SUSPENDED SEDIMENT YIELDS OF NEW ZEALAND RIVERS AND THEIR RELATIONSHIP TO PRECIPITATION CHARACTERISTICS

A THESIS PRESENTED IN PARTIAL FULFILMENT
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ABSTRACT

Sediment ratings determined by plots of instantaneous suspended sediment concentrations and their associated discharges, were combined with the continuous flow record to give values of suspended sediment yields for 82 catchments throughout New Zealand. A discussion of the errors involved in this determination is undertaken and suggestions as to the best use of the current resources in order to lessen these errors is given.

Multiple regression analysis including flow characteristics and rainfall characteristics (depth, intensity and variation) determined from the wide network of daily storage rain-gauges, resulted in a national equation of weak prediction identifying 24-hour 5-year return period rainfall as the best explanatory variable of variation in suspended sediment yield. The country was divided into eight regions and the regression rerun revealing mean annual rainfall as the principal predictor in all but one region. The high explanation exhibited in some areas must be rationalised against small sample numbers. A combination of four regions into one gave good prediction, supporting overseas workers' contentions that sediment yield is strongly influenced by rainfall depth and its variability. It is suggested that introduction of a bed material size component into the prediction equation may allow incorporation of at least two further regions into the combined region.

The coefficients of the regional logarithmic equations relating sediment yield to mean annual precipitation are analysed. Important conclusions reached are that in relation to suspended sediment, catchment conditions are not necessarily reflected in rainfall depth or vegetation cover but primarily to the volume of transportable material in storage in the channel subsystem. The volume of sediment in storage in some catchments greatly exceeds annual export,

stressing the limitations in determining erosion rates from sediment yield values. In Region 2 (East Cape) storage is so large that limits on yield are not controlled by the rate of supply but the competence of the rivers to carry it; some of these rivers may well be carrying limiting yields therefore.

Evidence available suggests that a predictive equation derived herein can also be applied to streams draining largely glaciated areas.

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LIST OF ABBREVIATIONS

In this study, the following abbreviations have been used:

D.S.I.R.	- Department of Scientific and Industrial Research
M.O.W.D.	- Ministry of Works and Development
N.W.A.S.C.O.	- National Water and Soil Conservation Organisation
N.Z. Met. S.	- New Zealand Meteorological Service
TIDEDA	- Time Department Data. A computer based system for the storage and retrieval of New New Zealand hydrological data
W.M.O.	- World Meteorological Organisation

LIST OF DEFINITIONS

In the study the following definitions are applied to the key words:

- bedload: that part of the material load which moves by bouncing (saltation), sliding and rolling along the channel bed.

- solution load, wash load or dissolved load: that part of the material load composed of the very finest particles who have vanishingly low rates of settling.

- specific annual yield: the yield per unit area per unit time. In the study it is given as tonnes per square kilometre per year ($t\ km^{-2}\ yr^{-1}$).

- suspended sediment concentration: the weight of material in suspension per unit volume of water. In the study it is given as grams per cubic metre ($g\ m^{-3}$).

- suspended sediment discharge: the rate of transport of the material in suspension, given as weight per unit time. It is the product of flow discharge and suspended sediment concentration. Customary units are kilograms per second ($kg\ sec^{-1}$).

- suspended sediment load: that part of the material load transported and held in the flow by turbulent mixing processes that prevent the settling of the particle under the influence of gravity.

- yield: the measured quantity of material carried by a river.

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CHAPTER 1
INTRODUCTION

1.1 THE PROBLEM

The determination of suspended sediment load requires a detailed knowledge of river discharge and sediment concentration. The ideal is for both water discharge and sediment concentration to be measured continually but this cannot be justified on economic grounds. Waugh and Fenwick (1979) estimate that to establish a water level recorder station without adverse construction difficulties, to service it, develop and maintain ratings and process data, costs in the order of $20,000 dollars (1977 costs) for a ten-year period.

Suspended sediment is just one part of the total load transported through a given channel cross-section. The other components are wash load and bed load, the latter being even more difficult than suspended load to measure reliably. This consideration, coupled with the requi[illegible] of a long period of record (in the absence of continuous recorders) to adequately define the temporal variability in sediment yields, makes accurate determinations almost impossible at present.

It is, however, still necessary to measure suspended sediment yields. Measurement is required for feasability of dams, resevoirs and river training works; for consideration of ecological and recreational uses; for assessment of upland erosion rates; for determination of a river sediment budget for extraction of metal and contribution of material to the coastal sediment system.

The economic constraints as well as those concerning the sampling procedure (length and quality of record), mean that only a small proportion of streams have good sediment yield data. A considerable body of literature exists regarding suspended yields calculated by a number of methods for various New Zealand catchments, some of which have been derived from poor records. These are listed in the Appendix. This study presents suspended sediment yields for 82 catchments by a single, repeatable method. It also attempts to develop a procedure for the estimation of suspended sediment yields for rivers with no flow records.

1.2 AN APPROACH

The suspended sediment yield carried by a river is generally limited not by its transporting capacity, but the amount of material supplied to it (Thompson and Adams, 1979). Climate, particularly rainfall, is a controlling factor in the supply of sediment to the river channel. This suggests that a predictive equation relating rainfall to sediment yield can be of value in synthesising sediment yield data for ungauged catchments.

One of the most easily measured and widely available rainfall variables is mean annual rainfall. Thompson and Adams (1979), Adams (1980), Griffiths (1981, 1982) have performed multivariable analyses for suspended yield predictors and found a relationship between mean annual rainfall and suspended sediment yield for a number of New Zealand catchments.

This study takes the above finding and investigates the underlying distribution of mean annual rainfall in order to better understand the spatial variability of suspended yields. It investigates why for a given mean annual rainfall, there should be differing sediment yields in different parts of the country. It has been suggested that rainfall intensity (McSaveney, 1978) and variability (Harlin, 1980) are strong influences on the quantity of material supplied to a channel. The aim of this study is to determine a set of predictive equations for suspended sediment yield based largely upon three rainfall characteristics (annual depth of rainfall, and the variability and intensity of events which comprise that depth), and in turn to provide for a better understanding of some of the controlling factors on the widely differing sediment yields of New Zealand catchments.

1.3 A METHODOLOGY FOR THE APPROACH

A predictive equation for sediment yield should be able to include the large number of variables which contribute to the sediment yield phenomenon. Multiple linear regression is such a method which allows for the consideration of many possible variables influencing a dependent variable.

The method has been widely used in many disciplines. With reference to New Zealand hydrology, McKerchar and Waugh (1976) have used regression analysis to demarcate regions of similar flow characteristics and Soons (1970) to determine factors influencing runoff.

The methodology outlined above must be viewed with some caution. Often the techniques of regression have appeared so successful they have impaired the capacity to model the complexness of the causal relationships. It is therefore wise that an attempt is made to model the sediment yield phenomenon, in order to realise the limitations placed on it by the methodology.

CHAPTER 2

THE RAINFALL—SEDIMENT YIELD MODEL

2.1 THE CATCHMENT SYSTEM

This study seeks to quantitatively evaluate the amount of suspended sediment carried by a stream using the catchment's precipitation characteristics. In order to clarify the nature of the catchment system and the scope of the research, a model was first developed.

Bennett (1974) suggests that the sediment yield phenomenon can be divided into two broad stages or subsystems - the slope subsystem and the channel subsystem. The slope subsystem is intrinsically connected to the precipitation event by virtue of it being the receptor of the incoming precipitation. Hence, the mechanics of the precipitation event can be seen as the major controlling factor in sediment yield. Rainfall impact causes loosening of the slope regolith and surface runoff entrains this material. The degree to which this occurs depends on the intensity, frequency and duration of the rainfall inputs and to other controlling factors which include vegetation cover, slope angle, soil condition, and land use. In the channel subsystem a precipitation event, apart from determining the total quantity of water available and its time of arrival, has very little control on the sediment yield. Controlling factors in this subsystem are channel geometry, channel slope, velocity of flow, and bed and bank materials.

Linkage of the two subsystems is by mass movement and sediment runoff components. Carson and Kirkby (1972) see the basic distinction between the two linkages as movements in which neighbouring particles stay close together, the material moving as a coherent whole (mass movement), and movements in which each particle moves as an individual with little or no association with neighbouring particles (sediment runoff). Mass movement can possibly be viewed as a variant of water-borne movement where the proportion of fluid is low.

Emmett (1965) has shown that the contribution of mass movement in south-western United States is small, constituting less than one percent of the amount contributed by sheet erosion. In New Zealand mass movement plays a much more significant part (Whitehouse, 1981). Scree slopes are common in unvegetated parts of schist and greywacke ranges. Generally scree is of too coarse a nature to be transported as suspended sediment load and must first be reduced to finer particles by weathering on the slope or by trituration[1] and abrasion during bedload transport. Mass movements which provide material easily carried in suspension are characteristic of hill country comprised of Tertiary siltstones and mudstones. In the Poverty Bay-East Cape region mass movement is a very important source of suspended sediment (Smith, 1974). A high proportion of the mass movement in this region can be classified as flows - the 'wettest' kind of mass movement and strongly controlled by precipitation events (Gage and Black, 1979).

The quantity of material provided by mass movmements as compared to fluvial slope processes, does not particularly matter. Their presence in the model merely serves as a description of the movement of material from the slope subsystem to the channel subsystem.

Figure 2.1 shows the interaction between variables within each subsystem. Arrows suggest dependence and independence, a '+' represents a direct relationship, a '-' an inverse relationship. Not all the controlling factors for each subsystem output are included, the relationships shown merely seek to exhibit the complexity of the system. The simplest functional components of the subsystem when linked are termed a canonical structure (Amarocho and Hart, 1974).

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[1] trituration: grinding to a fine powder

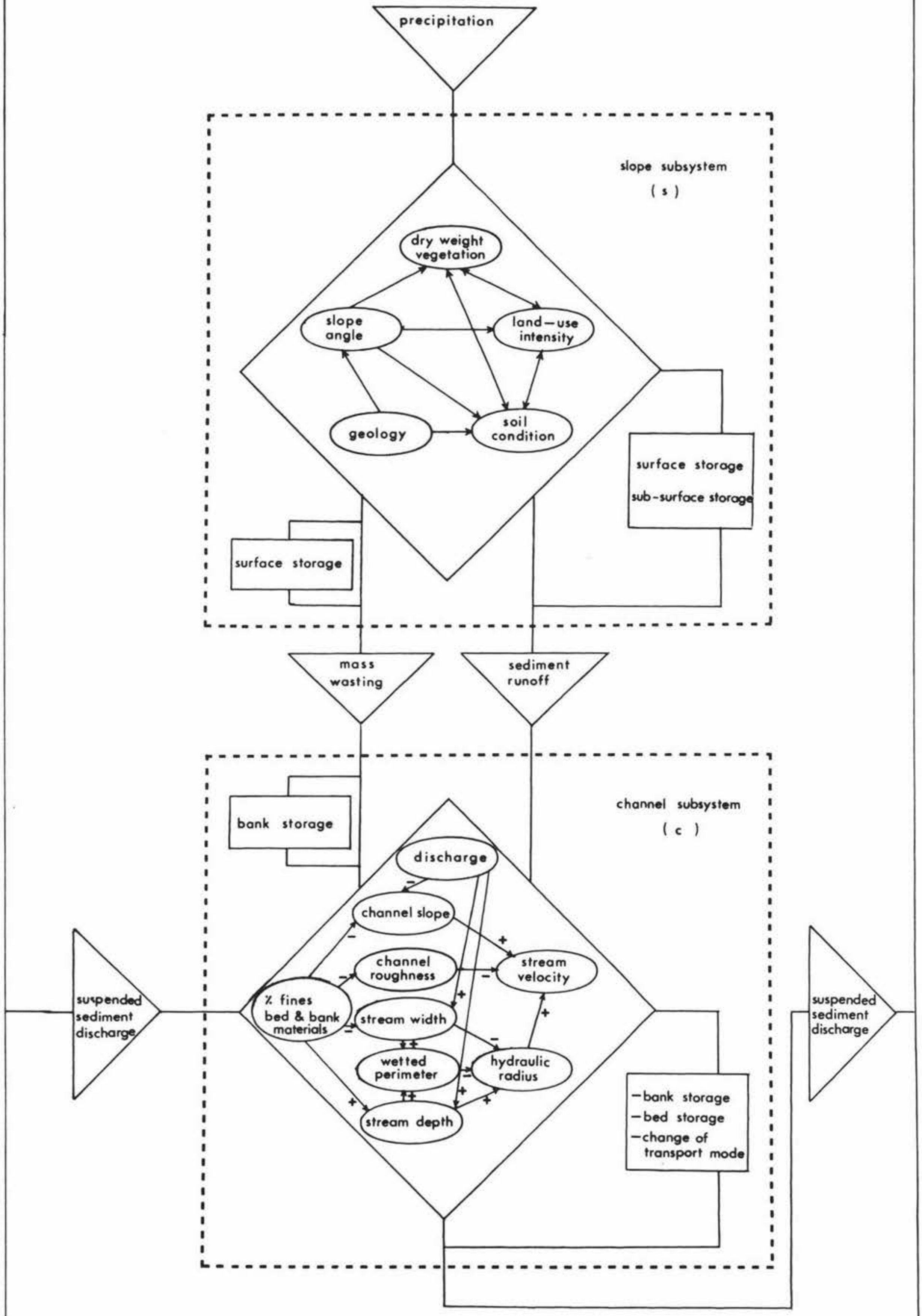

Figure 2.1: Generalised rainfall - sediment yield model.
(note: only some of the factors are shown)

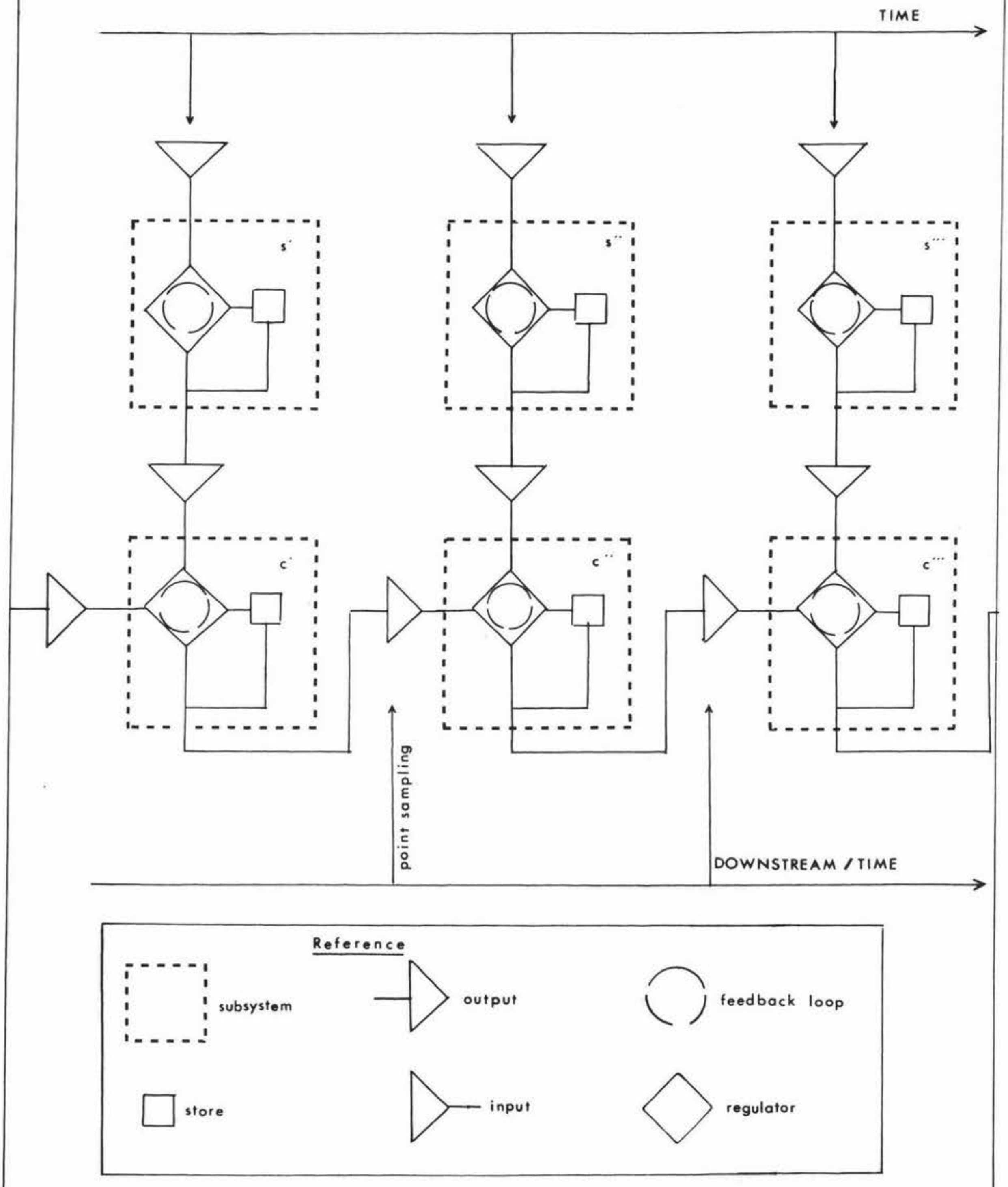

Figure 2.2: Canonical structure of the generalised rainfall-sediment yield model.

Figure 2.1 is simplified to its canonical structure in figure 2.2. The structure of figure 2.2 is further complicated in that:

(i) feedback loops interact with each other. Feedback can be seen as the application of a stress to a system, or part thereof, with a readjustment of the associated variables to reach a new equilibrium. The effectiveness and speed of operation is inversely proportional to the degree of complexity of the interaction. Feedback loops are generally negative (drive toward self regulation), but can be positive (Melton, 1958).

(ii) links represent correlations that are not perfect, that is correlation coefficients are less than unity.

(iii) lag times between the action of the process and its response may vary widely.

A neglected but essential part of the canonical structure is storage (Swanson, 1981). Leliavsky's (1955) stable channel, in which the particles are in constant movement but the general form of the channel remains unchanged through immediate replacement of a removed particle by another from upstream, is untenable. Pearce and O'Laughlin (1978) argue that change in channel sediment storage may be a major source of accelerated sedimentation due to management practices. Griffiths (1981) thinks though that land use (with the exception of highly man-modified catchments), exhibits less than a second order effect in that rivers with similar flow ranges have similar concentration ratings regardless of management practice. Hayward (1980) has found in a small mountain stream with a high proportion of the sediment load moved as bedload, that sediment yield is strongly influenced by the quantity of channel storage. Studies of small forested catchments in Idaho by Megahan and Nowlin (1976) suggest sediment stored even in second or third order drainage basins greatly exceeds annual export.

The consequence of this is that even with no change in hillslope erosion substantial fluctuation in sediment yields may result from changes in storage. The storage component in Figure 2.1 may therefore be a very important element in the rainfall-sediment yield relationship.

The two subsystems will be treated as grey boxes, linked by the mass movement and sediment runoff components. These components can be seen as embodying two relationships:

(i) a relationship between rainfall and the regolith removal process (sediment runoff or mass movement).

(ii) a relationship between the regolith removal process and sediment yield.

Due to the discontinuous nature of mass movement, little progress has been made in developing sediment yield models (Pain and Hosking, 1970). Rainfall-runoff models in the New Zealand context have been developed in general studies such as those of Boughton (1968) and McLay (1980) and specific studies such as those of Pittams (1970) and Soons (1970). Runoff-yield relationships are not well understood at present and the interim use of regression methods is suggested (Shen, 1976). The development of a rainfall-sediment yield model negates the construction of rainfall-regolith removal process and regolith removal process-sediment yield models.

2.2 SAMPLING OF THE SYSTEM

The rainfall-sediment yield model also seeks to represent the discontinuous nature of streamflow measurement. Sediment eroded from a watershed undergoes either deposition or scouring along the path of transport, before reaching a particular channel cross-section where measurement occurs. The ratio between the observed sediment yield at a stream cross-section and the gross amount of soil eroded in the basin above that point is known as the sediment delivery ratio (Sutherland, 1978; Mou Jinze et al, 1981). Due to the changing nature of the physical variables and consequently the sediment delivery ratio along a channel reach (say for example between c' and c" in figure 2.2), measurement of sediment discharge should be seen as point sampling of the system, both in a spatial and temporal sense. It is impossible to measure all sites from an economic standpoint and a practical standpoint (Ibbitt, 1979), so a grey or black box approach must be employed. The hydrologist must, when employing this approach, recognise the real, discontinuous mode of operation of the system.

In summary, the general rainfall-sediment yield model treats as grey boxes the two physical subsystems of the drainage basin (slope and channel subsystems). It requires measurement only of rainfall and sediment discharge in order for a relationship to be established between the two, so that sediment yields can be predicted solely from the measurement of rainfall. Sediment yields so determined cannot be precise due to the complexity of the system (particularly storage components), the semi-independence of mass wasting from the precipitation event and the inadequate sampling of the system, both in a temporal and spatial sense.

CHAPTER 3

MAGNITUDE AND FREQUENCY OF HYDROLOGIC EVENTS

The operation of a process-response system is fundamentally controlled by the magnitude and frequency of inputs into the system. Hence the response (sediment discharge), is the result of a number of inputs each with a magnitude inversely proportional to their frequency or return period. The inputs of concern here, are rainfall events[1], which Coulter (1969) has shown to have a gamma frequency distribution (see Chapter 4.2). These events can be seen as applied stress acting upon the slope subsystem. If the gamma distribution is continuous and the rate of movement from the slope subsystem is some power function of the stress, then the relation between stress and the product of the frequency and rate of movement must attain a maximum. The frequency at which this maximum is achieved, provides a measure of the magnitude of the event that performs the most work (Wolman and Miller, 1960).

Many more occurrences of the smaller sediment-moving event often belies the total work performed when compared to the 'obvious' sediment delivery of the catastrophic (rare) event. Wolman and Miller suggest that the relative importance of different river flows, can be evaluated by knowledge of the quantities of material carried by flows of various magnitudes and their given probability of occurrence. Assigning a probability of occurrence to an event implies consideration of the available record length. For a number of catchments flow records are much too short for assigning return periods.

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1 Coulter has shown that the frequency distribution of daily, monthly and annual rainfall events has a gamma distribution in New Zealand

Instead of determining the return period of the flow carrying the most sediment in the long term, a general observation was made of the suspended sediment rating curves of many of the study catchments. Many of the ratings exhibit suspended sediment concentrations varying through at least two orders of magnitude for a given discharge. An example of a typical rating is shown in figure 3.1. Scatter about the rating line is most pronounced at low flows, where geological considerations play a more significant part in controlling sediment loadings (Scarf, 1972; Waugh, 1976). During low flows a greater proportion of the total load is transported as washload, the concentration of which is substantially independent of the hydraulic variables of the channel subsystem (Einstein, 1950). The scatter at low flows and small contribution they make to total suspended sediment transport, were reasons for positioning the beginning of the rating at flows generally in excess of the mean flow. Figure 3.1 in common with many other ratings has very few or no sediment concentration samples above the mean annual flood, due to the infrequent and unpredictable nature of the events and the difficulty of being on hand to measure them. Thompson (1978) has observed that the greatest quantity of sediment is moved by flows less than the mean annual flood.

The mean annual flood is assigned a return period of 2.33 years (Gregory and Walling, 1973) and hence the bulk of the sediment may be expected to be moved by flows with a return period of less than 2.33 years. Sediment is moved through a stable alluvial channel, optimally adjusted to carry the flow with a recurrence interval on the annual series of about 1.5 years (Dunne and Leapold, 1978). Optimal conditions are a requisite for maximum work, which suggests that flows with a return period of about 1.5 years may be the event which carries the most sediment on a long term basis.

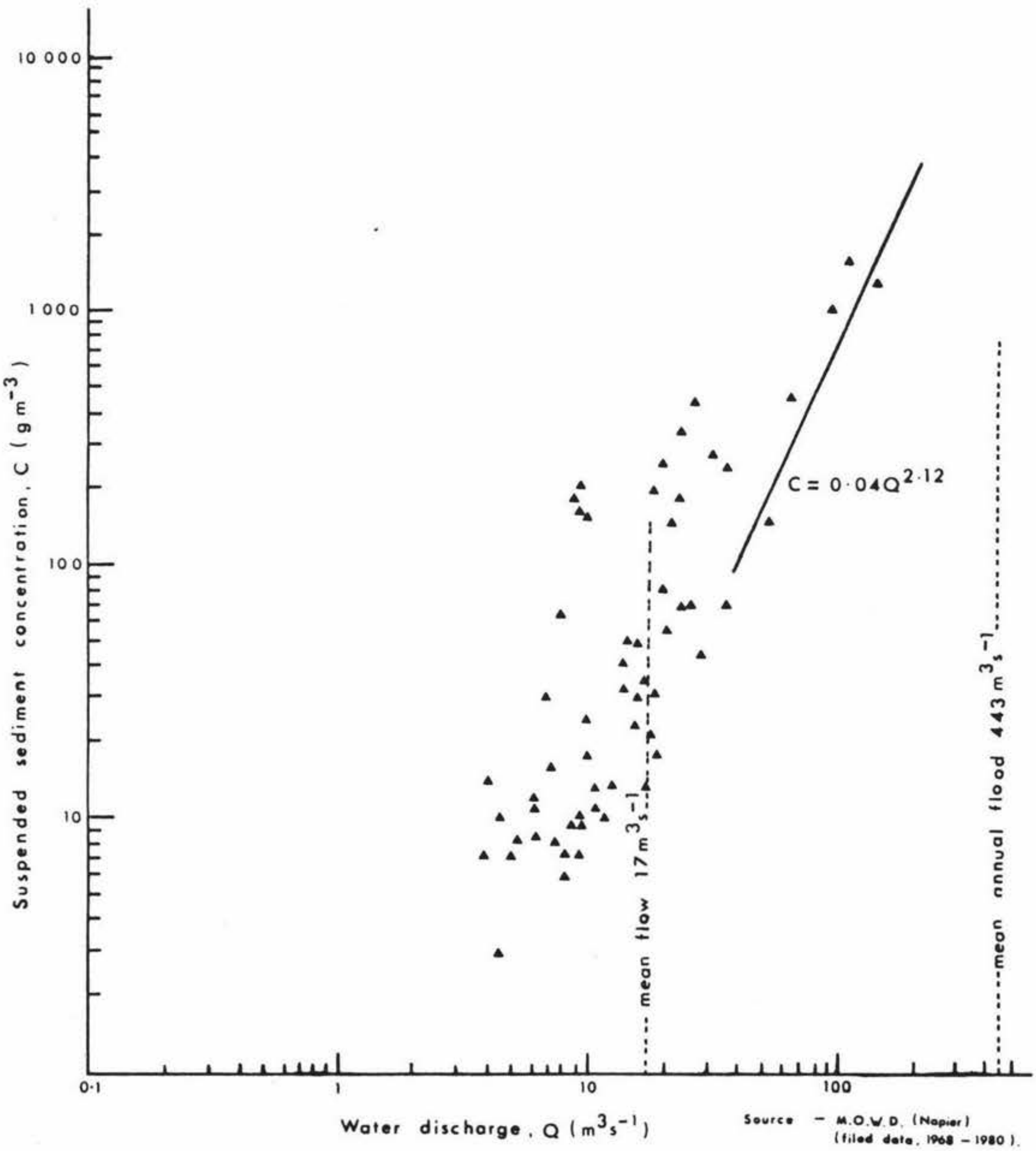


Figure 3.1 Sediment rating for Tutaekuri River at Puketapu (23001)

An assumption is required in the rainfall-sediment yield model that the 'average' storm produces the 'average' flood. Reich (1968) and Thomas and Benson (1970) suggest caution is required in this approach, in that unit hydrograph studies show the most effective storm rainfall duration varies with basin characteristics. Harvey (1977) found that maximum annual daily rainfall is a reasonable surrogate for discharge, in that it is sufficiently large enough to have a direct effect on streamflow. To some extent this has been found to be the case in New Zealand (Boughton, 1968). Rodda (1969) found that the mean annual flood is related to catchment area and mean annual maximum daily rainfall. From the literature it appears therefore, that the input which could perform the greatest total work in moving sediment from the slope subsystem to the channel, may be reflected in annual maximum daily rainfall.

A rainfall characteristic has been chosen to represent the optimum sediment yield event, that is the event that will yield more sediment than any other. It is also necessary to know the range of events which provide the overwhelming majority of sediment. Wolman and Miller (1960) argue that the greatest bulk of suspended sediment is carried by flows with return periods less than five years. Workers in New Zealand, for example Grant (1966) and Adams (1979), have substantiated this proposition. Griffiths (1979) has shown that for the Waimakariri River, 90 percent of the total load is transported by floods that recur at least once in seven years. It is for this reason that the twenty four hour five-year return period rainfall was used as a measure of rainfall intensity, as it will generally cover the range of storms providing the greatest quantity of sediment over a long time period.

The possibility of rare very high magnitude storms occurring within the record period cannot be discounted. Occurrences of such uncharacteristic events pose a major constraint upon the construction of accurate models, but can be side-stepped to some degree by statistical techniques (Chapter 4.2). A high intensity storm may cause severe mass movement and profound channel change (Grant, 1966; Grant 1978; Whitehouse, 1981), so disrupting the channel subsystem that reworking of the sediment may have an effect on the yield for many years after (Pain and Hosking, 1970; Selby, 1976). This assertion is explored more fully in subsequent chapters.

CHAPTER 4

MEASUREMENT

4.1 SUSPENDED SEDIMENT YIELD

Determination of Suspended Sediment Concentration

In 1959 the Ministry of Works and development (M.O.W.D.) began a programme of systematic sediment gauging to provide general sediment data for the entire country and to estimate rates of erosion in particular experimental basins. Prior to this date there had been occasional studies such as those of the Otago Catchment Board (1956). Sediment gaugings have been directed mainly toward suspended loads as bedload contribution is difficult to measure and in most rivers is thought to constitute only a small proportion of total load.

Suspended load can be defined as that part of the material load, transported and held in the flow by turbulent mixing processes that prevent the settling of the particle under the influence of gravity. Suspended particles travel downstream at essentially the same velocity as the fluid.

Bedload is that part of the material load which moves by bouncing (saltation), sliding and rolling along the channel bed. Drag, lift and gravity forces move the particles intermittently at velocities less than that of the fluid. Griffiths and Sutherland (1977) suggest gravel bed load moves aperiodically as sediment waves during flows of moderate or greater magnitude.

The third mode of sediment transport is in solution. Solution load (dissolved - or wash-load) consists of the very finest particles that are continually held in stream flow. This type of load is independent of discharge and directly related to the supply of material from the slope subsystem or channel banks (Einstein, 1950).

Adams (1979) in a survey of North Island rivers, suggests that on average 88 percent of the load is carried as suspended load, 10 percent as dissolved load and 2 percent as bedload. For the rivers draining the Southern Alps, Adams (1978) proposes that of the total load, suspended load constitutes 93 percent, dissolved load 4 percent and bedload 3 percent though in some areas percentage bedload is higher, reaching extremes in small mountainous catchments where the overwhelming majority of sediment yield is bedload material (Hayward, 1980; Jowett and Hicks, 1981). Einstein (1950) suggests there is continuous interchange of particles between suspended and bed transport, which complicates determination of yield estimates for particular transport modes. On average, the bedload contribution of any catchment used in this study is thought to be no more than 15 percent of the total sediment yield.

Accurate calculation of suspended sediment loads requires detailed measurement of sediment concentration and river discharge. Ideally both should be measured continually or in small time increments, but at present this cannot be justified on economic grounds. Suspended sediment gauging at most sites thus has a random temporal distribution.

Water-sediment mixtures are principally gathered by depth integrating samples. Collection is made at equally spaced stream verticals generally using US-DH 48 samplers for small streams and US-DH 49 samplers for larger rivers. As suspended sediment moves at the same velocity as the stream flow, the mean concentration for the sampled vertical multiplied by the discharge for the cross-sectional area represented by the vertical, is the sediment discharge for that area of cross-section (Sutherland, 1978).

A continuous record of suspended sediment concentration can be synthesised over the temporal variation of flow by combination of instantaneous concentration samples with a continuous discharge record. As continuous monitoring of discharge has proven difficult, it has been customary to measure stage continuously and then by means of a stage discharge relationship (rating curve), produce a continuous discharge record. Maintenance of a continuous stage record requires care in the choice of gauge site, but at times through the necessity to have knowledge about a particular drainage basin, sub-optimal locations are often used.

Eighty-two gauging sites with continuous stage measurement were chosen for analysis. Criteria for selection were:

(i) adequate flow ratings and stage data for at least four years available on M.O.W.D. TIDEDA system.

(ii) concentration measurement covered enough observations so that on average rated flows carried at least eighty percent of the average annual load.

(iii) sediment ratings possessed a well defined trend.

(iv) little flow 'modification' or disturbance (through for example: lakes, dams, diversions, construction phase activities).

In consideration of criteria (iv), McPherson (1975, 253) in determination of specific suspended yield for a number of Canadian drainage basins defines as the contributing area: 'the total area of the basin expressed in square miles minus the portions of the watershed which lies upstream of lakes or storage dams'. This definition is unacceptable, in that sediment traps such as lakes cause attenuation of hydrographs for an appreciable distance downstream (Ward, 1978). Einstein (1972) in a study of the Red River (U.S.A.) below a reservoir, concludes that 320 kilometres of channel are required for rating recovery. Red River possesses a gentle channel slope and a sand bed in contrast to the steep, gravel bedded river of the Ohau which Griffiths (1981) suggests takes less than 16 kilometres for downstream recovery from Lake Ohau. While there is a large difference between the recovery distance of the two rivers, the impact in both examples is considerable over the affected reach. Consequently, rivers with extensive lake systems or swamps were not considered. Where 'disturbance' has taken place, pre-disturbance records were used if they satisfied the other criteria (Tongariro River and its attendant power scheme is an example).

A further criterion of minimum basin size was considered for inclusion. Langbein and Schumm (1958) suggest that for very small catchments, rates of sediment yield are greatly influenced by random perturbation arising from details of land use and local features of terrain. The New Zealand Regional Flood Estimation Report (Beable and McKerchar, 1982) restricted its data set to catchments with contributing area greater than $20km^2$. It was found subsequently that much smaller catchments (possibly as small as $2km^2$) could have been incorporated. This study includes small catchments such as Butchers Creek (M.O.W.D. site number 90605) of $4km^2$ and Tauranga Stream (17301) of $5km^2$. Both of these catchments are M.O.W.D. representative basins and have good data bases adequately fulfilling the selection criteria mentioned above. If the hypothesis that suspended sediment yield is primarily determined by precipitation characteristics is to be accepted, then a situation imposed by a large variation in basin size will serve to improve the range of catchments to which the relationship is applicable. Conversely, for very large catchments, the rainfall-sediment yield model suggests that very poor estimates of sediment yield may arise, due to the limited areal flow sampling of a very large area. Large catchments were retained in the subsequent analysis though the insensitivity of many of their catchment characteristics should be kept in mind.

The location of the 82 stream flow stations is shown in figure 4.1, the spatial inequality in gauge site reflecting the availability of data. For example no sites have been chosen in Northland as records in general are too short for determination of good sediment ratings. The evidence

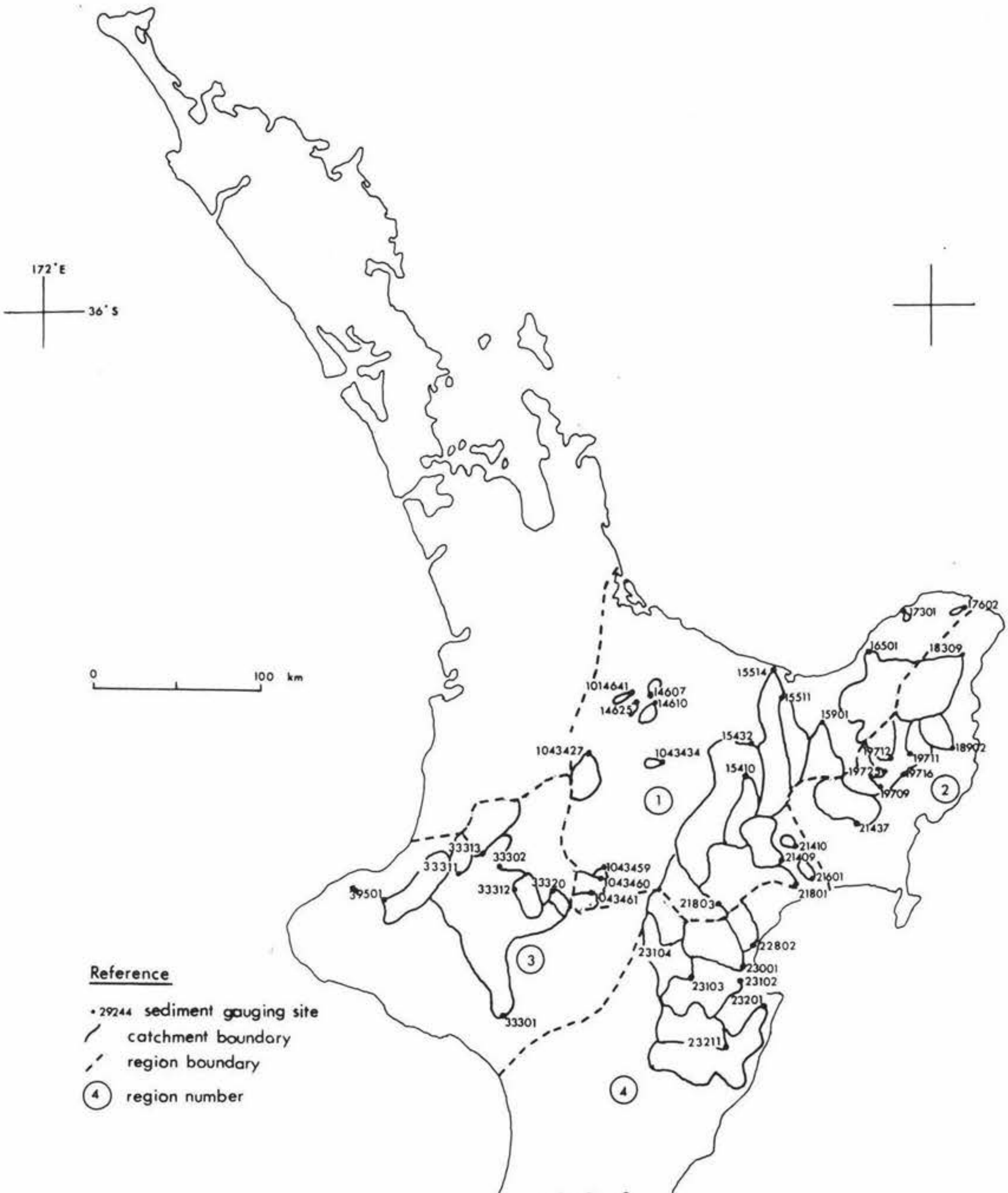


Figure 4.1 : Location of study sites.

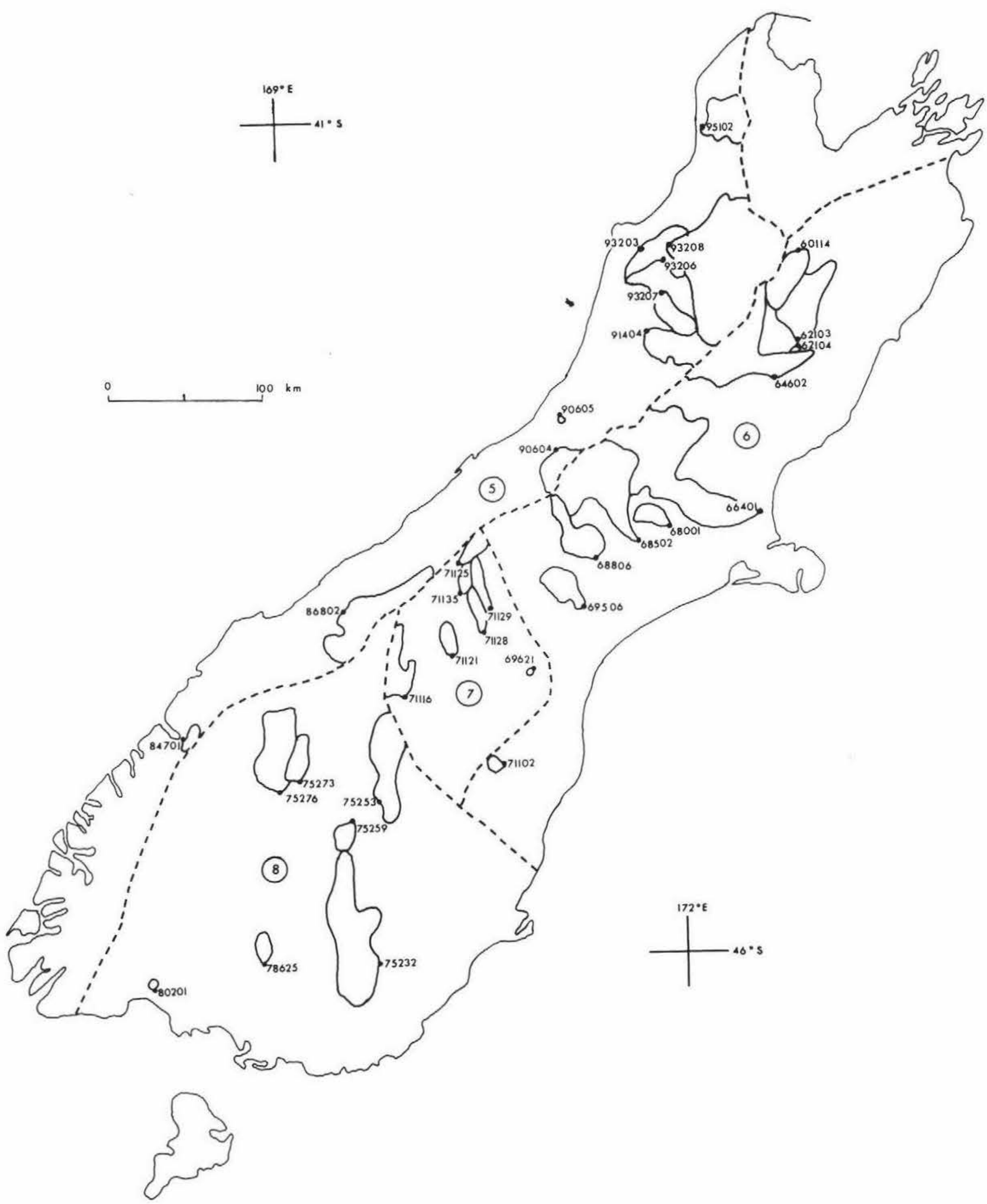


Figure 4.1 continued.

available suggests yields are low (M.O.W.D. 1968, 1970; Schouten, 1978). Nevertheless, the distribution of the flow gauging sites reflects the variations in the physiography, geology, and climate of New Zealand.

Determination of Suspended Sediment Yield

The relation between suspended sediment bad and discharge can be shown by means of a sediment rating curve, generally taking the form of a logarithmic plot of suspended sediment (concentration per unit of water or weight per unit of time) against discharge of the suspended sediment-water mixture.

In this study the sediment ratings have been constructed by the more realistic approach of plotting sediment concentration against discharge. A sediment rating curve, derived through sediment discharge (weight per unit of time), represents a mean condition suggesting a closer correlation than exists in momentary or daily values (Toebes and Ouryvaez, 1970). The reason is that the measure of yield (kilograms per day), is itself a product of sediment concentration times discharge. The covariance of the product when plotted against one of its factors (discharge), makes a rating developed by instantaneous suspended sediment concentration against water discharge preferable.

In developing a rating (say a mean value represented by a 'least squares' fit line through the measured points), it is hoped that period of above average concentration will be balanced by periods of below average concentration. The scatter of the data points about the best-fit line will be due to a number of factors. These include random errors in sediment collection and laboratory measurement and systematic errors involving water temperature, hysteresis, sediment availability, relative timing of the sediment and water hydrographs, seasonality and so on.

Walling (1977) has investigated the effects of scatter in computing suspended sediment yields from rating curves. His data included continuous discharge and concentration records for 309 observations done aperiodically (with a bias towards sampling storm events). His conclusions were that:

(i) summer sediment concentrations at the same discharge are higher than those of winter. This conclusion is also supported by the work of Brown (1972).

(ii) the rising stage has a higher concentration than the falling stage, a situation known as loop rating (see Schouten (1978), Christian and Thompson (1978) for New Zealand examples). In some cases though the reverse may be true (Ward, 1978).

The paucity of detailed measurement for most catchments, means that the specific contribution of factors such as those mentioned above to the scatter about the least squares regression, cannot be ascertained. Studies such as that on the Pauatahanui Stream (Curry, 1981), are providing insights into the effects of some of these factors on the temporal distribution of suspended yield. Errors involved in sample collection, laboratory analysis and unreliable flow data are inevitable, however the greatest contribution to error will be in the inadequate sampling of the temporal variability in yield.

Thompson and Adams (1979) and Adams (1979) in developing a sediment rating for determination of sediment yields from a number of New Zealand catchments, reject the use of linear regression. They argue that the scatter of points about a best-fit line of concentration versus flow are much too large to be explained by sampling errors of flow or concentration and instead, may be due to loop rating. The relationship between sediment concentration and flow is not constant during a flood as the flushing effect exhausts the transportable sediment, resulting in more load being carried by the rising limb than the falling limb. As most New Zealand rivers rise and fall rapidly measurement of sediment concentrations is generally on the falling stage. Thus the data is biased towards lower sediment concentrations, which means sediment ratings developed by regression lines fitted through the centre of gravity of the scatter, underestimate sediment yield. To compensate for this possible underestimation, the authors choose to eye-fit a rating line so as to give equal weight to the limited number of measurements taken at rising stages, but their method seems to have been inconsistently applied, for example:

(i) their rating for Waimakariri River at Gorge (66402) has been drawn through the middle of the scatter of all data points. It gives equal weighting to the numerous low flows which the authors themselves claim: 'transport such a small part of the total load' (Thompson and Adams, 1979, 227).

(ii) the rating in (i) for the higher flows (above mean flow), bisects the data points almost all of which have been taken at the falling stage.

(iii) the ratings for Acheron at Clarence (62103) and Ahuriri at South Diadem (71116), do not appear to be weighted for the measurements at the rising stage.

In short, the method employed makes consistency in rating construction difficult. A further criticism is that:

(iv) a constant slope has been employed for the rating equations (2.3 in the study of Thompson and Adams and 2.3 and 1.7 in that of Adams, corresponding to rivers cut in greywacke and soft tertiary sediments respectively), which incorporates some insensitivity into the ratings (Griffiths, 1982).

Due to the above reservations, the traditional approach used by McPherson (1975) and Griffiths (1981, 1982) has been adopted. From the two latter works many of the suspended sediment yields used here have been taken.

Griffith's (1981, 1982) method develops an individual sediment rating for each catchment by fitting a 'least squares' line through the logarithmically transformed instantaneous suspended sediment concentration and respective discharge points. The rating is begun where the scatter of points is less than one order of magnitude, which generally corresponds to a discharge in excess of the mean flow - see for example the rating of Tutaekuri at Puketapu (23001), shown in Figure 3.1. Little usable data is excluded by this cutoff point as the bulk of the sediment is moved by flows greater than the mean flow.

The rating established is then combined with the complete flow record to give a value of basin yield. The area of the basin is inserted into the denominator to give a value of specific yield to aid in direct comparison between catchments. Basin yield is computed by the following algorithm (Griffiths, 1981):

$$G_s = \frac{1}{1000\ AT} \sum_{i=1}^{n} 0.25(C_i + C_{i+1})(Q_i + Q_{i+1})\ \Delta t$$

where

G_s : specific annual suspended sediment yield (tonnes $km^{-2}\ yr^{-1}$)

Q : water discharge ($m^3\ s^{-1}$)

C : suspended sediment concentration ($g\ m^{-3}$)

A : catchment area (km^2)

T : water flow record length (years)

n : number of intervals between observations

i : summation integer

Δt : time between stage observations (seconds)

A value of 3600 seconds as the division of stage record, was used for t. The values of specific annual suspended sediment yield are given in Table 1.

Catchment Number	Sediment Region	River and gauging site name	Specific annual suspended sediment yield (tonnes km^{-2} yr^{-1})	Mean annual rainfall (m)	24-hour 5-year return period rainfall (mm)	Mean annual daily maximum rainfall (mm)	Coefficient of variation	Gamma statistic	Mean flow (m^3 s^{-1})	Mean annual flood (m^3 s^{-1})	Catchment Area (km^2)
14607	1	Waiohewa at S.H. 30 Bridge	55	1.4	152	102	18.07	32.52	0.34		11
14610	1	Utuhina at S.H. 5 Bridge	66	1.4	147	102	18.05	32.78	2.2	20	60
14625	1	Puarenga at FRI Bridge	46	1.3	147	111	19.11	28.90	1.9		75
15410	1	Whirinaki at Galatea	143	1.5	138	84	15.13	46.57	15	121	534
15432	1	Rangitaiki at Kopuriki	83	1.5	135	88	16.71	38.76	57	260	2318
15511	1	Waimana at Gorge	722	1.8	188	105	21.15	24.63	20	387	440
15514	1	Whakatane at Whakatane	236	1.6	182	98	21.17	25.78	57	943	1557
15901	1	Waioeka at Gorge Cableway	592	2.3	159	116	18.37	29.37	11	819	640
16501	1	Motu at Houpoto	1961	2.7	171	102	16.05	38.37	94		1393
17301	1	Tauranga at Maruhinemaka	451	1.8	180	155	17.74	34.55			5
17602	1	Mangatutu at S.H. 35	1026	2.7	180	134	19.92	27.12	95		14
18309	2	Waiapu at Rotakautuku	19970	2.4	175	140	21.39	23.89	101	1674	1378
18902	2	Hikuwai at Willow Flat	13890	1.9	220	158	23.86	18.34	8.9	340	307
19709	2	Wharekopae at Killarney	709	1.3	140	77	21.94	20.38	3.9	144	181
18611	2	Waingaromia at Terrace	17340	2.1	165	103	17.31	21.54	7.3	170	175
19712	2	Mangatu at Omapere	7045	1.9	153	87	21.75	21.10	6.6	200	155
19716	2	Waipaoa at Kanakanaia	5836	1.6	141	89	20.44	20.96	41	1167	1582
19725	2	Waikohu at No. 3 Bridge	1040	1.3	138	82	20.83	20.91	13	330	597
21409	1	Waiau at Otoi	239	2.0	167	102	17.85	31.64	22	356	513
21410	1	Waihi at Waihi	301	2.1	160	110	17.52	33.10	2.3	97	50
21437	2	Hangaroa at Donneraille Park	622	1.4	152	96	21.14	27.74	17	376	578
21601	2	Tahekenui at Glenstrae	6969	1.8	160	105	24.78	17.90	0.71	40	21
21801	1	Mohaka at Raupunga	370	2.0	156	122	26.77	16.78	82	818	2370
21803	1	Mohaka at Glenfalls	340	2.4	154	131	30.32	14.30	35	459	997
22802	4	Esk at Waipunga	1096	1.5	165	117	22.17	21.63	6	216	254
23001	4	Tutaekuri at Puketapu	425	1.5	164	106	20.14	25.14	16	443	793
23102	4	Ngaruroro at Fernhill	467	1.5	160	85	18.87	38.83	45	918	1930
23103	4	Ngaruroro at Whanawhana	571	1.8	157	99	17.88	33.38	37	466	1090
23104	4	Ngaruroro at Kuripapango	593	2.3	172	110	16.47	37.82	17	209	370
23201	4	Tukituki at Red Bridge	445	1.5	124	78	17.68	40.06	50	1380	2380
23211	4	Waipawa at Waipawa	520	1.9	128	78	15.52	39.58	25		673
29201	4	Ruamahanga at Wardells	356	1.5	120	99	11.34	72.36	26	429	637
29202	4	Ruamahanga at Waihenga	247	1.4	121	70	16.26	38.27	80	896	2340
29244	4	Whangaehu at Waihi	259	1.2	107	70	20.38	26.33	0.6	28	36
30802	4	Pauatahanui at Gorge	98	1.1	120	68	17.94	30.65	0.64	27	39
33301	3	Wanganui at Paetawa	326	1.8	120	71	13.25	60.04	817	2337	6643
33302	3	Wanganui at Te Maire	164	1.9	115	76	12.84	64.66	83	818	2212
33311	3	Tangarakau at Tangarakau	211	1.9	122	68	10.74	83.74	12	265	238
33312	3	Retaruke at Kawautahi	577	1.9	112	71	10.14	65.92	8.5	330	256
33313	3	Ohura at Tokorima	167	1.8	107	66	13.04	65.48	24	268	668
33320	3	Whakapapa at Footbridge	650	2.8	153	88	13.66	65.20	12	382	184

Catchment Number	Sediment Region	River and gauging site name	Specific annual suspended sediment yield (tonnes km^{-2} yr^{-1})	Mean annual rainfall (m)	24-hour 5-hour return period rainfall (mm)	Mean annual daily maximum rainfall (mm)	Coefficient of variation	Gamma statistic	Mean flow (m^3 s^{-1})	Mean annual flood (m^3 s^{-1})	Catchment Area (km^2)
39501	3	Waitara at Tarata	644	2.2	182	99	15.40	50.51	32	572	725
1014641	1	Ngongotaha at S.H.5. Bridge	80	1.5	180	111	15.69	43.81	1.8		73
1043427	1	Mangakino at Dillons Rd	35	1.4	123	75	16.93	38.57	11	59	373
1043434	1	Mangakara at Hirsts	152	1.5	150	82	10.41	82.13	0.44	6	22
1043459	1	Tongariro at Turangi	555	2.0	146	108	16.99	38.12	53	365	772
1043460	1	Tongariro at Puketerata	295	2.1	172	105	15.94	41.82	35	322	495
1043461	1	Tongariro at Upper Dam	207	2.2	190	105	15.96	41.90	12	241	174
60114	6	Wairau at Dip Flat	545	2.0	193				25	260	505
62103	6	Acheron at Clarence	613	1.3	176	69	17.42	32.97	22	333	997
62104	6	Ribble at Airstrip	503	1.3	180	69	19.56	31.07	0.70	17	20
64602	6	Waiau at Marble Point	1300	2.0	154	69	16.70	37.48	90	1190	1980
66401	6	Waimakariri at Old Highway Bridge	1669	1.9	122	75	19.42	27.29	120	1725	3210
68001	6	Selwyn at Whitecliffs	584	1.3	94	65	17.82	31.09	3	85	164
68502	6	Rakaia at Gorge	1641	3.0	222	70	16.10	43.34	200	2340	2640
68806	6	South Ashburton at Mount Somers	574	1.4	128	70	21.19	25.83	8	108	540
69506	6	Orari at Silverton	650	1.1	114	65	20.67	25.69	11	267	520
69621	7	Rocky Gully at Rockburn	2	0.81	80	53	15.42	46.01	0.29	13	22
71102	6	Otekaieke at Stockbridge	447	0.93	57	44	17.69	33.93	1	33	79
71116	7	Ahuriri at South Diadem	98	1.6	144	54	20.96	23.10	21	227	557
71121	7	Twizel at S.H.B.	131	1.8	91	61	18.68	30.55	4	68	250
71125	7	Hooker at Ball Hut Rd Bridge	3538	6.5	400	232	24.35	17.10	21	261	103
71128	7	Irishman at Windy Ridge	11	0.82	75	54	21.05	22.70	1.4	36	142
71129	7	Fork at Balmoral	120	1.6	118	67	18.64	28.90	3	24	98
71135	7	Jollie at Mt Cook Station	198	2.4	212	85	23.29	19.85	8	63	139
75232	8	Pomohaka at Burkes Ford	29	0.93	54	43	15.34	45.51	26	359	1924
75253	8	Manuherikia at Ophir	35	0.83	59	39	16.74	37.25	8.4	211	2036
75259	8	Fraser at Old Man Range	84	1.0	45	37	20.96	26.03	2	22	122
75273	8	Arrow at Tobins Track	242	1.1	114	47	18.06	30.92	2.6	29	199
75276	8	Shotover at Bowens Peak	1019	1.6	167	96	17.70	44.19	38	456	1088
78625	8	Otapiri at McBrides Bridge	30	1.1	67	52	15.00	33.43	2	47	109
80201	8	Rowallanburn at Old Mill	51	1.1	76	56	12.82	64.02	1.4	39	72
84701	5	Cleddau at Milford	13300	7.0	400	261	15.73	41.10	32	549	155
86802	5	Haast at Roaring Billy	12736	6.5	443	185	15.90	43.73	193	3725	1020
90604	5	Hokitika at Colliers Creek	17070	9.4	587	278	15.51	45.67	99	2152	352
90605	5	Butchers at Lake Kaniere Rd	272	2.9	260	153	20.59	27.50	0.30	27	4
91404	5	Grey at Waipuna	552	3.0	152	104	15.76	44.80	48	602	642
93203	5	Buller at TeKuha	270	2.6	149	99	17.80	50.38	416	4500	6350
93206	5	Inangahua at Landing	725	3.0	141	87	14.23	53.65	73	1680	1000
93207	5	Inangahua at Blacks Point	167	2.5	147	84	15.00	48.19	13	460	234
93208	5	Buller at Woolfs	268	2.4	142	83	14.38	52.13	240	2634	4560
95102	5	Karamea at Gorge	325	3.3	241	154	16.63	66.50	105	1950	1160

TABLE 4.1: SUMMARY OF DRAINAGE BASIN HYDROLOGICAL CHARACTERISTICS

Determination of suspended sediment yield for many catchments throughout New Zealand have been calculated by numerous workers for various applications. While some have been used as a check for some of the more 'unusual' yields derived here and by Griffiths (1981, 1982), none have been used in this study, as direct comparison is impossible owing to the different methods of calculation. For reference sediment yields from other sources are given in the Appendix.

4.2 POINT RAINFALLS

Background

Rainfall measurements in New Zealand are made using several types of gauges. Manual gauges include long term storage gauges such as the 'Octapent' gauge used in remote areas and daily read gauges generally of the United Kingdom Meteorological Office Mark II gauge design. Automatic rainfall recorders are primarily the 'Lambrecht' natural siphon with weekly or monthly charts in remote areas and the Dines tilting siphon gauge with a daily chart.

Rainfall depth measurements for manual daily gauges are taken at 0900 hours New Zealand Standard Time and the measurement obtained is credited to the previous day.

Official rainfall measurement began in 1862 and there was steady growth in the number of gauges such that by 1941 there were 480 stations. In that year the New Zealand Meteorological Service (N.Z. Met. S.) undertook the coordination and publication of all rainfall records. Monthly rainfall depths for all stations had previously been published in the New Zealand Gazette (1889-1940) and more detailed meteorological observations for climatological stations were published by the Department of Scientific and Industrial Research (1928-1938) and the New Zealand Air Department 1939, 1940). During the 1950s an effort was made to improve and standardise exposures and replace non-standard raingauges (Hurnard and Coulter, 1979). From 1941-1966 the N.Z. Met. S. included rainfall observations in its publication 'Meteorological Observations'. In 1967 rainfall observations were extracted from the 'Meteorological Observations', to produce a separate publication: 'Rainfall Observations for New Zealand'. Today the N.Z. Met. S. collects rainfall information from over 1500 gauges with the National Water and Soil Conservation Organisation (N.W.A.S.C.O.) operating a further 900 gauges. The extent of the gauge network is published periodically in map form (see for example N.Z. Met. S. 98/60). Reasonable gauge coverage extends throughout the country except for areas west of the South Island Main Divide, the Kaikouras, eastern Bay of Plenty, West Taupo and Inland Wanganui.

Measurement Problems

Problems involved with precipitation measurement have been well documented, see for example Larson (1971). Errors in measurement are of two types: random or systematic. Random rain-gauge errors arise from three causes:

(i) variation in gauge manufacture, even within one design (see for example Morrissey (1967)).

(ii) microclimatological variations across the climatological measuring site (Hutchinson, 1969).

(iii) spatial and temporal variation of precipitation as it falls. Thus one gauge observation at a site, is merely a sample of the precipitation population of the site and is subject to random statistical error (Dreaver and Hutchinson, 1974).

In general random errors are small in comparison to systematic errors.

A very important systematic error is the effect of the gauge on the horizontal transferance of air flow (Green, 1970). If the gauge has its orifice above ground level, air is deflected causing a wind eddy effect (the higher the gauge the greater the effect), resulting in a reduction of catch. If the orifice is installed flush with the ground it is prone to insplash from the surrounding surface. Other factors resulting in underestimation of total depth include evaporation, outsplash, leaks, icing over and moistening of dry surfaces (Grant, 1961).

Precipitation measurement at high altitudes may be complicated by snowfalls. For catchments where a sizeable proportion of total precipitation is snow, other measuring methods must be used (see for example Chinn (1969), Archer (1970)).

Reduction in the magnitude of random errors can be achieved by a large sample (by use of a long record period), but attenuation of systematic errors due to exposure cannot be corrected. Faith has been placed in the operating authorities choice of gauge site and gauge design to minimise systematic error.

Another source of error, relates to the records used. Provisional totals for many sites were utilised, as time and financial constraints made it impossible to use edited rainfall totals exclusively.

Study Procedure

For computation of climatological normals the World Meteorological Organisation (W.M.O., 1962) recommends a period of at least thirty consecutive years. The thirty-year period should begin on 1 January 1901, 1911, 1921 and so on. The N.Z. Met. S. (1973) has adopted the period 1941-1970 to produce normals for approximately 1300 stations for New Zealand and the outlying islands.

Those stations refered to as 'Type 1' in the N.Z. Met. S. publication were used as a base network. To these were added stations that have concluded a consecutive thirty-year coverage during the period 1971-1980, and those with 25-30 years of record (after their record was checked with adjacent base network stations). This data set was still inadequate to give rainfall estimates for a number of study catchments and so gauges with 15-25 years of suitable record were included upon comparison of their record with those of surrounding base network gauges. Rainfall stations with less than fifteen years of record were not used.

As many of the gauges do not sample the entire 1941 to 1980 time span, comparison of gauge means can only be performed if there is an assumption of non-secularity in meteorological elements. Use of records from whatever period is available is consistent with the notion that they are random samples. While a larger standard error may result in the final multiple regression analysis, it is preferable to the possibility of biased data due to 'variability' or 'secularity' of rainfalls. Variability of rainfall has been discussed by Seelye (1946, 1950), Coulter (1968), Tomlinson (1980).

The short life of many recording stations coupled with the inherent variability of rainfall, cause difficultiess in the calculation of temporal variation of rainfall in the long term. Tomlinson (1980) using long term averages for twenty stations applied several filters to suggest that there were eleven–year cycles, together with more irregular three–year cycles. The combined length of gauges within catchments chosen here generally spans the entire forty year period, which negates any introduction of bias from possible eleven–year and three–year cycles.

Of greater concern is the possibility of an overall increase or decline of rainfall over the data period. Tomlinson's (1980) data suggested that there has been a reduction at the rate of four percent and seven percent per century for the North and South Island respectively. However, fluctuations about the trend line are so large that the standard errors for the rates are much greater than the rates themselves - the evidence therefore is not conclusive.

The study consequently assumes non-secularity of rainfall both in the short and long term.

An extensive and exhaustive search of yearly observations for some 300 rain-gauges which comprised the gauge network, was undertaken to collate rainfall totals. Observations were provided by a number of Catchment Boards, M.O.W.D. district offices, N.Z. Met. S. and from various publications ('N.Z. Met. S. Misc. Pub. 110' and predecessors, 'N.Z. Met. S. Misc. Pub. 118', 'N.Z. Mets. S. Misc. Pub. 162', 'Water and Soil Tech. Pub. 19').

While the most detailed information on precipitation events is available from recording rain gauges, the data set does not provide suitable areal coverage. It also does not furnish many stations with long term records. Use of the wide network of daily storage gauges provides a much larger data base with longer records, though it does limit the choice of rainfall parameters in that the shortest period of rainfall measurement is one day. The rainfall parameters selected are given below:

a) <u>statistical characteristics</u>:

(i) the gamma statistic which characterises the underlying distribution of New Zealand rainfall.

(ii) the coefficient of variation; a measure of the dispersion of rainfall amounts about the mean.

b) <u>intensity characteristics</u>:

(i) the mean annual daily maximum rainfall

(ii) the twenty-four-hour five-year return period rainfall event a(i) <u>the gamma statistic</u>

Rainfall distributions in New Zealand are skewed (N.Z. Met. S., 1979), in that they do not possess a symmetric distribution either side of the mean value. A skewed distribution can be misinterpreted if the mean is used as a measure of central tendency.

Any rainfall distribution has a physical lower limit (there cannot be less than zero rainfall) but no upper limit. Thom (1958, 1968) and Coulter (1968) have shown that the family of gamma distributions adequately defines the probability density function of temporal rainfall events. Coulter (1969) reasons that the positive skew of the gamma curve fits the positively skewed daily, monthly, seasonal and annual rainfall distributions of New Zealand. Hurnard and Coulter (1979) conclude however, that for parts of New Zealand annual rainfall total are almost normal, but this need not necessarily be a problem due to the 'flexibility' of the gamma function as discussed later.

The gamma distribution is a two parameter frequency distribution which allows for the change in power function to occur at any abscissal value. Thom (1958) gives the equation as:

$$g(x) = \frac{1}{\beta^{r}\tau(r)} X^{r-1} e^{-X/\beta} \qquad \begin{matrix} \beta > 0 \\ r > 0 \end{matrix} \quad \ldots\ldots\ldots\ldots\ldots \quad (4.1)$$

where

X : random variable, in this case annual rainfall depth

β : scale parameter

r : shape parameter

τ : ordinary gamma function

The moments about zero of the gamma distribution g (X) are:

$M = \beta r$ .... 1st moment μ_1 .... (4.2)

$\sigma^2 = \beta^2 r$ .... 2nd moment μ_2 .... (4.3)

$2\beta^3 r$ .... 3rd moment μ_3 .... (4.4)

where

M : mean of the distribution

σ : standard deviation of the distribution

The coefficient of skewness is

$$\sqrt{b} = \frac{\mu_3}{\sigma^3} = \frac{2\beta^3 r}{\beta^2 r \beta \sqrt{r}}$$ from equations 4.3 and 4.4

and upon simplification

$$\sqrt{b} = \frac{2}{\sqrt{r}} \quad \text{.................................} \quad (4.5)$$

The gamma shape (r) can be given by the formula

$$r = \frac{1 + (1 + 4C/3)^{\frac{1}{2}}}{4C}$$ .... (N.Z.Met.S.,1979)... (4.6)

where $C = \ln\frac{M}{G}$ M: anthmetic mean: $M = \frac{X_1 + X_2 + \ldots\ldots Xn}{n}$

G: geometric mean: $G = \sqrt[n]{(X_1 . X_2 . \ldots X_n)}$

From equation 4.5 it can be seen that for the skewness (b) to approach zero (hence normality of the distribution), the shape parameter (r) must be large. For r greater than 50 the distribution can be seen as essentially normal. For r less than 20 the distribution possesses a noticeable positive skew. The gamma distribution is therefore of considerable benefit in modelling the distribution of rainfall as it possesses a lower bound, no statistical upper bound, no statistical upper bound, possesses positive skew but is capable of accommodating sites characterised by a more normal rainfall distribution as identified by Hurnard and Coulter (1979).

Gamma shape r was determined for the distribution of annual rainfall, for each rainfall station. 'N.Z. Met. S. Misc. Pub. 163' (N.Z. Met. S., 1979) lists gamma statistics and these were supplemented by calculation of r via equation 4.6 from the yearly observations extracted from other sources.

a(ii) coefficient of variation

The standard deviation of a sample of rainfall depths from the population is significant only in relation to the mean from which it is computed. A measure of dispersion expressed in relative terms is necessary for comparison among gauges. Such a measure is the coefficient of variation given by dividing the standard deviation by the arithmetic mean. It is a simple measure of the relative departure of sample values about the mean value.

Wilson (1973) reasons from his findings that because erosion is at a maximum under seasonal climates, sediment yield is more a function of climatic variability than mean annual precipitation. Harlin (1978) in a study of resevoir sedimentation across the United States, found that 63 percent of the total variation in sediment accumulation was explained by precipitation variability measured by the coefficient of variation. This study endeavours to explore the applicability of this assertion in a New Zealand context.

The coefficient of variation was determined for each station by computing the mean of its annual rainfall totals and dividing it into the standard deviation of those totals.

a(iii) and a(iv) <u>rainfall intensity</u>

Rainfall intensity is an important factor in the loosening and movement of material from slopes (Campbell (1945), Grant (1966), Selby (1972), McSaveney (1978)). The choice of intensity parameters has been discussed in Chapter 3.

Values of annual daily maximum falls were supplemented by values of annual twenty-four hour maximum falls, by dividing by a conversion factor of 1.14 which has been derived at through analysis of many twenty-four hour and daily falls (Coulter and Hessell, 1980). The factor of 1.14 is derived on the basis that 14 percent more rain falls in the period midnight to 9 a.m. than from 3 p.m. to midnight. The procedure for determining daily rainfall up to 9 a.m. and crediting it to the previous day, results in smaller daily values (on average 14 percent smaller) than twenty-four hour values.

Two companion publications have been released recently on high intensity rainfalls in New Zealand. Coulter and Hessell's (1980) publication 'The Frequency of High Intensity Rainfalls in New Zealand Part II', updates a publication of the same name by Robertson (1963). The publication gives point estimates of varying rainfall durations for given return periods. Its companion volume - 'Part I' (Tomlinson, 1980) - is concerned with areal catchment intensities.

Average catchment twenty-four hour five-year return period rainfall intensities for this study were determined by planimetry of the isohyetal map of this event provided in Part I of the 'High Intensity Rainfall Study'. In some cases the derived figure was weighted by means of the point estimates given in Part II to obtain a more accurate catchment intensity (see Chapter 4.3).

Daily maxima were extracted from the daily files of operating authorities, from the publications of yearly observations published by the N.Z. Met. S. (1941-1980) and from 'Part II' by taking the 24 hour duration fall listed for a station and dividing it by the correction factor (1.14).

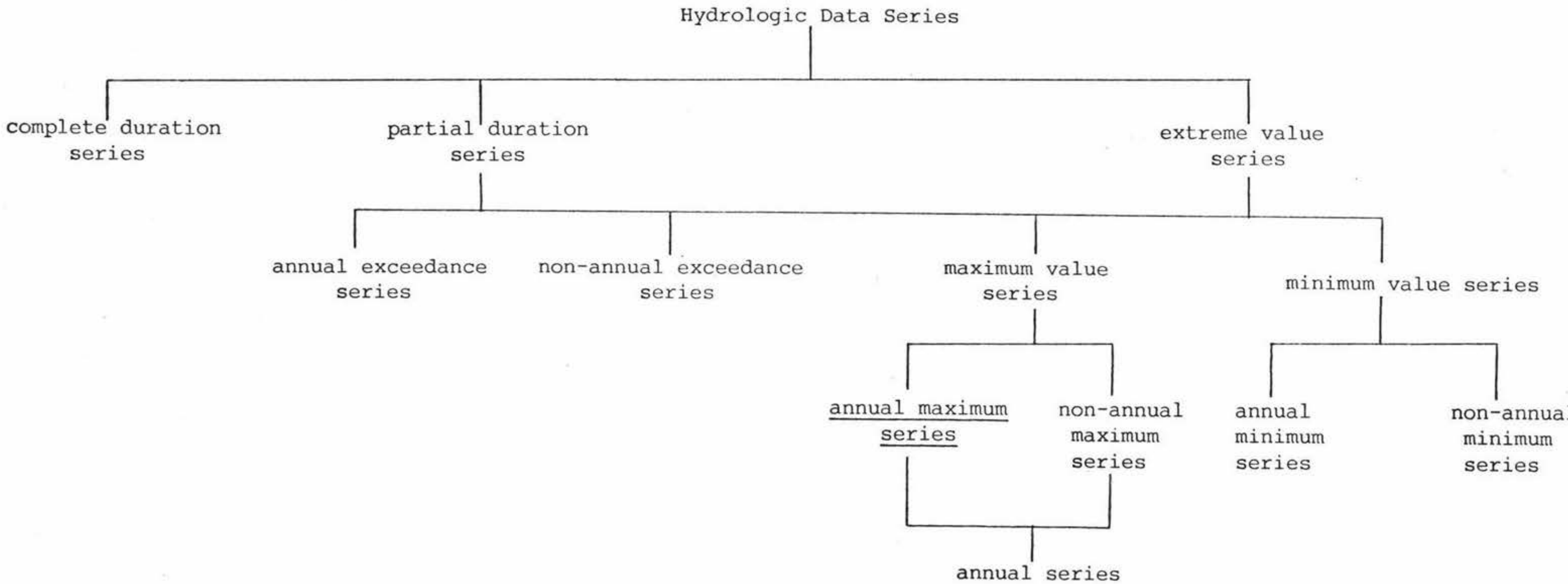
The annual daily maximum series is one of a number of possible series that could have been chosen. Its status is shown in figure 4.2. The advantage of the annual daily maximum series is that it is unlikely to be influenced by autocorrelated events. While the partial duration series samples all events above a certain threshold, these events may not be strictly independent and since the method includes 'high' rainfalls to the detriment of 'low' intensity rainfalls, it can give a more biased result than the annual series. Cunnane (1975) suggests that even though the partial duration series contains more data than the annual series it gives no guarantee of better estimates. These reasons provided further justification for the choice of the annual daily maximum series.

Outliers

The series of daily maxima for each rain-gauge were checked for the presence of outliers. An outlier may be defined as an element that plots at a position far removed from the trend of the frequency distribution shown by the other samples.

Three basic reasons can be given for the appearance of outliers:

(i) an incorrect observation resulting from an error of some type. Provisional data has been checked before going to publication and it is most unlikely that a value of very high magnitude has not been checked for instrumental or recording error.



Source: Ward (1978, 108)

FIGURE 4.2: BREAKDOWN OF THE HYDROLOGIC DATA SERIES SHOWING THE STATUS OF THE ANNUAL MAXIMUM SERIES

(ii) an infrequent occurrence resulting from the same phenomenon as all other occurrences.

(iii) an infrequent occurrence resulting from a different phenomenon from that which all other occurrences derive.

Any procedure for dealing with outliers requires judgements involving both mathematical and hydrological considerations. Possible procedures for dealing with outliers can be to:

(i) exclude the event, it being from a non-homogeneous population and assign a frequency distribution to the remainder of the series. A return period cannot be assigned to the outlier in this case, but it does assure the theory is not missapplied and leads to a better assessment of the return period of the remaining extreme events (Tomlinson, 1978).

(ii) include the event and select a more appropriate frequency distribution or plotting formula. Best fit lines were drawn through the probability plots which allows some flexibility in the choice of frequency distribution as the trend of the data points suggests the fitted line. There may though be limitations on the selection of plotting formula.

(iii) include the event and assign a return period to the outlier which is more likely to conform to the remainder of the distribution.

To determine whether suspected outliers should be excluded from the annual maximum series probability plots were constructed. The return period plotting positions were calculated using the Weibull formula (equation 4.7), which has been shown by Chow (1953) and W.M.O. (1974) to be theoretically suitable for plotting annual maximum series.

$$Tp = \frac{N + 1}{i} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (4.7)$$

where

Tp : return period plotting position of daily maximum years

N : length of record in years, or number of annual maxima

i : rank of annual maximum in series (largest = 1, smallest = N).

This formula gives results that can be intuitively expected, with the greatest rainfall depth in an annual series possessing a return period only one year greater than the length of record.

A dimensionless form of the rainfall depth was determined by dividing through by the mean of the annual maxima series ($\bar{P}$), determined thus:

$$\bar{P} = \frac{1}{N} \sum_{i=1}^{N} P_i$$

where

P_i : an individual rainfall maxima in mm

N : length in years of the annual series

Plots of $P/\bar{P}$ against a given Weibull determined return period were constructed on Gumbel probability paper. The best fit line was drawn using the values of the sample excluding the suspected outlier and the deviation of the outlier from the line determined by reallocating a return period for it as in (iii) above. If the return period was significantly greater than the second ranked maxima then it was assumed to be drawn from a different population and excluded from determination of the mean, of the annual daily maximum series. An example of such an outlier is shown in Figure 4.3.

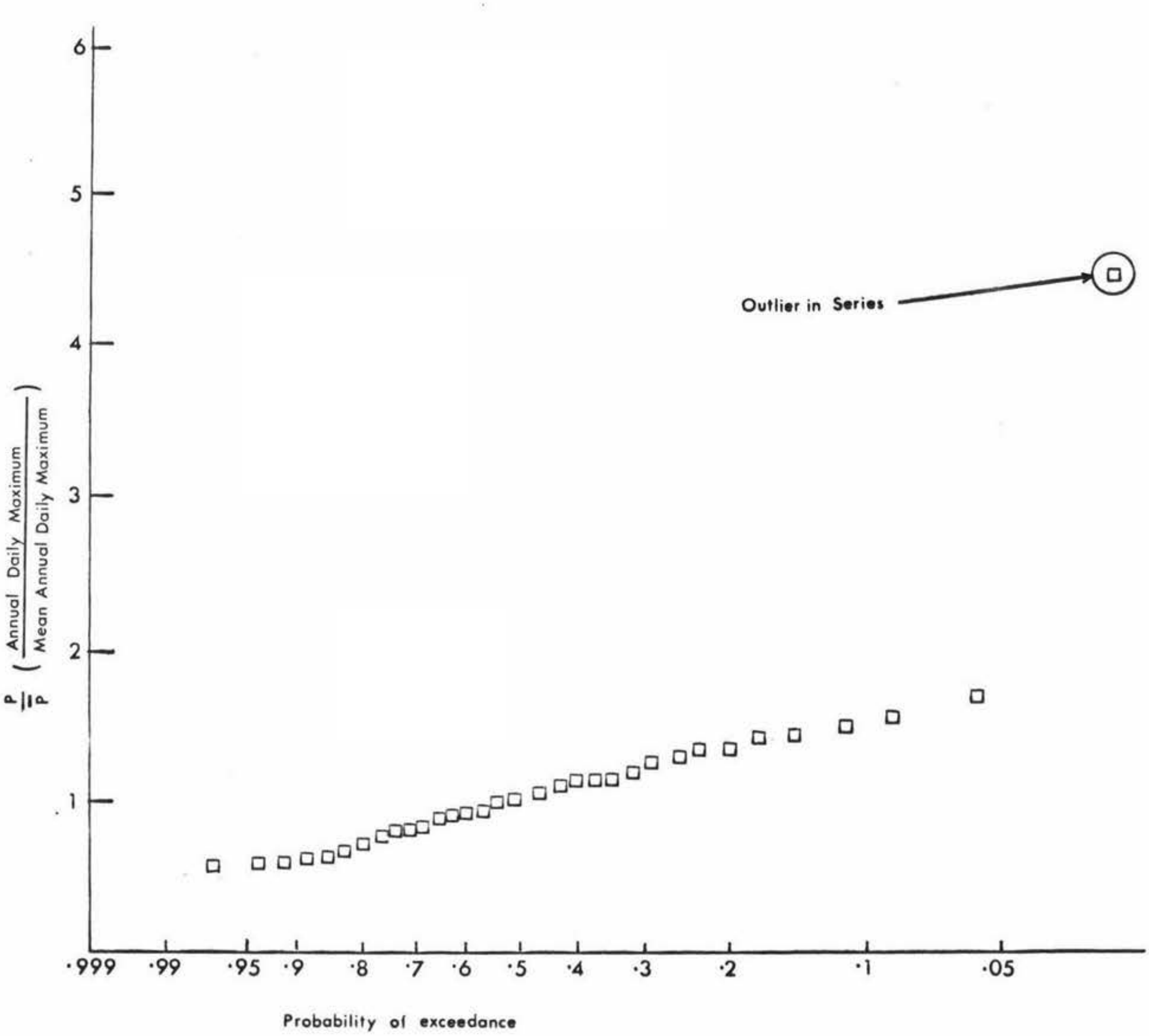


Figure 4.3 : Probability plot of annual daily maxima series for Eskdale (D96483), showing outlier.

4.3 AREAL RAINFALLS

A conventional standard rain-gauge with its orifice positioned a certain height above ground level, provides an underestimate of the amount of rainfall reaching the ground (Mandeville and Rodda, 1970). Even the most dense catchment network can only but sample a proportion of the total rainfall inputted to the catchment. The usual catchment network suffers more, with large areas not sampled at all. The problem is one of extrapolating point observations to areal catchment estimates.

Area reduction curves developed by the United States Weather Bureau (United States Weather Bureau, 1958), have been widely used to indicate the probability of a particular reduction of rainfall depth with increasing area from a centrally located rainfall gauge. Reduction curves have been calculated for a large number of rainfall durations and return periods. Their application in many parts of New Zealand is unwise due to the strong rainfall gradients resulting from the rugged nature of the country and marked maritime influences.

In areas where it is difficult to establish a satisfactory gauge network some authors have determined rainfall depths from measured runoff and estimated evapotranspiration Wallen (1968) has used this method for mountain- lands in Norway and Sweden and Jowett and Thompson (1977) and Brash and Murray (1978) for New Zealand. This approach has benefits in determining rainfall character for some of the study catchments, but relies to a degree on stream flow measurements and so was not used, as one of the principal aims of the study was determination of sediment yield from catchments with no flow gaugings.

Techniques that have been effective for areal integration from direct point rainfall measurement include objective procedures such as arithmetic means and Thiessen polygons and subjective drawing of isohyets or percentiles.

The Thiessen method assumes that the rainfall depth at any station can be applied halfway to the adjacent station in any direction. It is applied by construction of a polygon network, each polygon being formed by the perpendicular bisectors of lines adjoining adjacent stations. The proportional area of each polygon to the catchment area is determined and is used to weight the rainfall depth of the station in the centre of the polygon. Summing of the weighted polygons, gives the catchment total.

Arithmetic mean and Thiessen procedures imply that there can be a juxtaposition of similar amounts of rainfall and as such should not be used where there are marked rainfall gradients. Many of the catchments possess large elevation changes which significantly affect rainfall amounts. For this reason, the arithmetic mean and Thiessen methods were not used.

The isohyetal method, which was chosen for the study, consists of drawing lines of equal rainfall depths using observed depths at stations and any additional factors available to adjust or interpolate between stations. Computation of catchment rainfall characteristics are performed by determination of incremental volumes between adjacent isohyets, adding these incremental amounts and dividing by the total catchment area.

The plotting of isohyets requires careful judgement and several assumptions, for example the effect of relief on the distribution of rainfall. The assertion that rainfall depth generally increases with altitude is well documented and theoretically correct (Grant, 1969; Hurnard and Coulter 1979; Hessell, 1982). To be consistent with the observations available, isohyets in mountainous areas should be made strongly dependent on altitude. What must always be kept in mind though, is that information on rainfall in mountainous areas is sparse.

The most comprehensive country-wide isohyetal map (with isohyets dependent on altitude), reflected by the largest data set, is that of mean annual rainfall published as 'NZMS 19' (N.Z. Met. S., 1973). The eight maps in this series were considered acceptable for use, as there was no reason to suspect that topographic factors influencing mean annual rainfall, were spatially inconsistent in their effect on the gamma statistic, or that of intense rainfall events.

The various rainfall variables identified in Chapter 4 (with the exception of the twenty-four hour five-year return period rainfall), were plotted on catchment maps upon which the isohyets of 'NZMS 19' had been drawn. Each gauge value was assigned a certain isohyetal boundary, the area within which was determined by planimetry. The sum of the proportions of the particular isohyetal areas, multiplied by their respective gauge values, gave a mean catchment value. Mean catchment values so determined are shown in Table 4.1.

<u>Error</u>

Errors involved in point rainfall measurement at sites with long term records are low, generally no more than ±5 percent. Gauges with shorter records may show inconsistencies to adjacent long term gauges (due to natural climatic variation), in the order of ±10 percent. The greatest error involved though is in extrapolation of point samples to areal values. Some catchments possessed gauges with short or inconsistent records which would not give reliable catchment means, while others were in mountainous areas with strong rainfall gradients inadequately defined. In particular, the derivation of an average catchment twenty-four hour 5-year return period rainfall may have errors in the order of ±50 percent for small mountain catchments, due to the sparsity of gauges on which the isohyets have been defined and the scale of the map used. As yet no high country rain-gauge network has been established to accurately determine errors involved in the areal extrapolation of point rainfalls. Subjective judgement was therefore used to decide whether an adequate network of gauges existed for a catchment, to reasonably describe its rainfall characteristics. If the gauge network was considered inadequate to give a reliable areal value then the catchment was excluded. Wairau at Dip Flat (60114) was excluded for this reason.

CHAPTER 5

PREDICTION

5.1 CORRELATION AND REGRESSION ANALYSIS

Correlation and regression is a commonly employed method of analysis of process-response systems (Chorley and Kennedy, 1971). For a bivariate distribution the regression method holds fixed a variable at certain values and examines the distribution of another. Correlation does not restrict either of the variables, concerning itself solely with the joint variation of the two values (Riggs, 1969). The end-product of regression is an equation which predicts a response or value for y, for individual values of x. The end-product of correlation is the correlation coefficient, a measure of the degree of association between the two variables.

Regression analysis requires the following assumptions:

(i) the deviations of the dependent variable (y) for any fixed value of the independent variable (x) about the regression line are normally distributed, the deviation being homoscedastic at different values of x.

(ii) values of the independent variable are attained without measurement errors. As this is impossible, the assumption is one largely of degree.

(iii) values of the dependent variable are mutually independent, that is there is no serial correlation.

(iv) variables exhibit homogeneity, that is all items should have occurred under the same conditions.

In addition correlation theory requires:

(v) that data be drawn randomly from a bivariate normal distribution.

These assumptions were checked for either prior to entering the variables into the regression equation (assumptions (ii), (iii) and (iv), having been satisfied in Chapter 4), or after application of the regression analysis.

Assumption (v) requires that variables be drawn from a normal distribution. As previously stated (Chapter 4), the frequency distribution of annual rainfall in New Zealand can be characterised by a gamma distribution. The extent of the skewness identified by the gamma distribution must be determined before the variable can be entered into the subsequent analysis. Figure 5.1 shows a probability plot of annual rainfall depths against their respective z scores for Waiputaputa Station (D97031), which is characterised by a gamma statistic of 17.7. High correlation of the annual rainfall depths with their respective z scores is consistent with normality of the annual rainfall frequency distribution. The correlation for the station is 0.985 which is not significant at the five percent level (tabled value of 0.964) and therefore normality is assumed. Less than ten percent of the station rainfall frequency distributions used in the study have gamma statistics smaller than 17.7, thus fewer than ten percent will have non-normal distributions. Yevdjevich (1975) suggests that if the distributions are not too asymmetric, then transformation of the x and y variables can give more symmetric distributions and thus provide more reliable statistical inference for the correlation and regression parameters. Logarithmic transformations can be used for this purpose and are employed in this study.

A linear regression line is the best fit line which minimises the sum of the squares of the individual departures of y from that line. Linearity of the model is therefore required for a least-squares solution and logarithmic transformation of the raw data is one way to achieve this. Logarithmic transformations will often ensure that variance of error terms is homoscedastic (Riggs, 1969). For example,

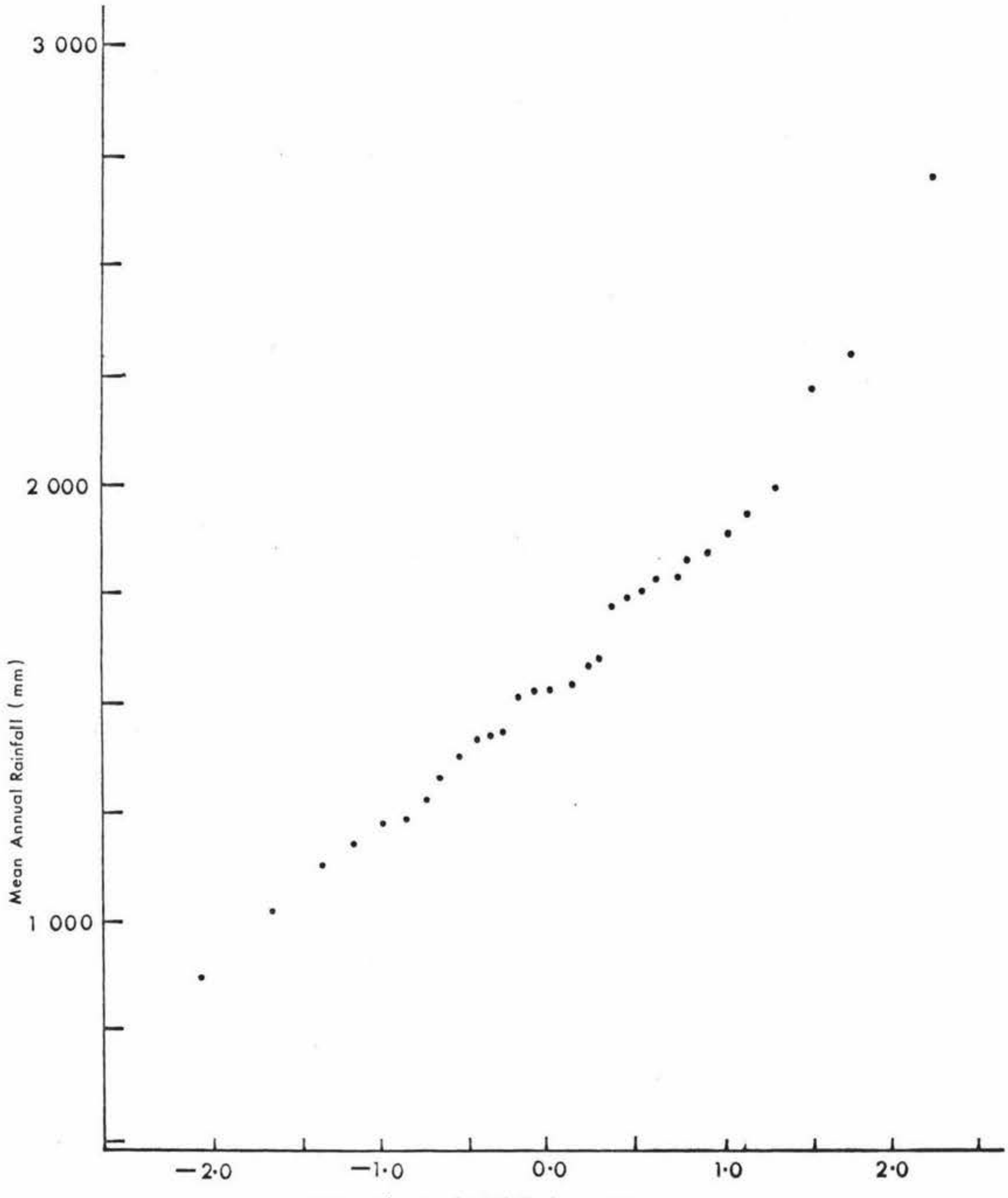


Figure 5.1: Probability plot of annual rainfall totals for Waiputaputa Station (D97031).

Source – N.Z. Met S. Misc. Pub. 110 (1941 – 1980).

a plot of specific suspended sediment yield against 24 hour 5-year return period rainfall is shown in figure 5.2a and the logarithmically transformed data (allowing the fitting of a 'least squares' regression line) in figure 5.2b. Similarly to achieve equal variance about the regression line throughout the range of x values logarithmic transformations have been used; the sediment rating for Tutaekuri River (figure 3.1) is an example.

Discussion so far has focused on a bivariate distribution. Often the response is due to many causes, of which a small number of the causes exert greater influence than do all others (Haan, 1977). Pure functional relationships in hydrology are rare. This study is no exception, and in order to cope with a multivariate system multiple regression techniques are used. While hydrologic knowledge can be used to select a number of variables to be part of the initial regression, the basis for inclusion is essentially statistical (McKerchar and Waugh, 1976).

Although the variables used are deemed to be independent of one another, often several may describe a general condition or factor. This factor may be related to a dependent variable and through the intercorrelation of variables may be entered into a regression model twice (as two different variables). This results in the effect on the dependent variable being divided equally between the two independent variables, leading to a conclusion that the partial regression coefficients have little meaning; a conclusion that is not necessarily correct. It is good practice, therefore to compare the general magnitude and sign of each partial regression coefficient to that which is expected (Thomas and Benson, 1970). Logarithmically transformed values of the catchment variables in Table 4.1 were correlated against one another, the summary of which is shown as a correlation matrix in Table 5.1.

TABLE 5.1: CORRELATION MATRIX FOR LOGARITHMS OF CHARACTERISTICS

	Mean Flow	Mean Annual Flood	10-year Flood	Mean Annual Rainfall	24-hr 5-yr Return Period Rainfall	Coefficient of Variation	Gamma Statistic	Mean Annual Daily Maximum Rainfall	Catchment Area
Mean Flow	-								
Mean Annual Flood	.945	-							
10-Year Flood	.971	.997	-						
Mean Annual Rainfall	.460	.576	.497	-					
24-hour 5-year return period rainfall	.295	.450	.497	.825	-				
Coefficient of variation	-.157	-.100	-.252	-.065	.134	-			
Gamma statistic	.252	.209	.431	.100	-.090	-.925	-		
Mean Annual Daily maximum rainfall	.231	.438	.488	.788	.825	.169	-.131	-	
Catchment area	.877	.823	.828	.115	-.015	-.074	.488	-.083	-
Suspended sediment yield	.344	.489	.579	.618	.626	.215	.254	.593	.173

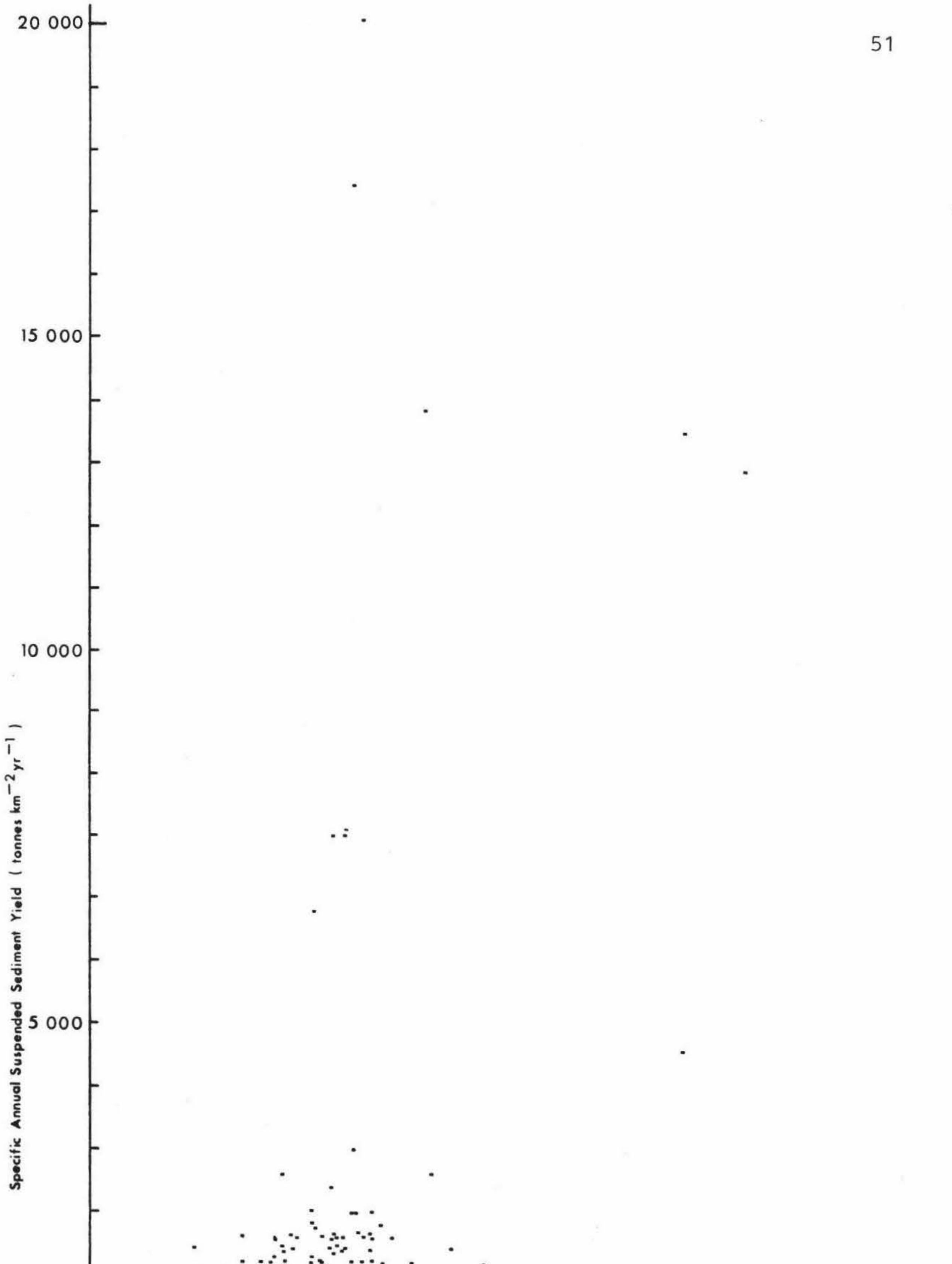


Figure 5.2a: Plot of sediment yield versus rainfall intensity for 81 New Zealand catchments.

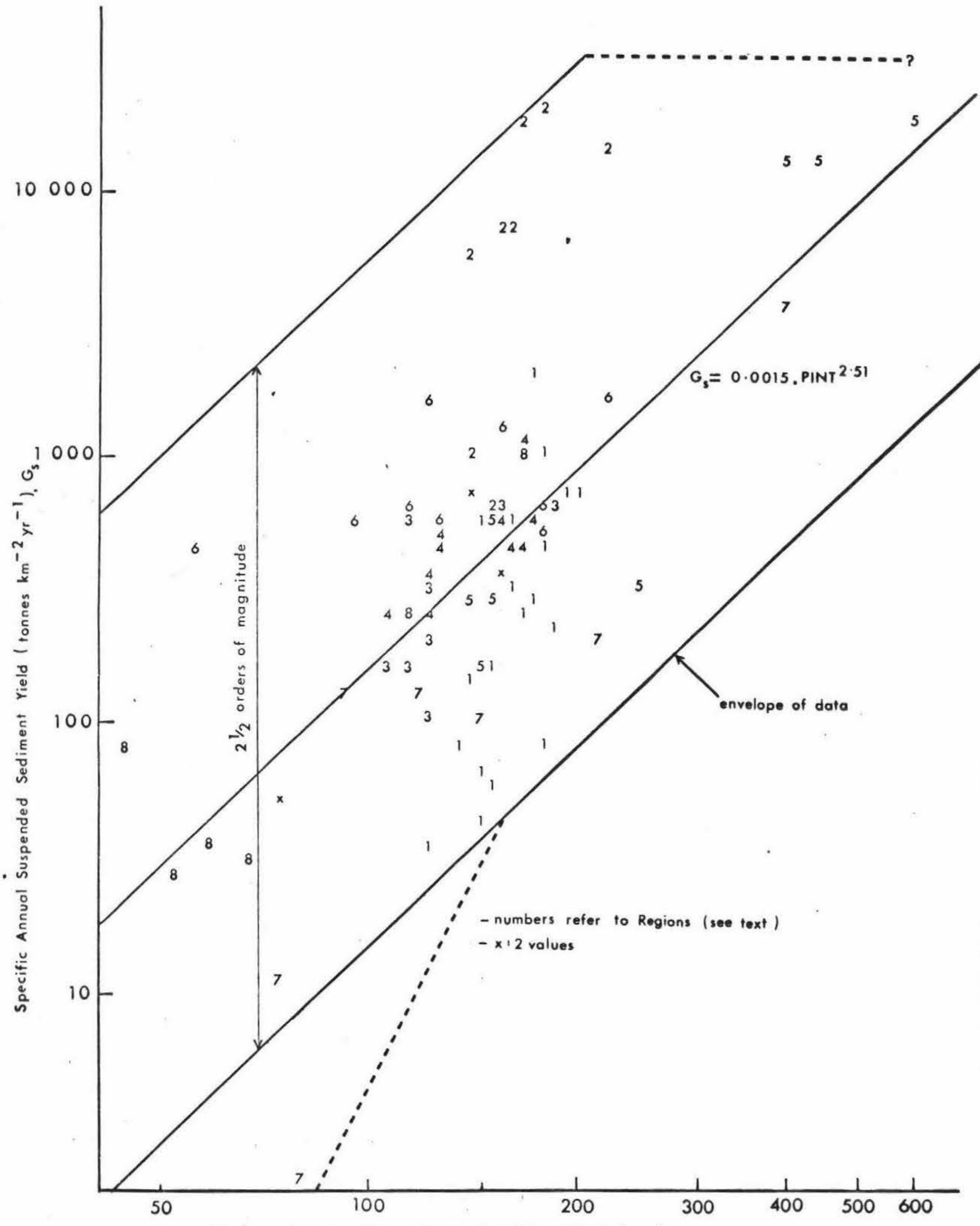


Figure 5.2b: Plot of logarithmically transformed variables of figure 5.2a, suspended yield versus rainfall intensity.

As expected there is substantial correlation between some catchment variables. All flow variables (mean annual flow, mean annual flood and ten-year flood) were highly correlated. The very high correlation of mean annual flood and ten-year flood (correlation coefficient of 997), suggested that only one of these variables need be included in the regression analysis. The correlation was expected as most catchments had too short a flow record for determination of the ten-year return period flood and instead it was determined through equations developed by Beable and McKerchar (1982), which uses mean annual flood as the principal parameter. The ten-year flood value was excluded from all subsequent analysis after it did not add to a significant reduction in the sum of the squares in the initial multiple regression analysis.

The two measures of rainfall variation (coefficient of variation and gamma shape), show strong negative correlation but are largely independent of other rainfall parameters. Mean annual rainfall and 24-hour 5-year return period rainfall show reasonable correlation - a finding discussed more fully later.

Complete independence of variables is not possible because nearly all climatic, hydrologic and topographic variables show some measure of interdependence (Thomas and Benson, 1970). A convenient way to eliminate highly intercorrelated variables (and the method used in the study), is to employ a stepwise linear regression technique. This technique adds new independent variables to the equation in the order that they decrease the standard deviation of the residuals (the observed value minus the expected value). Whether a variable is to be included in the multiple regression depends on the amount by which the standard deviation of the residuals decrease. This procedure rarely includes more than five or six variables in an analysis (McKerchar and Waugh, 1976).

Along with the precipitation variables identified in Chapter 4.2, four other predictors were entered into the equation. Three of these are measures of stream flow, the other catchment area. A stepwise linear regression was applied to both the raw and logarithmically transformed data using the nine predictors:

(i)	QBAR	mean annual flow
(ii)	QMF	mean annual flood
(iii)	QIOF	ten-year flood
(iv)	PBAR	mean annual rainfall
(v)	PINT	24-hour 5-year return period rainfall
(vi)	PMAX	mean annual daily maximum rainfall
(vii)	CV	coefficient of variation
(viii)	GAM	gamma statistic
(ix)	AREA	catchment area

The result was that the logarithmic equation (equation 5.2) provided a better fit than the arithmetic equation (equation 5.1).

$$G_s = -3.62 + 12.8\ PINT - 56.2\ GAM = 1090\ PBAR ...(R^2 = .36) \quad ......(5.1)$$

$$G_s = 148.\ PINT^{.854}.GAM^{-1.21}.PBAR^{1.74} ...(R^2=.48) ..... \ 5.2$$

Equation 5.2 identified PINT as the principal predictor of sediment yield and so it was regressed singularly with sediment yield, for both unlogged and logged data giving equations 5.3 and 5.4.

$$G_s = -2980 + 30.1PINT \qquad (R^2 = .33) ....\ 5.3$$

$$G_s = 1.51 \times 10^{-3}.PINT^{2.51} \quad (R^2 = .39) ....\ 5.4$$

Again the logarithmic equation (equation 5.4) explains more of the variation in specific suspended sediment yield than the arithmetic equation, a conclusion that can also be gained from a study of figures 5.2a and 5.2b.

Any parameter or statistical estimate must be seen as a number ± an error term which when added together, form a range of values for that estimate. Thus the application of a regression model embodies an error term as does the measurement of a parameter. The reliability of the regression equation can be measured by its standard error (the standard error for equation 5.2 is 0.531), which is the standard deviation of the residuals about the regression line. The range estimate for equation 5.2 is thus the standard error of regression ± the absolute errors involved in the determination of the regression equation. Absolute error of the variables identified in the regression equation 5.2 are difficult to determine, due to the lack of absolute standards against which errors may be assessed. The rigour to which these errors are determined, depends on the application to which the calculated sediment yield values are put. For engineering purposes the required accuracy will be influenced by the importance, economics and design life of the proposed structure.

The correlation coeeficient of each of the nine variables used in the regression analysis with suspended sediment yield is shown in Table 5.1. While PINT has the highest correlation coefficient in reference to its relation with suspended sediment yield, the correlation coefficient of PBAR is not much smaller. As mentioned previously the explanation of variability provided by PINT and PBAR cannot be added together because of the strong correlation of the two. The extent of the correlation is such that the use of the two parameters for predicting sediment yield, explains less than five percent more variance than if only one were used.

Nationally the 24-hour 5-year return period rainfall is statistically a slightly better parameter in the explanation of variance than mean annual rainfall identified by Griffiths (1981, 1982). It also provides a starting point for the separation of the amorphous parameter of mean annual rainfall into components that may be responsible for movement of material from the slope subsystem, to the stream channel subsystem.

Equation 5.4 is a national equation encompassing many of the diverse geologies and mesoclimates present in New Zealand. The relationship provided by the equation is shown in figure 5.2b about which is the data envelope, ranging through $2\frac{1}{2}$ orders of magnitude for a given rainfall intensity. Explanation of this wide variation in suspended sediment yield can best be undertaken by a regional treatment of the data.

5.2 REGIONALISATION

The geographic distribution of the residuals from equation 5.2 were mapped and regions were defined on the basis of areas of general over- or under-estimation. Boundaries of the eight suspended sediment yield regions so determined are marked on figure 4.1. Sediment yield regions derived here are in general agreement with those of Griffiths (1981, 1982).

The concept of hydrologic regions is based upon the premise that within areas of hydrologic homogeneity predictor variables correlate strongly with certain dependent variables. Within a region, or even within a basin, there may though be areas with different predictor variables for the dependent variables. Regionalisation is single purpose and may be quite different from a regionalisation derived for another purpose. For example the hydrological regions defined by McKerchar and Waugh (1976) based on similar low flow characteristics, vary from those of Beable and McKerchar (1982) for flood characteristics, which vary from those of Griffiths (1981, 1982) in relation to suspended sediment yields. Division into hydrological regions should thus be seen as approximate and based upon the most important factors of the study purpose (Toebes and Ouryvaez, 1970).

The purpose of the study is prediction of suspended sediment yield based on the characteristics of precipitation. The residuals give some indication of groupings of catchment sediment yields embodying variance related to factors apart from the hydrological characteristics used. For example, Mohaka River is physically located on the east coast of the North Island and possesses rainfall patterns characteristic of the eastern coast. The values of the residuals at its two gauge sites (21801, 21803) suggest that it belongs in the sediment yield region of the Volcanic Plateau - Bay of Plenty (Region 1). Almost the entire catchment of the upper flow gauging station (21803) comprises surface geology of Tertiary mudstones, siltstones and sandstones overlaid with varying thickness of Taupo, Whakatane and Waihi ash (Suggate et. al., 1978) and on geological grounds belongs in Region 1.

Arithmetic and logarithmic stepwise regressions were rerun for each of the sediment yield regions identified above. The result in all cases provided a better estimate of suspended sediment yield than the national equation 5.2 (in terms of improved coefficient of determination (R^2) values and reduction of the standard error), though different predictor variables featured in different regions. Preliminary regional suspended sediment yield equations together with their R^2 values, standard errors and sample sizes are given in Table 5.2.

As there is no selection procedure for results of this kind, both arithmetic and logarithmic results are listed. Application of an arithmetic model assumes that independent variables are additive in their effect on sediment yield, while a logarithmic model suggests that the effects are multiplicative. Consistency, so that comparison can be directly made between regional equations, requires that one model be selected. The R^2 values of Table 5.2 suggest that the logarithmic model gives better results and hence multiplicative effects of the independent variables on sediment yield. However where marked increases in explanation of variance are given by the arithmetic equation in comparison to the logarithmic equation (for example East Coast South Island (Region 6)), there may be a case for the use of the arithmetic model. The relationship of independent variables on the rate of change of the dependent variable need not be the same in every region. Region 6, in contrast to other regions, identifies AREA as the principal predictor variable and this parameter may have a significantly different effect on sediment yields than hydrological considerations.

With the exceptions of Regions 3 and 4, the prediction equations given in Table 5.2 can be considered reasonable though the small sample size means that 'high' and 'low' values can have a significant effect on the construction of the regression line and its associated coefficient of determination. Analysis of the standard residuals of the regional equations identified two outliers: Acheron (62103) in Region 6 (East Coast South Island) and Esk (22802) in Region 4 (Hawkes Bay-Wairarapa).

Acheron River possesses a large negative residual indicating sediment yields significantly lower than those expected. This result was surprising in that the river drains parts of the Bounds and Raglan Ranges, identified as major sediment contributing areas to the neighbouring Wairau River system (Simpson et. al., 1980). The rainfall network in and about the Acheron is reasonably sparse and rainfall totals derived from it may be inaccurate. However, rainfall depth is only revealed as a secondary predictor in the arithmetic sediment yield equation for Region 6, instead explanation should perhaps be sort in reference to factors related to catchment area. No explanation for the underestimation of yield related to these factors could be advanced and the catchment was retained in the equation

TABLE 5.2: PRELIMINARY REGIONAL SPECIFIC ANNUAL SUSPENDED SEDIMENT YIELD PREDICTION EQUATIONS

Region No.	Region Name	Sediment yield Prediction Equation	Coefficient of Determination	Standard Error	Sample Number
1	Volcanic Plateau-Bay of Plenty	$Gs = -1121 + 815\ PBAR$ $Gs = 1.05 \times 10^{-4} PBAR^{3.72} PINT^{2.45}$	.60 .82	288 0.203	21
2	East Cape	$Gs = -24015 + 18443\ PBAR$ $Gs = 2.99 \times 10^{8} PBAR^{6.10} GAM^{-5.09} AREA^{0.24}$	.90 .96	2365 0.117	9
3	Wanganui	$Gs = -363 + 373\ PBAR$ $Gs = 72.44 PBAR^{2.20}$	.50 .57	165 0.135	7
4	Hawkes Bay-Wairarapa	$Gs = -412 + 64$[illegible] $PINT$ $Gs = 213.8\ PBAR^{1.39}$	.33 .48	 0.135	10
5	West Coast	$Gs = -7156 + 2752\ PBAR$ $Gs = 8.04\ PBAR^{3.65}$	.97 .94	1751 0.180	10
6	Eastern South Island	$Gs = 211 + 0.328\ AREA + 193\ PBAR$ $Gs = 257.04\ PBAR^{0.7} AREA^{.121}$	.97 .85	94 0.088	9
7	Waitaki	$Gs = -909 + 640\ PBAR$ $Gs = 0.65 PBAR^{2.99} AREA^{0.62}$	.90 .99	412 0.126	7
8	South South Island	$Gs = -435 + 2.48\ PINT$ $Gs = 0.0019 PINT^{2.48}$	.83 .73	150 0.328	7

- parameters are defined on page 54

due to the high correlation coefficient exhibited, despite the presence of the outlier.

Esk River plotted as an outlier in Region 4 possessing higher sediment loads than precicted. Griffiths (1982) also found it to be an outlier in his regional equation, advancing the reason that the catchment experienced higher rainfall intensities than the surrounding area. The fact that this catchment still plots as an outlier in an equation which includes as the principal explanatory variable a measure of rainfall intensity, suggests Griffiths explanation is not acceptable for rainfall intensities with low to moderate return periods. Scrutiny of Table 4.1 shows that 24-hour 5-year return period rainfall (PINT) and mean annual daily maximum rainfall (PMAX) are no higher than other catchments in the region. For a possible explanation reference can be made to the sediment yield model (figure 2.1) and the discussion on rare events in Chapter 3. Very heavy rainfalls occurred in the area over the period 23-25 April 1938, resulting in silting of the lower valley to an average depth of one metre, with depths of two metres over a wide area. 'Slipping of the hillsides occurred on a spectacular scale' (Soil Conservation and Rivers Control Council, 1957, 70). The possibility of the gradual reworking of this sediment over a period of many years largely unrelated to the measured precipitation events, suggests that exclusion of this catchment from the regional equation is warranted. The result was an improvement of the coefficient of determination, a large reduction in the standard error and a change in the predictor variable from PINT to PBAR (see Table 5.3).

Final regression equations, together with sample size, coefficient of determination and standard error for each region, are given in Table 5.3. Griffiths (1981) regression equation for Region 8 (South South Island) using the same suspended sediment yield totals has a coefficient of determination of 0.96 and includes a factor of mean annual flood runoff which was not used herein. It is suggested that Griffiths equation, which is included in Table 5.3, be used instead for Region 8 where flow data is available to determine mean annual flood runoff.

TABLE 5.3: FINAL REGIONAL SPECIFIC ANNUAL SUSPENDED SEDIMENT YIELD PREDICTION EQUATIONS

Region No.	Region Name	Sediment Yield Prediction Equation	Sample Number	Coefficient of Determination	Standard Error
1	Volcanic Plateau-Bay of Plenty	$Gs = 1.05 \times 10^{-4} PBAR^{3.72} PINT^{2.45}$	21	.82	0.203
2	East Cape	$Gs = 2.29 \times 10^{8} PBAR^{6.10} GAM^{-5.09} AREA^{0.24}$	9	.96	0.117
3	Wanganui	$Gs = 72.44\ PBAR^{2.20}$	7	.57	0.208
4	Hawkes Bay-Wairarapa	$Gs = 213.80\ PBAR^{1.39}$	10	.65	0.082
5	West Coast	$Gs = 8.04\ PBAR^{3.65}$	10	.94	0.180
6	Eastern South Island	$Gs = 211 + 0.328\ AREA + 193\ PBAR$	9	.97	94
7	Waitaki	$Gs = 0.65 PBAR^{2.99} AREA^{0.62}$	7	.99	0.126
8	South South Island	$Gs = -435 + 7.80\ PINT$ $Gs = 6.31\ PBAR^{8.29} Rmf^{-1.42}$	7	.83 .96	150
3,4, 5,6	Central	$Gs = -1329 + 2136\ PBAR - 44.8\ GAM$	36	.90	1204

- parameters are defined on page 54   Rmf = mean annual flood runoff

CHAPTER 6
DISCUSSION

6.1 PRECIPITATION AND SEDIMENT YIELD

A consequence of the regionalisation procedure is that while the national sediment yield equation suggests that the rainfall intensity variable PINT is the best predictor, regional equations generally identify mean annual rainfall (PBAR) as that predictor. The variation within the envelope of data displayed in figure 5.2b may therefore best be explained by the regional relationships of sediment yield to mean annual rainfall. Figure 6.1 shows plots of suspended sediment yield/PBAR data pairs. Regional sediment yields to a limited extent possess a hierarchical distribution and this is in general accordance with the hierarchical nature of regional PBAR values (probably due to the way in which topography (demarcating the regional boundaries) influences rainfall mechanisms (Hessell, 1982)). PBAR also exhibits a wider range of values (almost an order of magnitude) in comparison to PINT, the wider range of values being more consistent with the widely ranging sediment yields.

In figure 6.1, East Cape (Region 2) has data points far removed from the trend displayed for the rest of the country. Removal of this region from the data set and regression of the remaining values gave the following equation:

$$G_s = 72.PBAR^{2.37} \quad \text{.............................} \quad (6.1)$$

Equation 6.1 improves the coefficient of determination of the national equation (5.2) from 0.48 to 0.57 and also reduces the number of explanatory variables from three to one. The other important result is that equation 6.1 replaces the principal explanatory variable PINT with PBAR, such that it bears relationship to the principal variable

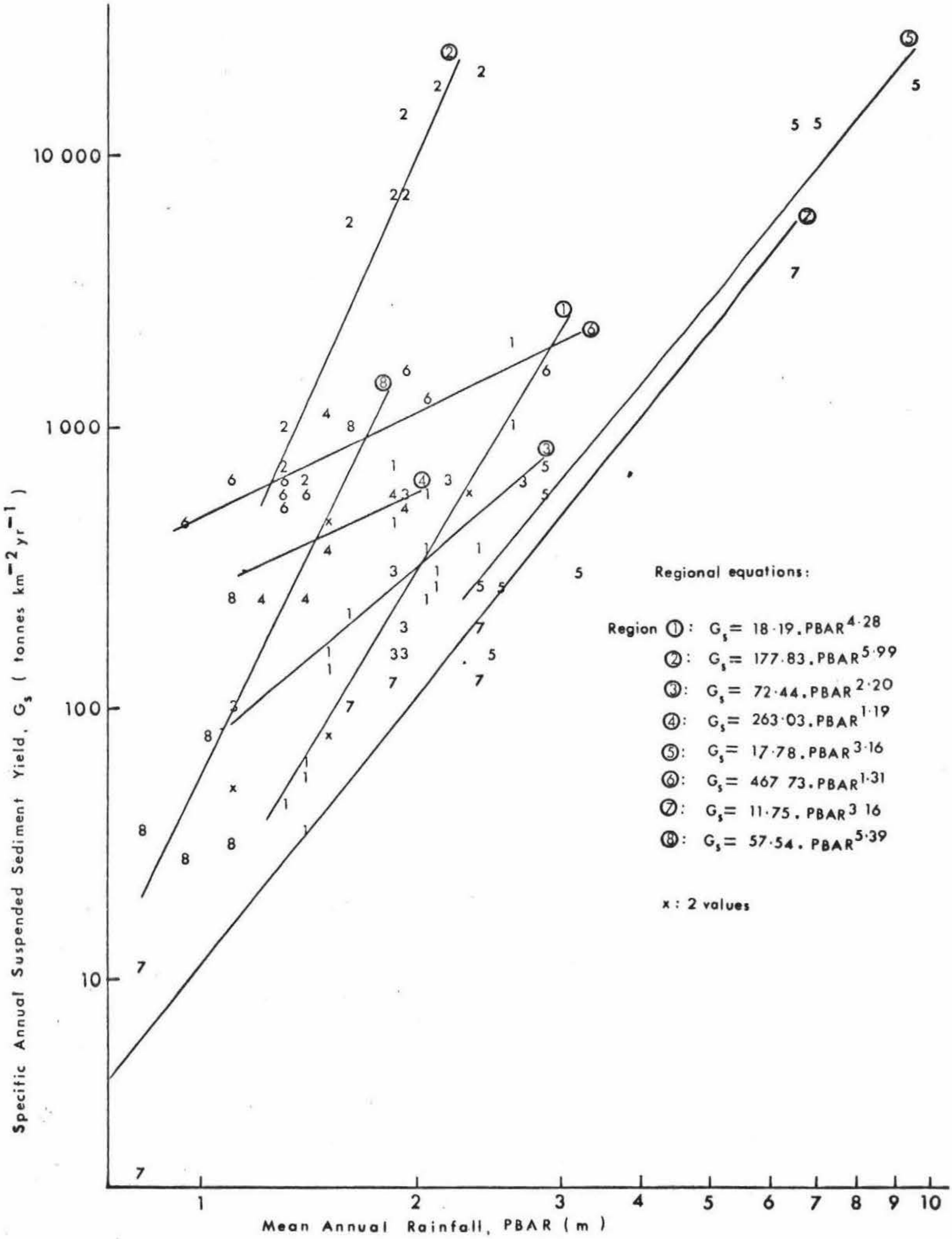


Figure 6.1: Regional plots and equations showing the relationship of sediment yield to mean annual rainfall.

in most of the regional equations.

A simple rank correlation coefficient test was undertaken on the groupings of catchments with the same annual rainfall totals to ascertain whether variation in yield could be explained by variation in intensity. The general conclusion was that sediment yields for a given annual rainfall are largely independent of intensity.

6.2 UNIVERSAL APPLICATIONS

Numerous workers have proposed sometimes conflicting relationships that predict suspended sediment yield as a function of precipitation. Langbein and Schumm (1958), Douglas (1967), Rango (1970), Wilson (1973) have developed curves applicable for particular climate types. Fournier (1960) has presented a universal curve for prediction of suspended sediment yield, which has been verified in part by the other workers, though Wilson (1973) indicates that perhaps no curve is valid on a world-wide basis. None of the above studies have numerous observations drawn from temperate maritime climatic zones which characterises New Zealand.

Equation 6.1 identifies that increases in suspended sediment yields are proportioned to mean annual precipitation raised to the power of 2.37 (Fournier's 'universal' equation suggests the power to be 2.65), though there is wide variation regionally. Fournier's curve does not extend to the high annual rainfall values experienced in parts of New Zealand and so direct extrapolation of the 'universal curve' to these values is one of speculation.

6.3 NATIONAL APPLICATIONS

While sediment yields of New Zealand catchments are generally in accordance with the world trend (Thompson, 1976), there is some tendency for underestimation of yields for given rainfalls. Most notable in this respect is the East Cape region (Region 2), and hence its exclusion from the data set providing equation 6.1.

Explanation of this very large underprediction of sediment yield for Region 2 is required. O'Byrne (1967) argues that lithology plays an important part in the distribution of erosion in this region. Mudstones, argillite, sandstone and shale are the dominant rock types (in decreasing order) in the catchments of Region 2 (Smith, 1974), with the exception of the Hangaroa River (21437) which possesses lower yields. Mass wasting and fluvial slope processes acting on the regolith of these rock types result in soft, generally fine material being delivered to the channel subsystem. Sorting and the important processes of trituration and abrasion result in a large proportion of the fine sediment transported in suspension (Griffiths, 1982). Unstable channels, caused by aggradation of the channel bed and soft channel banks allow the rivers to migrate across their floodplains, entraining further fine material. Geology is thus important in this region and Griffiths (1982) suggests that the addition of a bedmaterial size component into the sediment yield equation, such as that proposed by White et. al. (1976), may enable the construction of a more reliable national equation incorporating this region.

It is possible that for the highest yielding catchments in this region, the amount of sediment transported may not be limited by the rate of supply of the material, but by the transport capacity of the river. The system may be operating at a maximum, an idea which has been proposed by Jowett (1979) who suggests an upper limiting sediment concentration from his observations on the Tongariro and Clutha Rivers. Figure 6.2 reveals a levelling off of sediment yield values towards a 'limiting yield' at higher mean annual rainfalls for the region, though this assumption is made on few data points.

Campbell (1962) has suggested the use of suspended sediment measurements in the study of catchment conditions. Bauer and Tille (1967) have studied variations in the constants of the simple suspended sediment rating curve, that is:

$$\log Q_s = \log a + b \log Q$$

where

Q_s : suspended sediment discharge
Q : stream discharge
a,b : rating curve constants

They found that 'b' (the rating slope) was related to mean annual discharge, while the parameter 'a' (the y intercept) was associated with geological contrasts. Application of the general sediment yield prediction equation used in this study is of the form:

$$\log G_s = \log a + b \log PBAR$$

where G_s (specific annual suspended sediment yield) replaces suspended sediment discharge and PBAR (mean annual rainfall) replaces mean annual discharge. Table 6.1 lists the values of 'a' and 'b' derived for each region from the regression lines of figure 6.1. Coefficient 'a' has been termed the catchment condition index, for it represents factors of sediment yield not directly related to rainfall, but rather to the physical condition of the catchment. Coefficient 'b' has been termed the rainfall influence index which reflects the rate of increase of sediment yield to increasing mean annual rainfall.

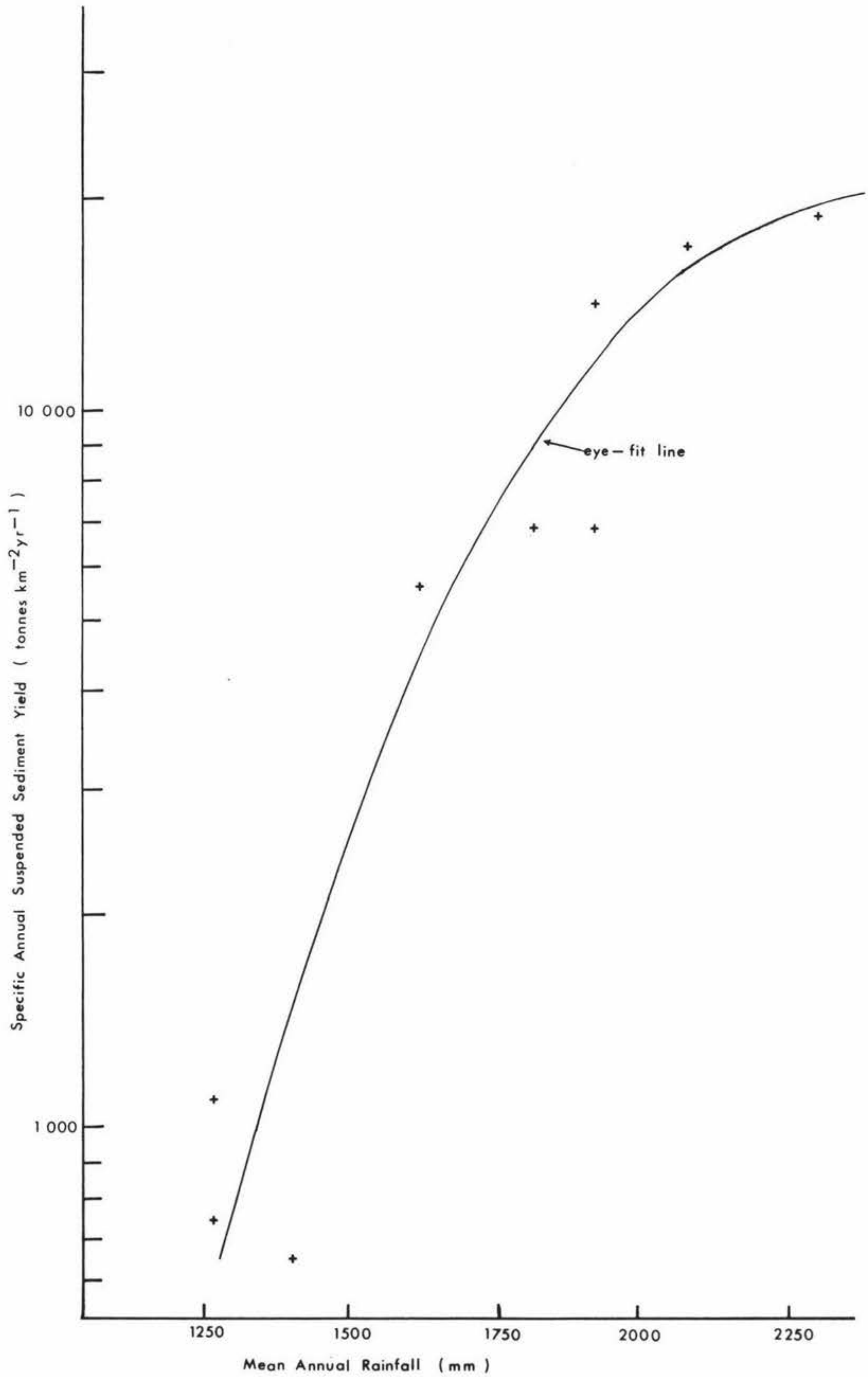


Figure 6.2: Plot of sediment yield versus mean annual rainfall for Region 2 (East Cape), showing tendency towards a limiting yield.

TABLE 6.1: VALUES OF REGIONAL REGRESSION LINE COEFFICIENTS INDICATING CATCHMENT CONDITION AND RAINFALL INFLUENCE INDEXES

Value of 'a' catchment condition index		Region number	Region name	Region	Value of 'b' rainfall influence index	
poor	467.73	6	East Coast South Island	4	1.19	low
	263.03	4	Hawkes Bay-Wairarapa	6	1.31	
	177.83	2	East Cape	3	2.20	
	72.44	3	Wanganui-Taranaki	5	2.20	
	57.54	8	South South Island	7	3.16	
	18.19	1	Volcanic Plateau-Bay of Plenty	1	4.28	
	17.78	5	West Coast South Island	8	5.39	
good	11.75	7	Waitaki	2	5.99	high

It is preferable that the values of the East Coast South Island (Region 6) are ignored, due to the fact that in figure 6.1 it plots discordantly with the general trend. While concern is with prediction of specific yield (that is yield/km^2) and therefore catchment area should have little influence, the principal predictor in this region is identified as AREA (see Table 5.3), with rainfall characteristics only providing secondary explanation of variance. Within this region are three very large catchments in which rainfall is an insensitive parameter which may account for the demotion of rainfall variables to secondary predictors.

From Table 6.1, West Coast South Island (Region 5) and the high country catchments of the Waitaki River system (Region 7), possess the best catchment condition index with moderate to low rainfall influence index. Region 5 in actual terms, because of the very high rainfall, contains some catchments with specific yields as high as any in the study, yet exhibits a good catchment condition index. The catchments in general have extensive forest cover and the high rainfall ensures that little sediment is stored in the channel subsystem. The response to rainfall is therefore 'true' in that the depth of rainfall strongly influences the amount of material removed from the slope subsystem and transported through the channel subsystem (there is a high coefficient of determination for the single predictor variable PBAR - Table 5.3). Storage components of the sediment yield model play little part in this region.

In contrast to West Coast South Island (Region 5), Waitaki (Region 7) contains extensive areas of unvegetated slopes commonly mantled with scree. The catchments are still in good condition in that the nature of the regolith (generally schist scree) is too coarse for transport in suspension. This, along with the generally low annual rainfall, produces a low volume of sediment for transport in suspension. An exception is the Hooker (71125) which experiences very intense rainfall events and a high mean annual rainfall. As a consequence, there is a greater competence to move the coarser material through the channel, reflecting the catchment's high suspended sediment yield. It is important to realise that the catchment condition index refers to suspended load. A different condition could, and for Region 7 should, be expected with reference to bedload yields which account for transport of the coarser fractions.

Volcanic Plateau - Bay of Plenty (Region 1) also possesses good catchment condition but has a higher rainfall influence index. Again geology may be important in that for small- to moderate-sized rainfall events the permeability of the volcanic rocks results in much smaller hydrograph volumes than would be expected in other regions (Schouten et. al., 1981). For high magnitude storms runoff becomes more direct and causes a greater volume of sediment per volume of stream flow, than would be suggested by extrapolation of small storm events. The result is a steep rating curve.

Those regions with poor catchment conditions, reflected in high indexes, are East Cape (Region 2), Wanganui-Taranaki (Region 3), Hawkes Bay-Wairarapa (Region 4), all with rivers draining lithologies comprising finer sediments which are more easily transported in suspension.

Hawkes Bay-Wairarapa (Region 4) plots discordantly with the general trend in figure 6.1. The relationship between specific yield and mean annual rainfall is weak (coefficient of determination of 0.16). There is considerable evidence though to suggest that catchment conditions are poor, in that there is widespread high country erosion causing problems of aggradation downstream (Mosley, 1977; Hawkes Bay Catchment Board, 1980). The storage components of the channel subsystem may be considerable. Mosley (1977) for example has found that in the upper reaches of the

Kumeti and Tamaki Rivers in the southeastern Ruahines, the volume of stored sediment was 10-40 times the estimated mean annual supply of sediment. The sediment delivery ratio (Chapter 2) in this instance is low and demonstrates the limitation of trying to measure erosion rates from sediment yield measurements.

The situation as regards East Cape (Region 2) has already been discussed, but consideration of the magnitude of the rainfall influence index (rates of sediment yield increase in excess of the sixth power of mean and rainfall) should be commented upon. Fluvial erosion by redissection and slopewash provides a small quantity of the total sediment supplied to the channel, in comparison to mass wasting (Gage and Black, 1979). Only small rainfall inputs are needed to activate quite large mass movements, especially when they are added to high antecedent soil moisture conditions. This type of activation of mass movement combined with the processes previously discussed, are possible reasons for the strong influence moderate precipitation events have on sediment yields in this region.

Some limitations of this approach can be seen with the data set of South South Island (Region 8). Figure 6.1 shows the regression line and the data points to which the line was fitted. The sample set is small (seven values) and one value (Shotover at Bowens Peak (75276)), exerts great influence both on the slope of the regression line (hence 'b' the rainfall ifnluence index) and the coefficient of determination. Many of the regions possess similarly small sample sizes so caution must be applied in conclusions from the ratings.

The discussion of the regional values of the constants in the regression equations has been a generalised one. It has however, highlighted other variables, particularly geology, which are important in the differences of regional sediment yield response to rainfall inputs.

To widen the scope of applicability of the yield equations, their use in glaciated catchments was investigated. Within the study there were several catchments which possessed glaciers (for example the Hooker (71125) and Jollie (71135)). The Hooker has in excess of fifty percent of its catchment under permanent ice, yet it fits the prediction equation of Region 7 well. Robinson (1981) has determined that for Ivory Glacier catchment with an area of 2.2 km^2 and mean annual rainfall of 10,500mm, specific suspended sediment yields are in the order of 13,000 to 23,000 tonnes km^{-2} yr^{-1}. Substitution of the rainfall and area values into the predictive equation for Region 7 (Table 5.3) gives a suspended sediment yield prediction of 14,000 tonnes km^{-2} yr^{-1}, within the range proposed. This suggests that yields from glaciated and non-glaciated catchments at present are similar and that the predictive equation is applicable for both fluvial and glaciofluvial processes.

Some justification on physical grounds has been provided for the division into sediment yield regions. The statistical applicability of the regional approach was investigated by analysis of variance. Regions have been defined on a certain characteristic (the magnitude and sign of the standard residuals from the national equation 5.2) and strictly speaking are not random samples. The purpose here is to investigate the possibility of particular sediment groupings which due to their 'geography' have been separated into different regions, in other words testing the arbitrayness of the method.

Analysis of variance defines on F ratio, which is the ratio of the mean sum of the squares among groups to the mean sum of the squares within groups. If the ratio of the between group variation to the variation within group falls below a certain value then it can be said that the groups do not statistically differ and that they are drawn from the same population.

Analysis of variance of the suspended sediment yields of the eight regions identified in Chapter 5.2 gave an F ratio of F = 8.37. The resultant analysis of variance table is given in figure 6.3 as well as the tabled value at the one percent level, of 2.91 (Snedecor and Cochrane, 1967). As the test statistic (8.37) is greater that the tabled value (2.91), there is a significant difference between at least two of the regions. Observation of:

(i) the regional means and their corresponding confidence intervals exhibited in figure 6.3

(ii) the map of the standardised residuals of the national yield equation as to their magnitude and homogeneity

suggested that the country could be divided into four areas. Waitaki (Region 7) and South South Island (Region 8) were shown in the analysis of variance to possess the 'same' mean and standard deviation and could be considered as a joint area. East Cape (Region 2) was also deemed distinctive. Investigation of the positioning of the mean sediment yield value and associated standard deviation of the remaining regions in the analysis of variance table, suggested that the Volcanic Plateau - Bay of Plenty could also be isolated as distinctive from the other areas. A fourth area combining Wanganui-Taranaki (Region 3), Hawkes Bay-Wairarapa (Region 4), West Coast South Island (Region 5) and East Coast South Island was proposed. An analysis of variance on the four regions comprising the combined area (hereafter named Central) gave an F ratio of F = 1.66. As the tabled value at the one percent level is 4.44 and the five percent level 2.89, there is statistical justification in accepting the combined area Central. Linear stepwise regression was performed on Central giving the following arithmetic and logarithmic equations:

$$G_s = -1329 + 2136 \text{ PBAR} - 44.8 \text{ GAM} \quad \ldots.(R^2 = .90)..(6.2)$$

$$G_s = 7586 - \text{PINT}^{0.43}.\text{GAM}^{-1.59}.\text{PBAR}^{1.18} \quad ..(R^2 = .74).(6.3)$$

ANALYSIS OF VARIANCE

Due to	Degrees of Freedom	Sum of Squares	Mean Sum of Squares	F-Ratio: 8.37
Factor	7	19.61	2.80	Tabled value:
Error	72	24.10	0.34	2.91
Total	79	43.71		at the 1% level

	Region	Mean	Standard deviation	Sample Size
1	Volcanic Plateau-Bay of Plenty	2.301	0.478	20
2	East Cape	3.645	0.599	9
3	Wanganui-Taranaki	2.456	0.315	8
4	Hawkes Bay-Wairarapa	2.659	0.187	10
5	West Coast South Island	2.937	0.895	10
6	East Coast South Island	2.892	0.226	9
7	Waitaki	1.911	1.021	7
8	South South Island	1.930	0.576	7

Individual 95 percent confidence intervals for Regional means (●):

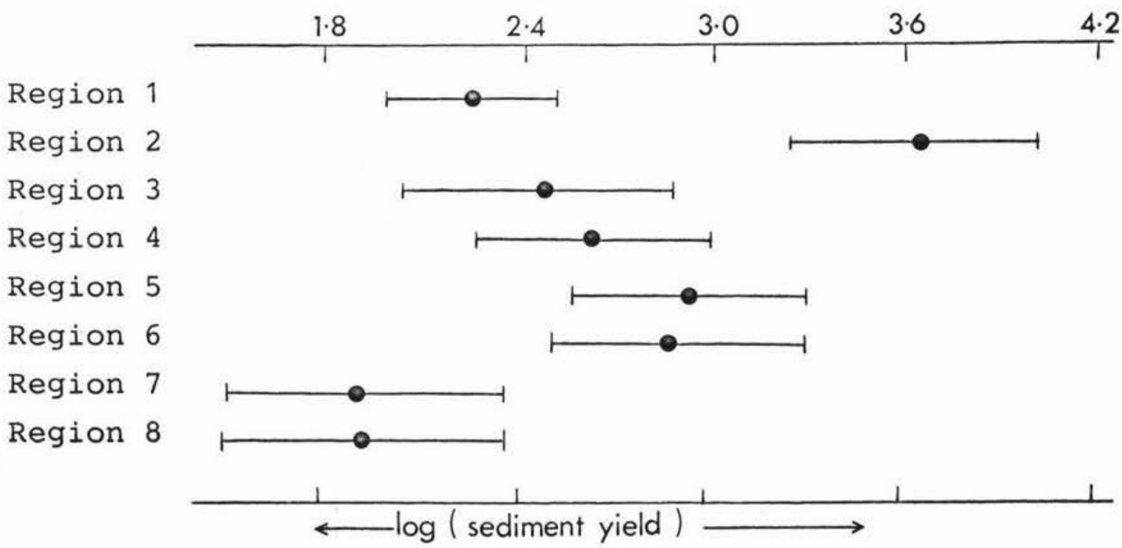


FIGURE 6.3: ANALYSIS OF VARIANCE TABLE FOR THE 8 SEDIMENT YIELD REGIONS.

Equation 6.2 possesses a coefficient of determination of 0.90 and considering the wide range of basin size, surface geology, topography and land use reflected in the region, the explanation of variation in suspended yield by the measurement of rainfall depth (mean annual rainfall) and its year to year variation (gamma statistic), is encouraging.

The absence of a rainfall intensity parameter in equation 6.2, the occurrence of PINT as secondary predictor variable in only a few of the regional equations and the outcome of the rank test performed in Chapter 6.1, suggest that the measures of rainfall intensity (mean annual daily maximum and 24-hour 5-year return period rainfall) do not significantly influence the spatial distribution of specific suspended sediment yield. Mean annual rainfall therefore seems to be the dominant control in the spatial distribution of sediment yield.

The temporal variability of mean annual rainfall is described by the frequency, intensity, duration and variation of rainfall events. Harvey (1977) in a study of a small upland catchment in Cumbria, England, proposes that sediment production events occur on average thirty times a year and are strongly controlled by rainfall events. An analysis of storm frequency is needed to verify this assumption. Revfeim (K.J. Revfeim, N.Z. Met. S., pers. comm.) is currently developing a method to estimate rates of occurrence of 'intense' rainfall events, which McSaveney (1978) sees as the real sediment production events. The model being developed is based on an implied underlying rainfall process of irregular occurrences and varying amounts allowing for small sample estimates of maximum amounts and recurrence times. Initial findings suggest that at Kelburn the rate of occurrence of intense rainfall events is twenty-five 24-hour events and twenty 48-hour events[1] per year, which is similar to the number of events suggested by Harvey (1977). As yet the model has not been tested for other

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1 Some of the 24-hour events will be included in the 48-hour event tally

sites, but if it has national application then it may provide a direct measure of storm frequency. The relationship of storm frequency to specific yields can then be explored and application to ungauged rivers undertaken, which was not possible in the work of Griffiths (1981, 1982) as he measured storm frequency through the stream flow record.

Equation 6.2 identifies the gamma statistic (a measure of rainfall variability) as a predictor in explaining variation in sediment yield. It is notable that the other measure of rainfall variation used in the regression analysis (coefficient of variation) is not significant in any of the predictive equations. Harlin (1978) found that rainfall variability expressed by the coefficient of variation, was a major influence in his study of resevoir sedimentation in the United States. New Zealand in comparison to the United States, does not possess such a marked range for this statistic, due to the strong maritime influences which result in the lowest rainfall areas still receiving above 400mm annual rainfall (N.Z. Met. S., 1973). A measure of rainfall variability is still however important in describing differences in sediment yields through the country, and in combination with the principal predictor, mean annual rainfall, supports Fournier's (1960) equation. His index of climate p^2/P (p: rainfall in wettest month, P: mean annual rainfall) reflects seasonality as well as absolute depth of precipitation. Equation 6.2 reveals that as gamma decreases so the sediment yields increase. Rainfall variation, as reflected in the gamma values, are not significantly marked in New Zealand to propose that low gamma values reflect poor vegetation cover as in other studies (for example Harlin 1978, 1980), due to the absence of very low rainfall areas. Rather, the gamma statistic can be seen as representing disequilibrium in the system, caused by wide fluctuations of inputs about the mean value for which the system is 'tuned'.

The evidence suggests then, that the effect of rainfall variability on sediment yields as with other rainfall characteristics comprising mean annual rainfall, cannot be adequately determined at the scale used here. Consequently much more intensive measurement at greatly reduced scales would seem to be the only way to provide such information.

CHAPTER 7

CONCLUSION

Specific annual suspended sediment yields have been calculated for 82 drainage basins throughout New Zealand. The data set samples catchments of widely different size, climate, topography and geology, though there are areas that were not sampled (Northland) and poorly sampled (Southland, Nelson, Marlborough, Manawatu-Horowhenua) due to short record lengths or poor sediment ratings.

The greatest contribution to error in the determination of suspended yield was the inadequate sampling of the temporal variability in sediment yield upon which the sediment rating was derived. In this report, it is concluded that there is little need generally to measure discharges below mean flow as they transport such a small part of total suspended sediment load. Instead, resources should be concentrated toward measurements at discharges in excess of mean flow and during the rising stage of the storm hydrograph. In some regions channel storage of material greatly exceeds annual export and the movement of material from these stores only occurs at times of high flows (flows occurring once every 1-5 years), which stresses the importance of longer periods of record to adequately sample these events. The amount of material held in storage in some catchments implies that it is not good practice to predict erosion rates from sediment yield measurements alone.

Rainfall has been identified as an important influence on suspended sediment yields in many studies. The principal aim was to provide a method of predicting sediment yields for areas with poor or no stream gaugings, so choice of rainfall characteristics were directed towards those easily measured and widely available. Length of record period and large sample size suggested the use of the wide network of daily storage gauges throughout the country. Consequently the rainfall parameters used are limited to the least-period sample of one day which cannot provide for an in-depth study of the effect of rainfall on sediment yield in a temporal sense.

In order to cope with the many variables that were considered to affect sediment yield, the desire to eliminate highly intercorrelated variables and the computing packages available, stepwise linear regression was used. The result was a reasonably poor national equation identifying 24-hour 5-year return period rainfall as the best predictor of sediment yield. The explanation provided by 24-hour 5-year return period rainfall had only a slightly better coefficient of determination than mean annual rainfall. These two values were strongly correlated nationally, in that use of both variables in the regression equation adds only a five percent increase to the explanation in sediment yield variation than if only one were used. Analysis of sediment yield/annual rainfall plots revealed that the catchments of the East Cape region (Region 2) plotted discordantly from the general trend. Upon exclusion of this region, prediction was improved and the principal predictor became mean annual rainfall.

Sediment yields range through four orders of magnitude, while 24-hour 5-~~hour~~ year return period rainfall possesses a very narrow range of values. In comparison, mean annual rainfall varies through a wider range (one order of magnitude) and to some extent possesses a regional hierarchical nature (due to the controls of gross regional topography affecting rainfall mechanisms), in accordance with a regional hierarchy displayed by sediment yield. The regional hierarchy of sediment yield could not be fully explained by rainfall characteristics and evidence has been given to suggest the influence of geology on this phenomenon.

Regionalisation on the basis of inspection of the sign, magnitude and homogeneity of the standardised residuals of the national equation (equation 5.2) yielded eight regions. In all but one of the regions, rainfall elements were identified as the principal explanatory variable. East Coast South Island (Region 6) was the exception, with catchment size as the predictor variable, for within this region are three large drainage basins with insensitive rainfall paramaters due to large variations across the catchment. The regional equations resulted in considerable improvement in the coefficient of determination and reduction of the standard error. However the small sample size meant that in some cases very high or very low sediment yield values had a great influence on the slope and coefficient of determination of the regional equations. The small sample size in some cases, also combined with the number of predictor variables to give high coefficients of determination which may be unrealistic due to the reduction in the degrees of freedom, associated with the determination of that coefficient from the regression analysis. This consideration lead to the combination of four regions into one. A predictive equation was developed for the combined area which indicated that 90 percent of the variance in sediment yield was related to two variables, mean annual rainfall and gamma statistic. These parameters support contentions by overseas workers who see world wide sediment yields as primarily controlled by depth of rainfall and its variability. Considering the wide variation in many factors between catchments in the combined area, the result is encouraging towards production of a national equation.

To this end it is suggested that incorporation of a bed-material size variable into the predictive equation will allow for inclusion of the East Cape region (Region 2) and the Waitaki region (Region 7). Region 7 posseses an abundance of coarse material and in general its yields are over-estimated by the national equation for low mean annual rainfalls. Region 2 conversely possesses an abundance of fine materials and application of the national sediment yield equation gives large under-estimates for a given rainfall.

It is proposed in Region 2 that the amount of material in storage reflects limits on sediment yield controlled by a limiting transport capacity, rather than rate of supply of material. This is in contrast to the general assumption that sediment yields carried by a river are generally limited by the amount of material supplied to the river and not by its competence to transport it. The situation in this region suggests that some of the rivers may be transporting maximum sediment loadings.

The study also proposes the use of the constants 'a' (intercept) and 'b' (slope) of the regional regression lines of sediment yield verses mean annual rainfall, to determine 'catchment condition' and 'influence of rainfall' respectively. Catchment condition indexes suggest that the poorest catchments are those of East Cape, Hawkes Bay-Wairarapa and Wanganui-Taranaki, all regions of lithologies yielding finer material readily transportable in suspension. Catchments in the best condition are to be found in the West Coast, Waitaki and Volcanic Plateau-Bay of Plenty regions. The corrollary of this is that rainfall depth and vegetation condition are not of prime importance in determination of catchment condition, rather the quantity of material in storage, capable of being transported as suspended load, is the most important factor. However catchment condition defined with respect to bedload is likely to have a different outcome.

Investigation of the regression slope is also warranted, for in the study it varies through at least three and a half orders of magnitude. Again geology is suggested as important in the regional variations. The very steep slope of Region 2 (rates of sediment yield increase in excess of the sixth power to mean and annual rainfall), may be due to the effect that small rainfall inputs have in triggering mass movements which are the major source of sediment supply to the channels.

The predictive equation derived for region 7 has been shown to be aplicable to catchments primarily controlled by glacial processes and suggests that present rates of fluvial and glaciofluvial erosion may be similar.

The investigation has revealed that the dominant controlling factor in the spatial variability of suspended sediment yield in New Zealand is total rainfall depth, with catchment intensity, gamma statistic (a measure of rainfall variability) and catchment area being secondarily important. There is a tendency towards a regional hierarchy of sediment yield related in part to the hierarchical distribution of mean annual rainfall but also to geological considerations. Given that generally predictable relationships now hold for spatial variability of sediment yield related to annual rainfall, investigation should be directed toward the temporal variability of sediment yield. Analysis of the temporal variability of sediment yield requires investigation of the components of mean annual rainfall (intensity, frequency, duration and variation of events) at the catchment level. At this level the nature of rainfall on suspended sediment yield can be better understood and may in turn allow development of a national sediment yield model.

APPENDIX

SUSPENDED SEDIMENT YIELDS OF NEW ZEALAND RIVERS BY OTHER WORKERS, GIVEN BY REGIONS:

REGION 1 (Volcanic Plateau - Bay of Plenty):

Hoare (1978) for tributaries feeding Lake Rotorua

Collander and Duder (1977) for Rangitaiki River

Schouten, Terzaghi and Gordon (1981) for Lake Taupo tributaries

REGION 2 (East Cape):

Jones and Howie (1970) for Waipaoa River

REGION 3 (Wanganui - Taranaki):

Rangitikei-Wanganui Catchment Board and Regional Water Board (1978) for Wanganui River

Rangitikei-Wanganui Catchment Board and Regional Board (1980) for Rangitikei River

REGION 4 (Hawkes Bay - Wairarapa):

Curry (1981) for Pauatahanui Stream

Mosley (1977, 1978) for rivers draining the south-eastern Ruahine Range

Cunningham (1978) for rivers draining the eastern flanks of the Ruahine and Tararua Ranges

REGION 5 (West Coast South Island):

Pearce and O'Loughlin (1978) for small forested catchments in northern Westland

O'Loughlin and Pearce (1976) for the Upper Grey River

REGION 6 (East Coast South Island):

de Joux (1980) for Orari River

Hayward (1980) for Torlesse Stream - a small mountainous stream of the Waimakariri River

Simpson (ed) (1980) for Wairau River (Marlborough)

Cuff (1977) for Ashburton River

REGION 7 (Upper Waitaki Catchment):

Cuff (1974) for Upper Opihi River

Robinson (1981) for Ivory Glacier meltwater stream of the Waitaha River

REGION 8 (Southern South Island):

Jowett and Hicks (1981), Thompson (1976, 1978) for Clutha River and tributaries

Ministry of Works and Development (1977), Otago Catchment Board (1956) for Shotover River

Christian and Thompson (1978) for the Mararoa River

OTHERS:

Adams (1979) in a wide study of North Island rivers

Finley (1974) for lower Waikato River

Schouten (1978) for Puketurua Experimental Basin (Northland)

Thompson and Adams (1979) in a wide study of South Island rivers

Wilshire (1971) for Waihau River on the Hauraki Plains

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