse practices including swidden agriculture, which is a sustainable and traditional form of agriculture (Siwatabau, 1984), a trans-migratory form of agriculture (Stadtmeuller, 1990), and the application of agricultural technology at a level that is not appropriate to increased population pressure or level of yield.

Swidden agriculture consists of felling a patch of the forest at the beginning of the rainy season and planting (sometimes after burning) rapidly maturing crops. Yields diminish rapidly as such a large proportion of the nutrients in the forest ecosystem are held in the (now removed) biota. Cropping lasts between two and five years until which time the farmer moves on onto a new block.

Since it is easier to clear secondary forest than primary, in sustainable and traditional agricultural situations, repeated rotation in an area is preferred to continual movement. Such land use practices have been sustainable over centuries and should not be confused with the exploitative and unsustainable nature of trans-migratory agriculture.

Swidden agriculturalists know and practise erosion control on steep and vulnerable slopes. Soil is not disturbed unnecessarily. The stumps of cleared trees remain in the ground and provide mechanical support for many years until they finally decompose, long after fallow vegetation has re-established itself. A similar practice is done with the weeds which are chopped off at the surface rather than pulled out, leaving their roots to provide additional and valuable soil binding and erosion protection (Siwatabau, 1984).

Migratory shifting agriculture is a term most appropriately applied to situations where tropical forest land is cleared and people, often landless, move on to the land and commence agriculture in an unsustainable manner (Bruijnzeel, 1990). This has even been advocated as a development policy in areas of PNG as recently as the mid 1980s (Seddon, 1984) although it was apparently unsuccessful. Large areas of Kalimantan have also been used by farmers in this manner, not because of a desperate need for land for subsistence but for personal and economic advancement (Kartawinata and Vayda 1984) as their pepper crops prove. These areas have an estimated erosion rate of 50-120 t/ha/yr (Kartawinata and Vayda, 1984).

The clearing is either undertaken by the people themselves, or is in the wake of selective or clearfell logging. This form of agriculture is often undertaken on a temporal and spatial scale that exceeds the capacity of the forest to regenerate or supply nutrients. Thus the land degrades, and after only a few cropping seasons, the agriculturalists move on. The repeated impact of even a few years agriculture on recently cleared land can have serious depleting effects on not only the soil nutrients, but also the soil seed banks of forest tree species, further reducing the regenerative capacity of the forest irrespective of the nutrient status of the soil following the years of agriculture.

The lack of sustainability of shifting agriculture is associated with the difference between traditional subsistence and commercial or surplus agriculture. Bruijnzeel (1990) has reported that land use practices that prove sustainable for centuries start to break down under increasing population pressure. Lack of sustainability becomes evident where cropping periods are too long or fallow periods are too short. This only happens where there is a shortage of, or competition for, suitable land, whether it be a shortage induced by a rising population, or from increased farm sizes as farmers start market gardening rather than just subsistence farming.

Inappropriate agricultural technology is a less easily defined problem that falls under the heading of slash and burn agriculture. This is because the traditional, sustainable, swidden agriculturalists and the trans-migratory agriculturalists are both involved.

Kartawinata and Vayda (1984), and Donner (1987) link increases in population pressure and lack of sustainability directly to access to modern technology and association with commercial markets. Where traditional societies, once self-sufficient are drawn into the market economy, surpluses need to be generated for trade.

Modern technology causes population increases through the raising of life expectancy and reducing infant mortality. The land has, therefore, to feed a greater number of people. Because of the higher demand, cropping phases are extended and fallow periods decrease.

Access to more modern agricultural technology and methods allows greater areas to be cultivated with the same effort, further surpluses are produced, competition for suitable agricultural land increases. Agriculturalists are forced on to more and more marginal land and the cycle of land degradation is initiated.

Although the impact of shifting agriculture on the micro-scale is very high during the cropping phase (Toky and Ramakrishnan, 1981), the actual impact of traditional or swidden agriculture is low. This is primarily due to the patchy distribution both spatially and temporally, of this impact (Bruijnzeel, 1991). Plot sizes are small, and fallow periods are rarely less than 10 or 15 years (Whitmore, 1990) and are often 20 to 25 years.

Shifting agriculture continues to be a sustainable form of agriculture as long as it is practiced within the ecosystems capacity to recuperate and to supply the nutrients required. Where either the cropping period is too long, or the fallow period is too short, the system will degrade (Odemero, 1984).

4.4 Urbanisation

The other main type of land use change that contributes to changing hydrological and sediment regimes is that of urbanisation. Urbanisation, while occurring in the pacific, is a highly localised problem. While the area is not great, or the increase in regional sediment yield very significant, the impact in the immediate area can be considerable. The process whereby urbanisation increases the sediment load is through removal of vegetation and decreasing the infiltration rate of the soil, which causes increased runoff.

4.5 Mitigation of Impacts of Increased Sediment Loads in the South Pacific

As increasing sediment yields in the South Pacific tend to originate more in the hills rather in the agricultural lowlands, impact mitigation should be directed to the causes rather than to the symptoms. These symptoms include impaired water quality, sedimentation of reservoirs and hydro-schemes, damage to irrigation schemes, harbours, ports, riverbeds, mangroves, reefs, and reduced fish productivity in affected areas (Dixon, 1990).

Using unsuitable agricultural techniques on marginal lands is, as Dixon (1990) states, easier and cheaper to remedy than the downstream effects such as flood mitigation, dredging and lost revenue from affected coastal and freshwater fisheries. The reason in many places for impact mitigation, rather than prevention occurs is the lack of quantitative analysis linking the causes with the effects, and the conservation measures with their benefits.

4.6 Conclusions

Changes in land use are the major cause of increased sedimentation and land degradation in the South Pacific. Changing land use disturbs the equilibrium between the physical properties, processes and interactions of soil, climate, vegetation and other biota.

Land degradation and sedimentation caused by agriculture in the South Pacific (as in the rest of the world) are often blamed on overpopulation and a high population growth rate. It has been shown, however, that in parts of the South Pacific there has been a massive depopulation since the arrival of the Europeans (Falanruw, 1990). This is seen in the extensive areas of abandoned taro terraces. These terraces are as complex as the irrigated rice terraces of South East Asia, and show that areas that are now degrading under increasing population and environmental pressure, at one time sustainably supported far greater populations.

The techniques and strategies of sustainabilitiy have been abandoned or forgotten, and the management strategies now being applied apply to low density populations and low yields. They are not appropriate to the high yield required by today's increasing populations and more distant markets.

5. Suspended Sediment Data in the South Pacific Region

One of the major aims of this study was to investigate the availability of suspended sediment data in the South Pacific. A lack of data was found, highlighted by the fact that the assessment of a total sediment budget for the South Pacific region, undertaken as part of this study, had to resort to the use of an empirical method based on broad climatic data.

In the light of this lack of sediment data, it was decided to assess and recommend various methods by which the data base regarding suspended sediment in the South Pacific may be increased. This section reviews the main methods of sediment yield and suspended sediment assessment, including calculation, measurement and analysis. An outline of the equipment required and the advantages and disadvantages of different techniques is presented. Some recommendations are then made as to the ways in which the regional suspended sediment data base may be increased.

5.1 Sampling Total Sediment Yield and Suspended Sediment

In the South Pacific as elsewhere in the world, there has been a long history of anecdotal and descriptive work done in the field of suspended sediment and total sediment yield estimation. One reason for this is the difference in the methods and accuracy of the sampling techniques between those used for suspended sediment yield and those used for total sediment yield.

The techniques of measuring suspended sediment are relatively simple, and are outlined below. The techniques of sampling the total sediment load require the measurement of the bed load in addition to the of suspended load, As there are varying definitions of these terms, the definitions used in this study are given below:

Suspended Sediment Load

Suspended sediment load is that sediment transported in water either kept upwards by the movement of turbulent currents, or by colloidal suspension (Einstein, 1964), or the finer material carried by rivers that can be transported fully suspended, with no direct contact with the floor of the river channel. This, by convention, includes that sediment that is transported by saltation as the method of sampling is the same.

Bed Load

Bed load, is that proportion of the sediment load that is comprised of coarse sediment moving at or near the river bed by fluvial action. As the sampling of bed load is notoriously difficult and unrepresentative (Einstein, 1944; 1964; 1972; Hubbell, 1963; Leopold et al, 1966), quantitative data on total sediment load is therefore scarce and unreliable.

This study has investigated only the export of suspended sediment from catchments of the South Pacific region to the marine environment. Partial justification for this was that the bed load of most rivers that is transported to the marine environment is deposited in the estuarine and deltaic deposits as the water velocities diminish.

As a large proportion of the sediment transported within catchments is of a small enough size to be suspended at normal river velocities, up to 80 to 90% according to Einstein (1964) and as much as 95%, Smith and Stopp (1978), the assumption can be made that very little, if any bed load is exported from the catchment to the coastal zone. This assumption conveniently eliminates the necessity of inclusion of difficult and dubious sampling and calculation of the bed load in calculation of sediment yield at a catchment or greater scale.

5.1.1 Suspended Sediment Calculation

The sampling and determination of suspended sediment load is relatively simple. There are three methods of determination as described by Einstein (1964) and they are as follows:

- The weight of dried sediment is divided by the weight of the sample prior to drying.
- The weight of the dried sediment is divided by the weight of distilled water, equivalent to that of the volume of the original sample.
- The weight of the sample is divided by the weight of the water in the original sample including the dissolved material.

The most commonly used method it the third. This method requires the weighing of the sample, then the filtering of the sediment and washing to remove the last of the dissolved load. The sediment is then dried and reweighed.

The resultant sediment load is calculated as the weight of the dry sediment divided by the weight of the original sample with the weight of the dry sediment subtracted. The weight of the filter paper must be accounted for in this calculation.

The accuracy of the result depends on a number of variables including the accuracy and calibration of the balance, rounding errors introduced during the calculation, the efficiency of the filtering method and the representativeness of the sample. Of these four possible sources of error, the most likely, an hardest to test and correct for is that of the representativeness of the sample.

5.2 Possible Methods for Collecting Suspended Sediment Data in the South Pacific

It is with the difficulties of suspended sediment data collection and analysis in mind, that one of the primary objectives of this study was to assess the present methods of suspended sediment sampling and recommend a suitably simple and accurate method to encourage participation in a regional suspended sediment sampling programme. Participation would be expected to be undertaken by governmental and non governmental organisations soliciting assistance from agricultural and fisheries officers, school teachers, village headmen and any other person or persons suitably placed to assist in the taking and analysis of suspended sediment data in the less accessible areas of the region.

The size and interval of sediment samples needs to be carefully assessed, and this is largely dependant on the sampling technique. Failure to gather data appropriate for a particular end use, can nullify the expenditure of effort and money on the collection of the samples (Golterman et al, 1983). A discussion of some suspended sampling methods, their equipment requirements, and an assessment of their appropriateness for extending the South Pacific suspended sediment data base appears below.

5.2.1 Suspended Sediment Sampling Methods

There are two main methods of suspended sediment sampling, point integrated sampling, and depth integrated sampling.

Point Integrated Sampling

Point integrated sampling receives little attention in the literature due to its relatively simple methodology. Point integrated sampling is designed to collect a series of discrete samples at a single point over a given time. This can be done manually or automatically using an automatic sampler. The frequency and size of the discrete samples varies with the type of analysis required. This method is often utilised, in conjunction with suspended sediment, to analyse for a range of other water quality parameters.

There are a number of problems associated with point integrated sampling. These are primarily those regarding the representativeness of the sample, contamination of the sample through a variety of causes (to be outlined below), and the reliability of the sampling device.

The representativeness of the sample data can vary with the point of sampling. This is self explanatory; the suspended sediment distribution through the river cross section and reach is not uniform and thus the positioning of the sample intake effects the value of the sample. The easiest method of avoiding this problem is to place the sample point at a thoroughly mixed point of the river. This way a representative sample is more likely to be taken.

Contamination of the samples is a problem particularly associated with mechanical and automatic samplers. Although these machines are expensive, they are not always as reliable as the manufacturers claim and require careful operation and supervision in order to attain accurate results.

Particular problems arise with insufficient flushing of intake hoses and sample bottles. Also mechanical failures that result in the mixing, failure to take or the duplication of some samples. Contamination of the sample can also occur where the intake of a mechanical sampler breaks free and sucks material from the bottom of the channel. This usually gives abnormally high values of particularly large sediment.

Mechanical samplers also are notorious for the failure of their power supply. This supply can be clockwork or electrical, neither of which are particularly well adapted to use in situations where they may get wet. When the supply fails or fluctuates, the sample interval can change or even completely fail.

Point integrated sampling can also be undertaken by hand. A sample is taken from a suitable reach using a bucket or pump. Humans are also not always as reliable as they claim and require careful operation and supervision in order to attain accurate results. Samples taken manually are also subject to many of the contamination problems associated with automatic samplers. The sampling interval, while less uniform and reliable when taken manually, can be recorded accurately and easily thus any errors of assuming a regular sampling interval can be corrected.

Depth Integrated Sampling

Depth integrated sampling is a technique that addresses the problems of the non-uniform distribution of suspended sediment throughout the cross section of a river. This is done by taking a sample that contains an equal proportion of water and sediment from throughout the water column.

At sampling sites where the cross section of the river is very wide, shallow, or there has a distinct latitudinal variability in the suspended sediment distribution; depth integrated samples can be undertaken at regular intervals across the river and a mean value found.

5.2.2 Resources Required for a Suspended Sediment Data Base

There are a number of materials required for the sampling and analysis of suspended sediment. These are: A sampling device, a weighing device, a method of determining the volume of a sample, materials to filter the sample and somewhere to record the data. The quality, accuracy and reliability of the weighing device determines the accuracy of the results. The design of the sampling device and method of sampling determines the representativeness of the sample.

Analytical Equipment Requirements

The types, benefits and or advantages of different weighing devices will not be covered in depth here, except to mention that as the South Pacific is a region where power supply, electronic know how and technical support are often variable or absent, the advantages of analogue and low-technology instrumentation often outweigh those of electronic or digital equipment.

The filtering equipment is crucial to the determination of the suspended sediment load. Without the filter, the sample has to have all the liquid boiled off and the sediment to be dried. In this case the weight includes the dissolved load, as well as that of the suspended load.

The filtering equipment, while important to the technique is very simple. A funnel and some standard scientific filter paper is all that is required. It is best to weigh each individual piece of filter paper prior to use rather than relying on the manufacturers mean value. Once the water sample has passed through the filter, it should be washed with distilled water to remove any residual dissolved load.

Recording can be as simple or as high-tech as is desired or required. Digital logging devices can be coupled to some point integrated sampling devices and digitally down loaded to personal computers for analysis; however, written records or graphs are equally efficient, especially with less frequent samples, and cost much less.

Sampling Equipment Requirements

The sampling equipment varies greatly from method to method. For point integrated sampling, there are a number of different sampling strategies (as outlined above), requiring different equipment.

The automatic sampler has been discussed above and further description is unnecessary; it must be reiterated, however, that these samplers are very expensive, usually require a power supply and require some supervision, regular servicing and careful operation in order to obtain good results.

The samples, once taken, require laboratory analysis to extract the data. In their favour, automatic samplers have obvious benefits. They can be left largely unsupervised and can therefore operate in remote areas over a periods and in conditions that would make manual sampling impractical. They can, when operated correctly, give very accurate data and they are cheap to run compared to manual sampling.

An alternative type of automatic sampler has appeared in recent years with the improvement of electronics. Called an optical transducer, it consists of a light beam that is trained on a light sensitive semiconductor device over a fixed distance. The amount of light the receptor receives depends on the turbidity of the water. The device requires calibrating to the site and a rating curve constructed between turbidity and suspended sediment load. Once calibrated, however, the device can be left unsupervised for long periods.

The optical transducer is usually coupled to a digital data logger, which enables the device to be left for months before needing servicing or down loading of the data. The digital nature of the logger means that the sample interval can be programmemed to collect data at intervals from as little as a few seconds, to hourly, daily or even longer.

The limitations of these devices are that they need calibration which requires analysis by some other sampling method over a period of time and a range of discharges. The complex electronics are vulnerable when spending long periods in close proximity to water. They can also be damaged or even washed away during high flow events, they can be damaged by animals or humans, they can suffer from algal growth, they sample the parameter indirectly rather than directly and they are relatively expensive to purchase.

Their advantages however are obvious, in that, once installed, they can be left unsupervised for long periods of time, render data that requires no further laboratory analysis and can be down loaded directly to a personal computer and they cost little to run once purchased.

The use of manual point integrated samples requires simple equipment such as a bucket or bottle on a rope, that can be lowered from the river bank or a bridge and retrieved with a sample. A pump and a length of hose can be similarly used, but this is susceptible to the same problems that the automatic samplers have, with insufficient flushing of the hose and contact with the bed.

Depth integrated sampling requires a carefully designed sediment sampling device. These samplers can be simple home-made devices, or more sophisticated, scientifically designed ones, referred to as a sampling fish due to their shape.

They work on the principle of allowing water to flow into a sample bottle at a constant rate while being lowered to and raised from the river bed at a constant speed (Leopold et al, 1964). In this way a sample with equal proportions from throughout the water column is taken. The benefits of the commercial sampling fish, rather than the homemade version of the device is that they are more likely to conform to the limitations of the technique. These limitations are that the intake velocity be constant, and that the intake velocity equal or exceed the ambient velocity of the river flow (Nelson and Benedict, 1951). The best results are achieved by this method where the sampler is raised and lowered a number of times.

5.3 Application of the Different Methods

The suitability of the two different methods of sampling suspended sediment, as described above, depends on a number of factors. These factors include the research objectives and the proposed end use of the resultant data, the availability of resources or funds with which to purchase the equipment required, and the availability and reliability of the personnel operating the equipment or analysing the samples.

The automatic samplers can be utilised to their best advantage where manual sampling is unfeasible due to remoteness, adverse conditions or where extended periods and unbroken data sets are required. The major disadvantage of automatic samplers apart from their initial cost is the possibility that they malfunction and cause samples to be lost or contaminated.

Manual sampling has a major difference from automatic sampling in that it is reliable as the operator. This variance can be consistent and acceptable, or can reduce the value of the data to that of anecdotal evidence. When using data from an unknown or secondary source the operator variance is virtually impossible to assess. An advantage of the manual approach to sampling that is often over emphasised, is that of cost. The cost of the equipment required to initiate manual sampling can be negligible. The ongoing costs of running a manual sampling programme in remote areas however is easily underestimated and can end up being more expensive than some of the automatic samplers with the high initial and lower running costs.

The quality of data from automatic samplers is probably more reliable than that from manual sampling, especially for those utilising the data on a secondary basis. The exception to this is where, as mentioned above, the data concerns a single site with known error or operator variance. The longer that sampling devices are left untended in remote areas, however, the more likely that through some mechanical fault or accident occurs to the device the data is lost. In the case of device such as the optical transducer there is the increased possibility over time, that the calibration of instrument shift. Such shifts in calibration are difficult to assess, however, even where such calibration shifts occur, relative data measured over time, can be almost as valuable as that of absolute data, especially where there is some knowledge of the system concerned.

5.4 Recommendations for Implementation of a Suspended Sediment Data Collection Programmeme in the South Pacific

The implementation of a data collection programme, and the usefulness of the data collected within that programme, is entirely dependent on the end use of the data (Golterman et al, 1983).

In the case of the South Pacific, as so little data is available, any additional data would be valuable and greatly improve the present data base. As the aim would be to construct a regional data base for, as yet unspecified uses, the data collected would be required to be as versatile as is possible. Such versatility would come only from the collection of data with a high level of accuracy, reliability, resolution and spatial coverage. Data with a high resolution can be summarised, while data with a low resolution and accuracy cannot be enhanced.

The possibility of implementing a wide scale manual sampling programme through the use of agricultural or fisheries officers, teachers or locals, while feasible, could result on a highly fragmented data base with little reliability due to the high number of operators and the lack of quality control or consistency. The usefulness of the data would rely on the sample interval, which, if taken by hand, is unlikely to be more frequent than daily.

In the small catchments of the South Pacific, a 24-hour sample interval could straddle and fail to record a sediment discharge event. Golterman et al (1983) noted that to obtain accurate suspended sediment discharge values for a river, during the first twelve months of sampling, measurements should be made frequently; at two to four hour intervals during events.

Such a programmeme would require the training of many operators all of whom would be unlikely to donate their services for free. The collection of either samples to be analysed or the resultant data (if the operators were to undertake the analysis themselves) would also require substantial organisation and logistics, and capital outlay if the analyses were to be undertaken on site by those doing the sampling. These problems would occur irrespective of whether the sampling utilised the depth or the point integrated method.

The alternative to a wide scale manual sampling programme, would be that of a large scale implementation of remote, automatic sampling devices such as the optical transducer. A large number of these devices could be set up, maintained and serviced by a few well-trained individuals. The data from such devices would be of a standard and consistency relatively easy to assess, making the data more useable for those working on it as a secondary source. The sample interval of the optical transducer is a great advantage. As the device can be coupled to a digital or programmemable data logger, the sample interval is restricted only to the storage capacity of the data logger and the regularity of the down loading of the data from it. This means that continuous records at an interval of five minutes or even less are possible.

Such data could be used for even the most complex analysis of the relationship of the response of the sediment regime of drainage basins to antecedent discharge and climatic conditions, especially where the sampling site included discharge data. Discharge can be measured by the same solid state electronics as used by the optical transducer, the only difference being that the sensor is a pressure sensitive device, recording stage of the river which is easily converted into discharge values by use of a rating curve.

The use of local people within the sampling programme is not precluded by the use of automatic sampling devices such as the optical transducer. Valuable data could be saved by regular monitoring of and basic maintenance to the sampling equipment. This is particularly so with the optical transducer which is vulnerable to algal growth, and the data logger which is vulnerable to power supply failure.

In some areas, extensive implementation of a programme involving such equipment might not be feasible due to initial set-up cost. High quality data obtained from an intensive programme of a lesser number of representative sites might prove as valuable and is likely to have greater scientific application (and cost effectiveness) than low quality data from a greater number of sites.

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Annexes

Annex 1: Rewa, Ba and Waimanu Watersheds: a Suspended Sediment Estimate

Introduction

As part of the aim of creating an estimated suspended sediment budget for the whole of the South Pacific, selection and testing of an empirical model was required. As work on erosion and sediment transportation rates and yield had been undertaken in Fiji (Fennel, 1986; Liedtke, 1984; 1988; Glatthaar, 1988; Raj, 1986; Hasan, 1986) there was sufficient data to allow comparisons of any empirically derived values that we had calculated, with those estimated and measured by others.

The method of calculating sediment yield selected was that of Fournier (1960). Fournier had studied the sediment transport rates of seventy eight catchments of varying size. He correlated sediment yield with a climatic parameter defined as:

$$p^2/P$$

where p is the maximum mean monthly rainfall in mm and P is the mean annual rainfall.

While this comparison showed the expected increased sediment yield with the increasing climatic rainfall parameter, it also showed significant dependence on relief. Fournier then classified his data into four different landscape/climate groups. These were:

- Basins of low relief and low p^2/P;
- Basins with low relief and high p^2/P;
- Basins with pronounced relief and humid climates; and,
- Basins with pronounced relief with arid and semi-arid climates.

A regression equation was calculated for each group.

Fournier combined the climate and relief factors into a single equation:

$$\log S_y = 2.65 \log (p^2/P) + 0.46 \log H \tan ø - 1.56$$

Where:

Sy = sediment yield in $m^3/km^2/yr$
H = mean height of basin in m
ø = mean slope angle.

The term *H.tan ø* was difficult to apply in large catchments, so Fournier adopted the original regression equations for further studies. The regression equation for catchments with high relief and humid climates:

$$S_y = 52.49\, p^2/P - 513.21$$

was selected for this study.

The Fournier regression equation was selected for the following reasons: data suitability and availability; simplicity of the calculations; the methods applicability at a regional scale; the p^2/P climatic factor which circumvents much of the subjectiveness encountered in other techniques such as the Universal Soil Loss Equation by Wischmeier and Smith (1978).

The USLE was rejected for this study as a large body of literature (Hudson, 1985; Elwell, 1981; Roose, 1977; Troe et al, 1980) indicated that there were serious doubts to the applicability of the method to the humid tropics, and to areas larger than field or plot sized areas that its data is based. The Fournier equation was developed on drainage basins with a large range of sizes, thus being restricted only by the resolution of the data available to the user.

Method

Two large catchments and one smaller sub-catchments were selected for this investigation. The Ba river is situated on the northern dry side of Viti Levu in Fiji, where the natural vegetation type is predominantly grasslands.

The second catchment is the Rewa river, on the South West wet side of Viti Levu in Fiji. Here the predominant natural vegetation is that of tropical rainforest. This rainforest however has been largely removed in the delta flatlands and foothills which make up about a quarter of the catchment and is coming under increasing pressure in the steeper upper parts.

The Waimanu is a sub-catchment of the Rewa river and has among the lowest rainfall in the whole Rewa Basin. Situated in the Southern section of the Rewa basin, its proximity to Suva means it has seen a rapid increase of cash cropping on increasingly marginal lands (Liedtke, 1988).

The sedimentation and erosion of the two catchments (Rewa and Ba) has been investigated by Liedtke (1984), Hasan (1986) and Raj (1986). Liedtke (1988) and Glatthaar (1988) also worked in conjunction in the Waimanu sub-catchment. As the three catchments have been subject to comparatively intensive scrutiny for the region, they offer a good opportunity for the testing and calibration of the technique selected for this study.

The Calculations

Rewa Catchment

The Rewa basin is extensively covered by rainfall data, with over sixty stations within its 2917 km^2 watershed (see Hasan, 1986) for raw data). Of these, thirty one were selected as suitable for this assessment. These were selected on their location and quality and length of their record.

The p^2/P values for each of the selected stations were calculated and a mean catchment value was derived. This value was then used in the Fournier regression for catchments with high relief and humid climate:

$$Sy = 52.49\, p^2/P - 513.21$$

This with the mean p^2/P value of seventy resulted in an estimated sediment yield of 3161 $m^3/km^2/yr$, giving with a specific gravity of 2.1 to 2.6 (Liedtke, 1988) a sediment yield of:

$$= \quad 6638 \text{ to } 8220 \text{ t/km}^2\text{/yr}$$

$$= \quad 66 \text{ to } 82 \text{ t/ha/yr}$$

or a total for the catchment of:

$$= \quad 19{,}363{,}046 \text{ to } 23{,}977{,}740 \text{ t/yr}$$

Ba Catchment

In the Ba watershed (960 km^2) there are a total of 18 rainfall stations (Hasan, 1988) and eight were selected for use in this study. This selection was made on the basis of position, to give an even spread of stations over the catchment.

The p^2/P values for the eight stations were calculated and from this a mean value of 134 was obtained. Using the Fournier regression:

$$Sy = 52.49\, p^2/P - 513.21$$

a value of 6520 $m^3/km^2/yr$, which, with a specific gravity of 2.1 to 2.6 (Liedtke, 1988) = 13692 to 16953 $t/km^2/yr$

or a total for the catchment of:

$$= \quad 11{,}443{,}200 \text{ to } 16{,}273{,}920 \text{ t/yr}$$

These values were considered rather high; however, critical examination of the data shows that there were few complete data sets and many with only three or four years of data. The data also contained that of 1985 which was a multiple-cyclone year, bringing unusually high magnitude rainfalls and making the mean values less representative.

Calculation of the sediment load was redone, using Rawawai mill data only, this being the only extensive (over 100 years) and reliable set of data in the catchment. The Rawawai mill data by itself has a p^2/P value of 78, which by the same Fournier regression as used in the previous calculations yields a suspended sediment value of 3581 $m^3/km^2/yr$, which, with a specific gravity of 2.1 to 2.6 (Liedtke, 1988):

$$= \quad 7520 \text{ to } 9310 \text{ t/km}^2\text{/yr}$$

or a total for the catchment of:

$$= \quad 7{,}219{,}200 \text{ to } 8{,}938{,}200 \text{ t/yr}$$

Waimanu Catchment

The Waimanu catchment, situated at the southern end of the Rewa basin has a total land area of 165 km^2. Its small size means that the catchment has only four permanent rainfall stations but these stations have a sufficiently long record to be considered reliable, and a mean p^2/P value of 32 was derived. This value gives a sediment yield of 1166 $m^3/km^2/yr$, which, with a specific gravity of 2.1 to 2.6 (Liedtke, 1988):

$$= \quad 2451 \text{ to } 3034 \text{ t/km}^2\text{/yr}$$

or a total for the catchment of:

$$= 404{,}415 \text{ to } 500{,}610 \text{ t/yr}$$

Discussion and Results

The results of this investigation in Table A1 show that the Fournier equation compares favourably to estimates of sediment transport made by other methods.

In the Waimanu catchment the value estimated using the Fournier method was less than that made by either Hasan (using Flemmings method, based on mean annual discharge as the main influencing factor) or Glatthaar, who used direct measurement. Glatthaar's value however being a direct measurement of sediment transport might fail to account for some re-deposition of sediment in the lower reaches of the basin.

There is a greater difference on the Fournier calculated value for the Rewa than that calculated by Hasan. However as Hasan points out, the Flemming method used in that calculation was developed for, and applies to, undisturbed, forested catchments. Thus as none of the catchments are undisturbed forest, and the Ba catchment is virtually all grassland, all of the values derived by Hasan using this method would be expected to underestimate the sediment discharge. This underestimation is highlighted in the Ba catchment where Liedtke's 1984 measurements are six times that of Hasan.

The values for the Ba catchment calculated using the Fournier equation are well within the range, and confirmed by those measured by Liedtke.

The problem of unreliable data used in the calculation of the Ba catchment sediment load makes little impact in the outcome of the results, however it does highlight the importance of the representativeness of small data sets.

Conclusion

This investigation was undertaken in order to assess the applicability of the method of suspended sediment estimation proposed by Fournier (1960) for use in the tropical steeplands of the South Pacific.

The method, from the results of this investigation, appear to compare favourably to those results obtained by a number of other researchers using a number of different methods. The conclusion of this assessment must therefore be: That the Fournier (1960) method is suitable for use in the South Pacific, especially where data availability either, is restricted to that of simple parameters such as mean rainfall data, or precludes assessment or estimation by any other method.

Table A1: Summary of Sediment Loads calculated by the Fournier and of other methods.

CATCHMENT	MIN SEDIMENT LOAD t/ha/yr	MAX SEDIMENT LOAD t/ha/yr	SOURCE OF ESTIMATE
WAIMANU	**24**	**30**	Fournier method
	8	11	Hasan (1986)
	N.A	53	Glatthaar (1988)
BA	**122**	**151**	Fournier method all data
	75	**93**	Fournier method Rawawai mill data
	77	171	Liedtke (1984)
REWA	**66**	**82**	Fournier method
	N.A	32	Hasan (1986)

Annex 2: Suspended Sediment Calculations for each South Pacific country and territory

American Samoa

Tutuila

Tutuila is the only island in American Samoa that has significant drainage except for Ofu and Olosega whose combined land area is less than 7 km^2 and thus can be ignored as insignificant in there contribution of sediment load. Tutuila has two rainfall data sets:

$p = 404$ $P = 3519$ · p^2/P $= 46$ at Pago Pago

$= 355$ $= 3168$ $= 40$ at Pago Pago Airport

....

$\Sigma x/n$ $= 43$

Fourniers regression

S_y = $52.49\ p^2/P - 513.21$

= $1741\ m^3/km^2/yr$

at a specific gravity of 2.1 to 2.6 (Liedtke, 1988):

= 3657 to $4526\ t/km^2/yr$

with a total drainage area of 145 km^2

= 530,265 to 656,596 t/yr

Cook Islands

In the Cook Islands there is only Rarotonga that sustains any effective drainage. The islands of Manaue and Mauke being classical Darwinian fringed high islands, both have surface water, however the limestone fringe is large enough and the drainage small enough so that none actually reaches the sea but rather recharges the limestone aquifers. This means that the drainage is not effective and can be discounted for our purposes.

There is a set of rainfall data for Avarua

$p = 276$ $P = 2063$ $p^2/P = 37$

Fourniers regression

Sy = $52.49\ p^2/P - 513.21$

= $1424.9\ m^3/km^2/yr$

at a specific gravity of 2.1 to 2.6 (Liedtke, 1988)

= 2992.5 to $3705\ t/km^2/yr$

with a total drainage area of 67.2 km^2

= 201,096 to 248,972 t/yr

Federated States of Micronesia

Yap

There are three islands in the YAP group which have significant surface drainage: Gagil-tamil, Tol and Moen. These three islands have a combined land area of 98.5 km^2 (Van de Brug, 1980)

Rainfall Stations

- A US coast guard station on Gagil-Tamil gave a reading of

  $p = 383$ $P = 2946$ $p^2/P = 49$
- A US Weather Service station at Yap airfield gave readings of

  $p = 362$ $P = 3073$ $p^2/P = 43$
- A US coast guard station at Colonea gave readings of

  $p = 428$ $P = 3022$ $p^2/P = 60$

  $\Sigma (p^2/P)/n = 50$

Fournier regression is:

S_y = $52.49\ (p^2/P) - 513.21$

= $2111\ m^3/km^2/yr$

At a specific gravity of 2.1 to 2.6 (Liedtke, 1988)

= 4433 to $5489\ t/km^2/yr$

The catchment geometry which is very short would disallow large volumes of sediment storage, a very high (up to 100%) rate of sediment export could be expected.

With a total drainage area of 98.5 km^2:

= 436,660 to 540,627 t/yr

Chuuk/Truk Island

There are three islands in the Chuuk/Truk group that support significant drainage systems. They are Tol, Moen and Dublon which have a combined land area of 61 km^2.

Rainfall Stations

There is one reliable and complete set of rainfall data for each island:

Tol p $= 294$ P $= 3175$ $p^2/P = 27$

Moen $= 392$ $= 3657$ $= 42$

Dublon $= 294$ $= 2971$ $= 29$

$\Sigma x/n = 32$

Fourniers regression:

$$S_y = 52.49\,p^2/P - 513.21$$
$$= 1166\ m^3/km^2/yr$$

At a specific gravity of 2.1 to 2.6 (Liedtke, 1988)

$$= 2449 \text{ to } 3032\ t/km^2/yr$$

with a total drainage area of 61 km²

$$= 149{,}389 \text{ to } 184{,}928\ t/yr$$

Kosrae

Kosrae is a single island with a high relief, having a total land area of 108 km².

There are three reliable rainfall stations on Kosrae, at:

Lulu	p = 701	P = 8333	p2/P = 58
Mwot	= 716	= 6461	= 79
Utwa	= 535	= 4648	= 61
			Σx/n = 66

Fourniers regression:

$$S_y = 52.49\,p^2/P - 513.21$$
$$= 2951\ m^3/km^2/yr$$

At a specific gravity of 2.1 to 2.6 (Liedtke, 1988)

$$= 6197 \text{ to } 7672\ t/km^2/yr$$

with a total drainage area of 108 km²

$$= 669{,}276 \text{ to } 834{,}576\ t/yr$$

Pohnpei

There is only one data set available to us for the island of Pohnpei, and this is at the main township of Kolonea:

Kolonea $p = 516$ $P = 4951$ $p^2/P = 54$

Fourniers regression

$$S_y = 52.49\,p^2/P - 513.21$$
$$= 2330\ m^3/km^2/yr$$

At a specific gravity of 2.1 to 2.6 (Liedtke, 1988)

$$= 4{,}893.5 \text{ to } 6{,}058\ t/km^2/yr$$

with a total drainage area of 334 km²

$$= 1{,}634{,}429 \text{ to } 2{,}023{,}372\ t/yr$$

Palau

There is only one island in the Palau group that sustains significant drainage - Babelthuap - which has a land area of 396 km². There are three rainfall stations that were selected for this calculation. They are situated at:

Ngermetengre:	$p = 523$	$P = 4241$	$p^2/P = 64$
Ngesang:	= 383	= 3403	= 43
Airai:	= 441	= 3683	= 52
			Σx/n = 53

Fourniers regression

$$Sy = 52.49\,p^2/P - 513.21$$
$$= 2268\ m^3/km^2/yr$$

At a specific gravity of 2.1 to 2.6 (Liedtke, 1988)

$$= 4762 \text{ to } 5898\ t/km^2/yr$$

with a total drainage area of 396 km²

$$= 1{,}886{,}068 \text{ to } 2{,}337{,}200\ t/yr$$

Guam

Guam is a large island with a land area of 541 km². The island is almost evenly divided, one half being an uplifted limestone plateau with no significant surface drainage, and the other half being high relief volcanics with a highly developed drainage system. Thus the drainage area is approximately 277 km².

Rainfall Stations

There are two rainfall stations in the drainage area with suitable data sets, both operated and maintained by the US geological service, however, they are not ideal as one is on the very northern part of the island well away from the drainage development on the volcanic southern part and the second is in the in the rain-shadow of the high southern section. They are:

$p = 300$	$P = 2180$	$p^2/P = 41$
= 400	= 2561	= 62
		Σx/n = 51

Fourniers regression

$$Sy = 52.49\,p^2/P - 513.21$$
$$= 2163\ m^3/km^2/yr$$

at a specific gravity of 2.1 to 2.6 (Liedtke, 1988)

$$= 4542 \text{ to } 5625\ t/km^2/yr$$

with a total drainage area of 277 km²

$$= 1258217 \text{ to } 1558354\ t/yr$$

Northern Marianas

Saipan

There are only two small perennial streams on Saipan, where either karstic denudation has exposed the underlying volcanic sequences, or an organic alluvium has built up. There is one other ephemeral stream; however, this is disregarded as flow only occurs during low frequency flood events.

Rainfall Data

The best data set for this area comes from Maga reservoir, which is a US naval rainfall station.

$P = 2038$ mm $p = 338$ mm $p^2/P = 56$

Fournier's regression:

$$S_y = 52.49\,(p^2/P) \cdot 513.21$$
$$= 2426\ m^3/km^2/yr$$

at a specific gravity of 2.1 to 2.6 (Liedtke, 1988)

$$= 5094 \text{ to } 6308\ t/km^2/yr$$

The total combined catchment area for the Totolo and Hasngot streams is 5 km^2

$$= 25{,}470 \text{ to } 31{,}540\ t/yr$$

Total Suspended Sediment Load for the Federated States, Guam and Northern Marianas as Calculated by the Fournier (1960) Method

Pohnpei = 1634429 to 2023372 t/yr
Yap = 436660 to 540232 t/yr
Chuk = 149389 to 184928 t/yr
Kosrae = 669276 to 834576 t/yr
Palau = 1886068 to 2337200 t/yr
Guam = 1258217 to 1558354 t/yr
Saipan = 25470 to 31540 t/yr

Σx = 6059509 to 7510202 t/yr

Fiji

Taveuni

There are three rainfall data sets for Taveuni, at:

$p = 357$ $P = 2923$ $p^2/P = 43$
$= 723$ $= 6332$ $= 82$
$= 300$ $= 2506$ $= 36$

$\Sigma x/n = 53$

Fourniers regression

$$S_y = 52.49\,p^2/P \cdot 513.21$$
$$= 2268\ m^3/km^2/yr$$

at a specific gravity of 2.1 to 2.6 (Liedtke, 1988)

$$= 4764 \text{ to } 5898\ t/km^2/yr$$

with a total drainage area of Taveuni of 435 km^2

$$= 2{,}072{,}300 \text{ to } 2{,}565{,}600\ t/yr$$

Kadavu

There is only one set of rainfall data for Kadavu, which is located at Vunisea:

$p = 311$ $P = 2163$ $p^2/P = 45$

Fourniers regression

$$S_y = 52.49\,p^2/P \cdot 513.21$$
$$= 1834\ m^3/km^2/yr$$

at a specific gravity of 2.1 to 2.6 (Liedtke, 1988)

$$= 3851 \text{ to } 4768\ t/km^2/yr$$

with a total drainage area of Kadavu of 408 km^2

$$= 1{,}571{,}208 \text{ to } 1{,}945{,}344\ t/yr$$

Ovalau

Ovalau has an extensive rainfall data set at Levuka, the old capital of Fiji:

$p = 340$ $P = 2440$ $p^2/P = 47$

Fourniers regression:

$$S_y = 52.49\,p^2/P \cdot 513.21$$
$$= 1953\ m^3/km^2/yr$$

at a specific gravity of 2.1 to 2.6 (Liedtke, 1988)

$$= 4103 \text{ to } 5079\ t/km^2/yr$$

with a total drainage area of Ovalau of 100 km^2

$$= 410{,}300 \text{ to } 507{,}900\ t/yr$$

Koro and Gau Islands

The absence of data for these two islands and their similarity and proximity to Ovalau dictated the use of the Levuka data. Thus:

Sediment yield = 4103 to 5079 t/km^2/yr

Koro at 108 km^2 = 443124 to 548532 t/yr

Gau at 125 km^2 = 512875 to 634875 t/yr

Vanua Levu

UDU POINT	p = 364	P = 2420	$p^2/P = 55$
DREKETI	= 510	= 2681	= 97
DELAINASAU	= 440	= 2484	= 78
WAINUNU	= 462	= 3675	= 58
NABOUAWALU	= 348	= 2598	= 47
NASEALEVU	= 334	= 1929	= 58
LAGALAGA	= 518	= 3035	= 88
COQELOA	= 428	= 2394	= 77
VUNIKA	= 399	= 2183	= 73
NALEBA	= 365	= 2022	= 66
WAINIKORO	= 435	= 2512	= 75
NADURI	= 463	= 2483	= 86
SEAQAQA RES.	= 434	= 2546	= 74
TABIA	= 465	= 2413	= 90
SEAQAQA FOR.	= 524	= 3096	= 89
VUNIMOLI	= 469	= 2659	= 83
TUVUMILA	= 330	= 2569	= 42
DILOI	= 314	= 2444	= 40
DEVO	= 351	= 2686	= 46
NATUVU	= 364	= 2404	= 55
VALECI	= 286	= 2498	= 33
BALAGA	= 429	= 3137	= 59
MUANACULA	= 329	= 2581	= 42
VATUGISESE	= 282	= 2237	= 36
VUNILAGI	= 253	= 2037	= 31
VANAIRA	= 266	= 2079	= 34
			$\Sigma x/n = 62$

Fourniers regression

$$S_y = 52.49\ p^2/P - 513.21$$
$$= 2731\ m^3/km^2/yr$$

at a specific gravity of 2.1 to 2.6 (Liedtke, 1988)

= 5734 to 7099 t/km^2/yr

with a total drainage area of Vanua Levu 5538 km^2

= 31,754,892 to 39,314,262 t/yr

Viti Levu

	p =	P =	$p^2/P =$
TAVUA	435	1928	106
TAGITAGI	= 471	= 2006	= 111
YAGARA	= 408	= 1834	= 91
DRASA	= 411	= 1978	= 85
NATARAWAU	= 400	= 1900	= 84
NAILAGI	= 547	= 2525	= 118
MOTA	= 432	= 2073	= 90
VATUKOULA	= 490	= 2473	= 97
NADRAIVATU	= 521	= 2533	= 107
KORO-O	= 791	= 3657	= 171
LAUTOKA	= 741	= 3680	= 149
EVISO	= 365	= 1910	= 70
MEIQUNIYAH	= 358	= 1905	= 67
NADRAU	= 548	= 2998	= 100
VANUALEVU	= 532	= 2959	= 95
NARO	= 323	= 1755	= 59
NASARI	= 480	= 2509	= 92
TAU	= 326	= 1886	= 56
NANUKU	= 396	= 1884	= 83
PENANG	= 406	= 2227	= 74
DOBUILEVU	= 425	= 2697	= 67
NAIYAVU	= 479	= 3621	= 63
LODONI	= 350	= 3321	= 37
VUNIDAWA	= 451	= 3650	= 56
VUNIBAKA	= 451	= 3420	= 59
NADURULOU LOU	= 410	= 3410	= 49
CUVU	= 298	= 1858	= 48
NACOCOLEVU	= 285	= 1884	= 46
OLESARA	= 263	= 1789	= 39
KOROLEVU	= 304	= 2125	= 43
KOROVISILOU	= 381	= 2993	= 49
NAQARATUVA	= 538	= 4210	= 69
SAWANI	= 417	= 3577	= 48
COLO-I-SUVA	= 479	= 4262	= 53
WAILOKO	= 460	= 4287	= 49
NAUSORI	= 378	= 3141	= 45
N. AIRPORT	= 399	= 3044	= 52
NABUKAVESI	= 494	= 4695	= 52
SUVA	= 344	= 3125	= 38
LAUCALA BAY	= 382	= 3059	= 48
LAMI	= 503	= 4224	= 60
			$\Sigma x/n = 75.2$

Fourniers regression

$$S_y = 52.49\ p^2/P - 513.21$$
$$= 3434\ m^3/km^2/yr$$

at a specific gravity of 2.1 to 2.6 (Liedtke, 1988)

= 7211 to 8928 t/km^2/yr

with a total drainage area of Viti Levu 10389 km^2

= 74,915,079 to 92,758,174 t/yr

Tahiit/Moorea

There is only one reliable rainfall data set for the islands of Tahiti/Moorea - from Papeete-Fa'a:

$p = 355 \quad P = 1836 \quad p^2/P = 68$

Fourniers regression:

$S_y = 52.49\, p^2/P - 513.21$

$= 3056\ m^3/km^2/yr$

at a specific gravity of 2.1 to 2.6 (Liedtke, 1988)

$= 6417$ to $7945\ t/km^2/yr$

with a total drainage area of Tahiti/Moorea of 1052 km^2

$= 6{,}750{,}680$ to $8{,}358{,}140\ t/yr$

Hivaoa and Tahuata

$p = 355 \quad P = 1836 \quad p^2/P = 68$

Fourniers regression

$S_y = 52.49\, p^2/P - 513.21$

$= 954\ m^3/km^2/yr$

at a specific gravity of 2.1 to 2.6 (Liedtke, 1988)

$= 2003$ to $2480\ t/km^2/yr$

over 370 km^2

$= 741{,}110$ to $917{,}600\ t/yr$

Nukuhiva and Uapou

$p = 147 \quad P = 1110 \quad p^2/P = 19$

$S_y = 52.49\, p^2/P - 513.21$

$= 508\ m^3/km^2/yr$

at a specific gravity of 2.1 to 2.6 (Liedtke, 1988)

$= 1068$ to $1322\ t/km^2/yr$

over 435 km^2

$= 446580$ to $575070\ t/yr$

Raiatea and Tahaa

These two islands have no reliable or long term rainfall data of there own, however, they are close enough to Bora Bora to allow that data set to be used. Bora Bora itself has no significant surface drainage development.

$p = 273 \quad P = 2031 \quad p^2/P = 36$

Fourniers regression

$S_y = 52.49\, p^2/P - 513.21$

$= 1376\ m^3/km^2/yr$

at a specific gravity of 2.1 to 2.6 (Liedtke, 1988)

$= 2889$ to $3577\ t/km^2/yr$

with a total drainage area of Raiatea of 194 km^2

$= 560{,}466$ to $694{,}054\ t/yr$

with a total drainage area of Tahaa of 88 km^2

$= 254{,}232$ to $314{,}776\ t/yr$

New Caledonia

New Caledonia has thirty useable data sets.

	p	P	p^2/P
BOURAIL	= 172	= 1244	= 24
CANALA	= 287	= 1902	= 43
COROVIN	= 358	= 1869	= 68
GROMEN	= 175	= 1113	= 27
HIENGHENE	= 392	= 2122	= 72
HUAILOU	= 338	= 1869	= 61
KONE	= 160	= 1172	= 21
KOUMAC	= 152	= 1053	= 21
LA FOA	= 166	= 1238	= 22
NEGROPO	= 263	= 2189	= 34
NOUMEA	= 151	= 1067	= 21
OUACO	= 113	= 825	= 15
OUAMENIR	= 120	= 900	= 16
OUBATCHE	= 274	= 1891	= 40
OUEGOA	= 315	= 1492	= 82
OUITCHAMBO	= 214	= 1427	= 32
PAITA	= 185	= 1267	= 27
PAGOUMENE	= 119	= 850	= 16
PARAHOUE	= 351	= 1940	= 65
PLUM	= 194	= 1574	= 23
PORT LAGUERRE	= 163	= 1274	= 29
PONERIHOEIEN	= 494	= 2721	= 89
POYA	= 223	= 1373	= 36
ST JOSEPH	= 198	= 1201	= 40
THIO	= 241	= 1425	= 40
TIOUAKO	= 327	= 1886	= 56
TOUTOUTA	= 155	= 1101	= 21
TOUHO	= 462	= 2675	= 79
YATE	= 399	= 3181	= 50
YATE LIGHT	= 497	= 2933	= 78

$\Sigma x/n = 42$

Fourniers regression:

$S_y = 52.49\, p^2/P - 513.21$
$= 1694\ m^3/km^2/yr$

at a specific gravity of 2.1 to 2.6 (Liedtke, 1988)

$= 3557$ to $4404\ t/km^2/yr$

with a total drainage area of New Caledonia of 17130 km^2

= 61,274,010 to 75,440,520 t/yr

Papua New Guinea

ISLAND PROVINCES

Manus Island

There are six useable data sets on Manus island:

p	P	p^2/P
= 402	= 3992	= 40
= 325	= 3398	= 31
= 451	= 3922	= 52
= 450	= 3952	= 51
= 331	= 2692	= 41
= 333	= 3420	= 32

$\Sigma x/n = 41.2$

Fourniers regression

$S_y = 52.49\, p^2/P - 513.21$
$= 1654\ m^3/km^2/yr$

at a specific gravity of 2.1 to 2.6 (Liedtke, 1988)

$= 3473$ to $4300\ t/km^2/yr$

with a total drainage area of manus of 1943 km^2

= 6,748,039 to 8,354,900 t/yr

New Ireland

New Ireland has nine useful data sets.

	p	P	p^2/P
FILELBA	= 352	= 2872	= 43
GIL GIL	= 409	= 3034	= 55
KATU	= 465	= 3510	= 61
KAVIENG	= 330	= 3173	= 34
MARAGON	= 437	= 4129	= 46
MARITSOAN	= 381	= 3040	= 47
NORTH CAPE	= 433	= 3484	= 53
PANARAS	= 569	= 3501	= 92
SETAPIN	= 375	= 2891	= 48

$\Sigma x/n = 53.6$

Fourniers regression:

$S_y = 52.49\, p^2/P - 513.21$
$= 2304\ m^3/km^2/yr$

at a specific gravity of 2.1 to 2.6 (Liedtke, 1988)

$= 4839$ to $5991\ t/km^2/yr$

with a total drainage area of NEW IRELAND is 9974 km^2

= 48,264,186 to 59,754,234 t/yr

New Britain

There are twenty eight rainfall stations on New Britain, but because of their highly clumped spacing at the north-eastern end, only fifteen are useable.

These are:

	p =	P =	p^2/P =
ARAWE	692	4380	109
GASMATA	= 1121	= 6076	= 206
KABANGA	= 316	= 2356	= 42
KANDRIAN	= 813	= 4065	= 162
KERAVATAU	= 268	= 2656	= 27
KOKOPO	= 235	= 1978	= 27
KOLAI	= 906	= 5003	= 163
LINDENHAFEN	= 1132	= 6364	= 201
NAGANAI	= 694	= 4023	= 119
NOTRE	= 685	= 3896	= 120
PALMALMAL	= 1056	= 4860	= 229
RABUL	= 360	= 2244	= 57
RAPOPO	= 289	= 1969	= 42
RINGRING	= 1169	= 6061	= 225
TALASEA	= 763	= 4156	= 140

$\Sigma x/n = 125$

Fourniers regression

Sy $= 52.49\ p^2/P \cdot 513.21$

$= 6055\ m^3/km^2/yr$

at a specific gravity of 2.1 to 2.6 (Liedtke, 1988)

$= 12715$ to $15743\ t/km^2/yr$

with a total drainage area of NEW BRITAIN is 39807 km^2

= 506,146,005 to 626,681,601 t/yr

Bougainville

There are five data sets for Bouganville. These include:

	p	P	p^2/P
BUIN	= 518	= 3556	= 75
BUKA	= 328	= 2653	= 40
HAKAU	= 316	= 2401	= 41
KIETA	= 295	= 3009	= 29
RAUA RUGEN	= 323	= 2410	= 43

$\Sigma x/n = 45.9$

Fourniers regression

$S_y = 52.49\ p^2/P \cdot 513.21$

$= 1899\ m^3/km^2/yr$

at a specific gravity of 2.1 to 2.6 (Liedtke, 1988)

$= 3988$ to $4938\ t/km^2/yr$

with a total drainage area of Bougainville is 9300 km^2

= 37,088,400 to 45,923,400 t/yr

PNG Island Provinces Total:

598,246,570 to 740,714,135 t/yr

MAINLAND PROVINCES

Oro Province

	p	P	p^2/P
BUNA	= 363	= 3057	= 43
CAPE NELSON	= 487	= 3327	= 71
IOMA	= 469	= 3939	= 56
KOKODA	= 425	= 3585	= 50
POPONDETTA	= 356	= 2378	= 53
SANGARA	= 67	= 3382	= 64
TUFI	= 491	= 3296	= 73
YODDA KOKODA	= 504	= 4548	= 56

$\Sigma x/n = 58.4$

Fourniers regression

$S_y = 52.49\ p^2/P \cdot 513.21$

$= 2556\ m^3/km^2/yr$

at a specific gravity of 2.1 to 2.6 (Liedtke, 1988)

$= 5368$ to $6647\ t/km^2/yr$

with a total drainage area of ORO is 22800 km^2

= 122,390,400 to 151,551,600 t/yr

Milne Bay

	p	P	p^2/P
BARBARA	= 296	= 2473	= 35
BANAIRA	= 386	= 1834	= 44
DOGURA	= 223	= 1494	= 33
ESA-ALA	= 354	= 2484	= 50
KULA MANDAY	= 378	= 4184	= 34
LOSUIA	= 415	= 3953	= 43
MILNE BAY	= 331	= 2747	= 39
ORANGIE BAY	= 335	= 3038	= 36
SALAMO	= 345	= 2640	= 45
SAMARAI	= 314	= 2741	= 35
SEWA BAY	= 739	= 5115	= 106

$\Sigma x/n = 46$

Fourniers regression

$S_y = 52.49\ p^2/P - 513.21$

$= 1901\ m^3/km^2/yr$

at a specific gravity of 2.1 to 2.6 (Liedtke, 1988)

$= 3994$ to $4945\ t/km^2/yr$

with a total drainage area of Milne Bay is 14000 km^2

= 55,916,000 to 69,230,000 t/yr

Central and National Capital

	p	P	p^2/P
ABAU	= 249	= 2165	= 29
BARAMATA	= 326	= 2222	= 48
BOROKO	= 219	= 1109	= 43
BOMANA	= 168	= 1023	= 33
BEREINA	= 207	= 1187	= 36
ELOGO	= 336	= 2758	= 40
FANE	= 421	= 2925	= 60
ILOLO	= 305	= 2594	= 35
KAIRUKU	= 388	= 3256	= 46
KANOSIA	= 261	= 1553	= 44
KEMP	= 188	= 1516	= 23
MAGIGI	= 356	= 2170	= 58
ONONGE	= 381	= 2061	= 49
JACKSONS	= 202	= 1182	= 35
RINGO	= 169	= 1130	= 25
SUBITANA	= 493	= 2361	=102
TAPINI	= 274	= 1922	= 39
WAINGELA	= 402	= 2370	= 68
KATHERINE	= 180	= 1641	= 19

$\Sigma x/n = 44$

Fourniers regression:

S_y $= 52.49\ p^2/P - 513.21$
$= 1801\ m^3/km^2/yr$

at a specific gravity of 2.1 to 2.6 (Liedtke, 1988)

$= 3783$ to $4684\ t/km^2/yr$

with a total drainage area of Central and NCD is 29740 km^2

= 112,506,420 to 139,302,160 t/yr

Morobe

AWELKON	p = 608	P = 4387	$p^2/P = 84$
BAIUNE	= 243	= 1783	= 33
BAUNE	= 172	= 1573	= 18
BOANNA	= 292	= 2287	= 37
BUBIA	= 336	= 2957	= 38
BULOLO	= 216	= 1559	= 23
B. HOSPITAL	= 176	= 1546	= 20
CLIFFSIDE	= 235	= 1930	= 20
DREGER	= 726	= 1499	=351
EDIE	= 329	= 2725	= 39
ERAP	= 168	= 1186	= 23
FINSCHAFEN	= 655	= 4292	= 99
GARGING	= 320	= 2825	= 36
GIZARUM	= 425	= 2607	= 69
GURAKOR	= 348	= 2709	= 44
GUSAP	= 276	= 2075	= 36
KAIAPIT	= 367	= 2425	= 55
LABLAB	= 406	= 3345	= 49
LAE	= 526	= 4582	= 60
LAE FOREST	= 521	= 4268	= 63
MENYAMYA	= 202	= 1715	= 23
MOROBE	= 312	= 2809	= 34
MUMENG	= 210	= 1449	= 30
SASIANG	= 234	= 1482	= 36
SATTLEBURG	= 743	= 4587	=120
WANARU	= 528	= 3957	= 70
WONTAOT	= 273	= 2404	= 31
WATUT	= 185	= 1543	= 22
WAU	= 236	= 1943	= 28
WAU #1	= 212	= 1859	= 24
WAU COMPOUND	= 219	= 1717	= 27
YALU	= 230	= 2020	= 26
ZENANG	= 243	= 1899	= 31

Sx/n = 32.5

Fourniers regression

S_y $= 52.49\ p^2/P - 513.21$

$= 1196\ m^3/km^2/yr$

at a specific gravity of 2.1 to 2.6 (Liedtke, 1988)

$= 2511$ to $3109\ t/km^2/yr$

with a total drainage area of Morobe is 34500 km^2

= 86,629,500 to 107,260,500 t/yr

East Sepik and Sanduan

	p	P	p^2/P
AITAPE	= 289	= 2559	= 32
AMBUNTI	= 300	= 2492	= 36
ANGORAM	= 245	= 2091	= 30
BAINYUIK	= 193	= 1670	= 22
GREEN RIVER	= 390	= 3430	= 44
LUMI	= 314	= 2564	= 38
MAPRIK #1	= 214	= 1861	= 24
MAPRIK #2	= 197	= 1701	= 22
MARIENBURG	= 250	= 1762	= 35
TELEFOLMIN	= 356	= 3444	= 36
VANIMO	= 370	= 2640	= 51
PATR0L	= 270	= 2959	= 46
WEWAK	= 236	= 2184	= 25
YAMBI	= 270	= 2046	= 35

$\Sigma x/n = 34.5$

Fourniers regression:

S_y $= 52.49\ p^2/P - 513.21$
$= 1299\ m^3/km^2/yr$

at a specific gravity of 2.1 to 2.6 (Liedtke, 1988)

$= 2728$ to $3348\ t/km^2/yr$

with a total drainage area of EAST SEPIC at 42800 and SANDUAN at 36300 km^2, combined it is 79100 km^2

= 215,784,800 to 267,152,340 t/yr

Southern Highlands

	p	P	p^2/P
ERAVE	= 369	= 3449	= 39
IALIBUL	= 401	= 3811	= 42
KAGUA	= 379	= 3113	= 46
KUTUBA	= 446	= 4787	= 41
MENDI	= 307	= 2801	= 33
MISSION	= 303	= 2643	= 34
MORO	= 471	= 4418	= 50
TAMBUL	= 305	= 2694	= 34
TAVI	= 267	= 2620	= 27
TAVI MISSION	= 286	= 2868	= 28

$\Sigma x/n = 37$

Fourniers regression:

S_y = 52.49 p^2/P - 513.21
= 1472 $m^3/km^2/yr$

at a specific gravity of 2.1 to 2.6 (Liedtke, 1988)

= 3091 to 3827 $t/km^2/yr$

with a total drainage area of Southern Highlands is 23800 km^2

= 73,565,800 to 91,082,600 t/yr

Mandang

	p	P	p^2/P
AIOME	= 726	= 5602	= 94
AWAR	= 278	= 1990	= 38
BUNDI	= 518	= 4664	= 57
KOROBA	= 329	= 3360	= 32
KORUM	= 468	= 4053	= 54
KULILI	= 517	= 3729	= 71
KULKUL	= 528	= 3455	= 80
MANDDANG	= 433	= 3539	= 52
MANDANG A.P.	= 407	= 3452	= 47
SAIDOR	= 423	= 2645	= 67
SARUGA	= 371	= 3392	= 40
SIMBA	= 331	= 3001	= 36

$\Sigma x/n$ = 56

Fourniers regression:

S_y = 52.49 p^2/P - 513.21

= 2438 $m^3/km^2/yr$

at a specific gravity of 2.1 to 2.6 (Liedtke, 1988)

= 5102 to 6339 $t/km^2/yr$

with a total drainage area of Madang is 29000 km^2

= 147,958,000 to 183,831,000 t/yr

Western Highlands and Enga

	p	P	p^2/P
AMULIBA	= 236	= 2144	= 25
BAIYER RIVER	= 369	= 2617	= 52
JIMII	= 403	= 3209	= 50
KINJIBI	= 344	= 2534	= 46
KOMPIAM	= 368	= 3225	= 41
KORVLI	= 334	= 2504	= 44
KUTA	= 359	= 3184	= 40
LAIAGAM	= 265	= 2183	= 32
MINJ	= 283	= 2419	= 33
MT HAGEN	= 288	= 2622	= 31
NONDUGL A.P.	= 290	= 2477	= 33
NONDUGL	= 277	= 2534	= 30
NGUNA	= 331	= 2562	= 42
TALU	= 285	= 2348	= 34
TOGOBA	= 333	= 2776	= 39
TEREMEARNE	= 379	= 3219	= 44
WABLAGL	= 329	= 2945	= 36
WAPENAMANDA	= 237	= 2422	= 30

$\Sigma x/n$ = 38.5

Fourniers regression:

S_y = 52.49 p^2/P - 513.21
= 1507 $m^3/km^2/yr$

at a specific gravity of 2.1 to 2.6 (Liedtke, 1988)

= 3165 to 3919 $t/km^2/yr$

with a total drainage area of Western Highlands and Enga of 21300 km^2

= 67,414,500 to 83,474,700 t/yr

Simbu and Eastern Highlands

	p	P	p^2/P
AIYURA	= 265	= 2196	= 31
ARONA	= 306	= 2018	= 46
CHIMBU	= 293	= 2184	= 39
GOROKA	= 277	= 1929	= 39
HENGANOFI	= 273	= 1710	= 43
KAINANTU	= 321	= 2063	= 49
KEGSUGL	= 310	= 2284	= 42
KEROWAGI	= 330	= 2908	= 37
LUFA	= 295	= 2560	= 33
OKAPA	= 242	= 2201	= 26

$\Sigma x/n$ = 39

Fourniers regression:

S_y = 52.49 p^2/P - 513.21

= 1539 $m^3/km^2/yr$

at a specific gravity of 2.1 to 2.6 (Liedtke, 1988)

= 3237 to 4003 $t/km^2/yr$

with a total drainage area of Eastern Highlands and Simbu of 17380 km^2

= 56,259,060 to 69,624,280 t/yr

Gulf and Western Provinces

The Gulf and Western Provinces are both sufficiently lacking in long-term rainfall data to make the Fournier technique of little value. Extrapolation was therefore made from the sediment loads of the major rivers in these two provinces - the Purari (gulf province) and the Fly river (western province). Thus:

> The Purari river sediment load is 80 x10^6 t/yr (Pickup et al, 1979), and the catchment area is 31000 km^2.

S_y = 1727 $t/km^2/yr$
Gulf Province covers 34500 km^2
= 59,581,500 t/yr

> The Fly river sediment load is 74 x10^6 t/yr (Alongi, 1990), and the catchment area is 69900 km^2

S_y = 1058 $t/km^2/yr$
Western Province covers 34500 km^2
= 105,124,463 t/yr

PNG PROVINCES TOTALS

ORO PROVINCE	= 122390400 to 151551600
MILNE BAY	= 55916000 to 69230000
CENTRAL AND N.C.D.	= 112506420 to 139302160
MOROBE	= 86629500 to 107260500
EAST SEPIC AND SANDUAN	= 215784800 to 267152340
SOUTHERN HIGHLANDS	= 73565800 to 91082600
MANDANG	= 147938000 to 183831000
W. HIGHLANDS AND ENGA	= 67414500 to 83474700
SIMBU AND E. HIGHLANDS	= 56259060 to 69624280
GULF	= 105124463
WESTERN	= 59581500

PNG = 1,043,548,943 to 1,282,216,143 t/yr
$= 1.0 \times 10^9$ to 1.2×10^9 t/yr

Solomon Islands

Guadalcanal.

There are only nine appropriate rainfall stations on the island.

	p	P	p^2/P
Makina	= 516	= 4646	= 57
Maraunia	= 486	= 4125	= 57
Mt Austin	= 355	= 1888	= 66
Rove West	= 361	= 2162	= 46
Ruavatu	= 306	= 2763	= 33
Tangarare	= 512	= 3191	= 82
Tenaru	= 317	= 2021	= 49
Tetere	= 370	= 2124	= 64
Visale	= 382	= 2375	= 61
			Σx/n = 57

Fourniers regression:

$$S_y = 52.49\, p^2/P - 513.21$$
$$= 2478\ m^3/km^2/yr$$

at a specific gravity of 2.1 to 2.6 (Liedtke, 1988)

= 5202 to 6444 t/km²/yr

with a total drainage area of 6400 km²

= 33,292,800 to 41241600 t/yr

Choiseul

There are two rainfall stations on Choiseul that have any reliable records.

p	P	p^2/P
= 378	= 3525	= 40
= 320	= 3403	= 30
		Σx/n = 57

Fourniers regression:

$$S_y = 52.49\, p^2/P - 513.21$$
$$= 1323\ m^3/km^2/yr$$

at a specific gravity of 2.1 to 2.6 (Liedtke, 1988)

= 2780 to 3442 t/km²/yr

with a total drainage area of 2590 km²

= 7,200,200 to 8,914,780 t/yr

San Christobal

There are three rainfall data sets for the island of San Christobal

p	P	p^2/P
= 700	= 6828	= 71
= 544	= 5027	= 59
= 336	= 3479	= 32
		Σx/n = 53

Fourniers regression:

$$S_y = 52.49\, p^2/P - 513.21$$
$$= 2268\ m^3/km^2/yr$$

at a specific gravity of 2.1 to 2.6 (Liedtke, 1988)

= 4764 to 5898 t/km²/yr

with a total drainage area of 3125 km²

= 14,887,500 to 18,431,250 t/yr

New Georgia Group

These eight islands are of close enough proximity to each other and of a sufficient geomorphic homogeneity to enable them to be considered as one landmass. This greatly increases the significance of the data.

	p	P	p^2/P	drainage area
Rendova	= 488	= 4211	= 56	= 400
Vangunu	= 591	= 4901	= 71	= 520
Kolombangara	= 421	= 3479	= 51	= 685
	= 463	= 3466	= 61	
New Georgia	= 464	= 3849	= 56	= 2145
	= 441	= 3937	= 49	
	= 446	= 3636	= 54	
	= 375	= 3311	= 42	
Vella Lavella	= 446	= 2995	= 66	= 670
	= 373	= 3481	= 40	
	= 679	= 3606	= 127	
	= 449	= 3606	= 55	
	= 460	= 3232	= 365	
Ranonga				= 120 = 1
			Σx/n = 61	Σx = 4250

Fourniers regression

$$S_y = 52.49\, p^2/P - 513.21$$
$$= 2710\ m^3/km^2/yr$$

at a specific gravity of 2.1 to 2.6 (Liedtke, 1988)

= 5691 to 7046 t/km²/yr

with a total drainage area of 4250 km²

= 24,186,750 to 29,945,500 t/yr

Malaita

Malaita has four good rainfall data sets.

p	P	p^2/P
= 497	= 3429	= 72
= 590	= 4731	= 73
= 360	= 3391	= 38
= 768	= 4825	= 122
		$\Sigma x/n = 76$

Fourniers regression

$S_y = 52.49\ p^2/P - 513.21$
$= 3489\ m^3/km^2/yr$

at a specific gravity of 2.1 to 2.6 (Liedtke, 1988)

$= 7327$ to $9071\ t/km^2/yr$

with a total drainage area of $4900\ km^2$ (including Marimasike $700\ km^2$)

= 35,902,300 to 44,447,900 t/yr

Santa Isabel

There are only two rainfall stations on Isabel.

p	P	p^2/P
442	= 4187	= 46
= 456	= 3096	= 67
		$\Sigma x/n = 56.5$

Fourniers regression

$S_y = 52.49\ p^2/P - 513.21$
$= 2452\ m^3/km^2/yr$

at a specific gravity of 2.1 to 2.6 (Liedtke, 1988)

$= 5150$ to $6376\ t/km^2/yr$

with a total drainage area of $4122\ km^2$

= 21,228,300 to 26,281,872 t/yr

SOLOMONS TOTAL

	min	max
Guadalcanal	33293×10^3 t/yr	41242×10^3 t/yr
Choiseul	7200	8915
S. Christobal	14888	18431
New Georgia grp	24187	29946
Malaita	35902	44448
S. Isabel	21228	26282
	$\Sigma x = 136698$	$\Sigma x = 169263$
	136.7 to 169.4×10^6 t/yr	

Tonga

'Eua

There is no direct data for the island of Eua, but data from Nukualofa has been used to estimate the sediment load.

p = 227 P = 1686 $p^2/P = 30$

Fourniers regression

$S_y = 52.49\ p^2/P - 513.21$
$= 1061\ m^3/km^2/yr$

at a specific gravity of 2.1 to 2.6 (Liedtke, 1988)

$= 2229$ to $2759\ t/km^2/yr$

with a total drainage area of $15\ km^2$

= 33,435 to 41,398 t/yr

Tofua and Kao

Although the Island of Tofua has a total land area of $54\ km^2$, it has a calderic lake at the centre which effectively reduces the drainage area of the island by almost half to $28\ km^2$. Kao island has an effective drainage of only $1\ km^2$. The nearest rainfall data comes from the Ha'apai some twenty kilometres to the east. The data however gives p^2/P values that are consistent with data from other parts of the Tonga group.

p = 283 P = 1703 $p^2/P = 47$

Fourniers regression

$S_y = 52.49\ p^2/P - 513.21$
$= 1995\ m^3/km^2/yr$

at a specific gravity of 2.1 to 2.6 (Liedtke, 1988)

$= 4106$ to $5083\ t/km^2/yr$

with a total drainage area of Tofua ($28\ km^2$), andKao ($1\ km^2$)

Tofua = 114968 to 142345 t/yr

Kao = 4106 to 5083 t/yr

With Eua = 33435 to 41398 t/yr the total calculated suspended sediment load for the whole of the Tonga Group is:

Tonga = 152,509 to 188,826 t/yr

Aneityum

There are only two rainfall stations on Aneityum. These have:

p = 392 P = 2446 p^2/P = 63
= 332   = 2312   = 47

$\Sigma x/n = 55$

Fourniers regression:

S_y = 52.49 p^2/P - 513.21

= 2373 $m^3/km^2/yr$

at a specific gravity of 2.1 to 2.6 (Liedtke, 1988)

= 4984 to 6171 $t/km^2/yr$

with a total drainage area of 65 km^2

= 323900 to 401162 t/yr

Tanna

There is only one long term rainfall station on Tanna.

p = 338 P = 2403 p^2/P = 47

Fourniers regression:

S_y = 52.49 p^2/P - 513.21

= 1954 $m^3/km^2/yr$

at a specific gravity of 2.1 to 2.6 (Liedtke, 1988)

= 4103 to 5085 $t/km^2/yr$

with a total drainage area of 549 km^2

= 2,252,547 to 2,791,665 t/yr

Erromanga

There are three reliable rainfall stations on Erromanga:

- p = 378 P = 2823
= 287   = 1797   = 46
= 289   = 1779   = 47

Fourniers regression:

S_y = 52.49 p^2/P - 513.21
= 1953 $m^3/km^2/yr$

at a specific gravity of 2.1 to 2.6 (Liedtke, 1988)

= 4101 to 5077 $t/km^2/yr$

with a total drainage area of 975 km^2

= 3,998,767 to 4,950,075 t/yr

Efate

There are two stations on Efate:

Vila p = 311 P = 2107 p^2/P = 45
Nguna   = 389   = 2216   = 68

$\Sigma x/n = 56$

Fourniers regression

S_y = 52.49 p^2/P - 513.21
= 2426 $m^3/km^2/yr$

at a specific gravity of 2.1 to 2.6 (Liedtke, 1988)

= 5094 to 6307 $t/km^2/yr$

with a total drainage area of 915 km^2

= 4,661,010 to 5,770,905 t/yr

Epi

There are two stations on Epi.

Epi p = 300 P = 2472 p^2/P = 36
Tongoa   = 346   = 2842   = 42

$\Sigma x/n = 39$

Fourniers regression:

S_y = 52.49 p^2/P - 513.21
= 1533 $m^3/km^2/yr$

at a specific gravity of 2.1 to 2.6 (Liedtke, 1988)

= 3219 to 3985 $t/km^2/yr$

with a total drainage area of 444 km^2

= 1,429,236 to 1,763,405 t/yr

Ambrym

There is only one rainfall station in Ambrym.

p = 461 P = 3049 p^2/P = 69

Fourniers regression:

S_y = 52.49 p^2/P - 513.21
= 3108 $m^3/km^2/yr$

p^2/P = 50

at a specific gravity of 2.1 to 2.6 (Liedtke, 1988)

= 6526 to 8080 $t/km^2/yr$

with a total drainage area of 665 km^2

= 4,339,790 to 5,373,732 t/yr