FLUVIAL TRANSPORT IN THE NARRATOR BROOK, DEVON: A SUMMARY OF SOURCES, DYNAMICS AND CONTROLS

by

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FLUVIAL TRANSPORT IN THE NARRATOR BROOK, DEVON: A SUMMARY OF SOURCES, DYNAMICS AND CONTROLS. A.L. Murgatroyd

ABSTRACT

The Narrator Brook drains a catchment area of 4.68 km² which is entirely underlain by granite and which includes moorland, improved pasture and coniferous forest plantation. Observations of suspended sediment and solute transport by the Narrator Brook are based on stream sampling combined with laboratory analysis. Bedload transport is measured by a trap sunk into the stream bed. Respective yields of solutes, suspended sediment and bedload over the 19 months of observation (25/5/75 to 13/12/76) are 12.6 t/km², 4.0 t/km² and 0.1 t/km².

Afforestation in the Narrator catchment is responsible for accelerating the rate of bank erosion and this has contributed significantly to the sediment transported by the Narrator Brook. Soil well observations indicate that overland flow is both frequent and widespread in the Narrator catchment suggesting that catchment slopes also constitute a major source of sediment. With respect to the sources for solutes transported by the Narrator Brook, the atmosphere supplies 70.1% with the remaining 29.9% originating from rock weathering in the catchment.

Suspended sediment dynamics are characterised by clockwise hysteresis, and higher concentrations in summer for a given discharge than in winter. This, combined with the emergence from multiple regression analysis of precipitation intensity as the predominant control of suspended sediment concentration, reflects the importance of catchment slopes as a source of suspended sediment. Analysis of variations in solute concentration reveals the existence of both flushing and chemical buffering mechanisms in the Narrator catchment.

Suspended sediment yield is greatest below the region of improved pasture in the Narrator catchment and least below the moorland region of the catchment. Solute production is more uniform over the Narrator catchment than suspended sediment production but is slightly higher in the forested region than elsewhere. In the upper reaches of the Narrator Brook baseflow suspended sediment and solute concentrations are influenced by outflow from marshes which border the stream. In the lower reaches downstream variations in baseflow suspended sediment and solute concentration are determined respectively by channel gradient and area of catchment forested.
Mr. R. Cockerton and Mr. J. E. Fox rendered assistance in the field. Mr. R. Cockerton also assisted in the laboratory. Mr. B. Martin helped with the maps and diagrams. Mr. G. Taylor granted permission to instrument the Narrator catchment. The South West Water Authority supplied precipitation records for the Redstone gauge together with data on water chemistry and depths of silt in the Burrator Reservoir. The Totnes Sub-Aqua Club recovered samples of silt from the bottom of the Burrator Reservoir.

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Drs. J. L. Ternan and I. Reid supervised the research.
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CHAPTER 1
RESEARCH OBJECTIVES

1.1 Introduction

With the impetus provided by the recent hydrological decade, small catchment studies in Great Britain have proliferated. The majority of these, however, concentrate upon hydrological aspects at the expense of hydrogeomorphology (Gregory 1979). Catchment studies with hydrogeomorphological bias, which involve consideration of both stream sediment and solute transport, include Imeson (1969, 71a, 73, 74), Walling (1971, 74a, 74b), Oxley (1974) and Lewin et al (1974). Research of this kind gives valuable insight into how weathering and erosion in a humid temperate environment vary temporally in response to changing weather conditions and spatially in response to factors such as vegetation and rock type.

This study is concerned with the transport of material in particulate and solutional form by the Narrator Brook, a small stream on Dartmoor, S.W. England. The Narrator Brook feeds the Burrator Reservoir which is a major source of water supply for Plymouth and its environs. The catchment area of the Narrator Brook is 4.68 km² and is underlain entirely by granite. In terms of its physical characteristics the Narrator Catchment can be considered representative of the granite area of Dartmoor as a whole. The investigation involves detailed analysis of temporal and spatial variations in all three forms of fluvial transport, suspended sediment load, bedload and dissolved load. Although necessarily some consideration is devoted to runoff processes and pathways since water is the vehicle for sediment and solute transport in the catchment, the study is hydrogeomorphological rather than hydrological in emphasis. In this respect the study is intended to help redress the imbalance in contemporary small catchment research.

Detailed comprehensive studies in the mould of Imeson and Walling which include both sediment and solutes have
never been undertaken in Britain on granitic rocks. Such work has been done on granite rocks by Douglas (1968a, 68b, 68c, 73) in Malaysia and S.E. Australia and this provides a useful comparison with results from the present study.

Granite outcrops cover 6,000 km² in Britain and from this standpoint alone investigation of hydrogeomorphological processes in a granite catchment is overdue. In addition, from the point of view of weathering, erosion and fluvial transport, granite is of special interest for two reasons. First, since granite is typically very uniform, the composition of solutes in streams draining granite catchments can be compared with geochemistry of the granite in order to establish the nature of weathering processes affecting silicate minerals and also the relative mobility of weathered products (Feth et al 1964, Garrelts and Mackenzie 1967). Second, according to Moeyersons (1975), Stocking (1976), Ward (1977) and others, soils developed upon granite are characteristically sandy and susceptible to erosion, and this is likely to be reflected in higher rates of stream sediment transport.

In addition to its geomorphological significance, research relating to transport of sediment and solutes by streams is also important with regard to water resource utilisation. Dartmoor is becoming increasingly important for supply of water as surrounding metropolitan areas expand. Five existing reservoirs collect water draining the Dartmoor Granite and additional reservoirs are projected. Several of the findings of this study have implications for the management of water resources on Dartmoor.

Three points regarding the nature of the study need mention at the outset. First, although all three forms of fluvial transport are included in the study greatest weight is placed upon suspended sediment and least upon bedload. Second, while the practical implications of the results are discussed, the study is mainly geomorphological in outlook. Finally, this is the first major study in what is planned as a long term research project centred on
the Narrator Catchment. It is broad and exploratory in scope. The intention is to seek out any apparent anomalies in the operation of the catchment system which might warrant more detailed examination in future research efforts.

Six objectives for the present study can be isolated. These are:

1. To determine the relative importance of sources for sediment and solutes in the Narrator Catchment.

2. To define temporal dynamics in sediment and solute transport in terms of hydrological and/or hydrometeorological controls.

3. To investigate spatial variations in sediment and solute transport in response to variations in vegetation, soil type, physiography and channel characteristics within the Narrator Catchment.

4. To establish a tentative rate of denudation for the Dartmoor Granite region from the sediment and solute yields of the Narrator catchment.

5. To examine the practical implications of fluvial transport in the Narrator Brook with regard to supply of water from Dartmoor.

6. To determine the relative contribution of dissolved load, suspended load and bedload to total fluvial transport in the Narrator Brook.

Brief backgrounds to each of these topics appear be-
low under separate headings. The first three of the objectives listed above are regarded as the major ones and discussion of results related to these occupies the main body of the thesis covering Chapters 4 to 7 inclusive. Results relating to the last three objectives are discussed in the concluding chapter.

1.2 Sources of sediment and solutes

Sources of sediment and solutes exported from stream catchments can be classified into point and non-point sources (Rodda et al 1976). Point sources are generally associated with human activity. Supply of sediment from erosion of construction sites and supply of solutes from discharge of effluents into the stream, would fall into this category. In contrast to non-point sources, point sources are easy to identify. It is also a relatively simple matter to determine the individual contribution of point sources to total stream transport. For non-point sources, which are widespread over the catchment, this task becomes more difficult. In the Narrator catchment, as in most catchments selected for geomorphological investigations of fluvial transport, point sources are negligible.

The two categories of non-point sources for stream solutes are rock weathering and atmospheric fallout. The relative importance of these two varies greatly from catchment to catchment depending upon the factors which regulate the supply of solutes from each source. Since a major source of atmospheric salts is sea spray, distance from windward coasts is an important control (Gorham 1961, Douglas 1972). Stevenson (1968), in an analysis of the areal variation of precipitation solute concentrations over the British Isles, discovered a marked rising trend towards the west and south west coasts. As a result, for inland
catchments atmospheric supply is minor in relation to the contribution from rock weathering while for catchments closer to windward coasts atmospheric supply may in some instances predominate (e.g. Gorham 1957, Cryer 1976, Waylen 1979). Waylen (1979), for example, estimates that 80% of the solutes exported from a small catchment in the Mendips originate from the atmosphere. According to Rodda et al (1976), this situation is most likely to arise in catchments underlain by rocks which weather slowly and contribute little to stream solutes. It can be expected, therefore, that since the Narrator catchment overlies granite and is close to the windward south west coast of England atmospheric contribution to total stream solutes will be large. In order to extract any geomorphic significance from rates of stream solute transport, assessing atmospheric supply accurately is crucial. Walling and Webb (1978) simply deduct sodium and chloride from total stream solutes to determine spatial variations in chemical denudation over the Exe River Basin. This cannot be considered adequate because sulphate, magnesium, calcium and potassium are also supplied in large quantities by the atmosphere in coastal regions (Gorham 1961).

The sediment transported by streams can be divided among two major sources. On catchment slopes sediment may originate from sheet erosion and gulley erosion. Sediment originating from within the channel may be derived from mobilisation of bed material and from bank erosion. The relative importance of each of the sediment sources, as in the case of solute sources, varies considerably from catchment to catchment, but unlike the case with dissolved solids no positive underlying trend can be distinguished and no generalisations are possible. American research credits sheet erosion on catchment slopes as the predominant source of suspended sediment transported by streams (Glymph 1957, Piest 1970, Guy 1970). Einstein (1964), for example, estimates the contribution of sheet erosion to total sediment yield of the United States at 80-90%. Efforts at predic-
tion of catchment sediment yields from soil loss models has been a keynote of sediment research in the United States since the 1950's (Glymph 1954, Beer et al 1966, Williams & Berndt 1972, 77). In the wide sand floor rivers typical of the Great Plains region of the United States, bed material is also recognised as an important source of suspended sediment and modified bedload equation have been used for prediction of sediment yields (Hubbell & Matejka 1959, Colby 1964). With few exceptions (e.g. Coldwell 1957) bank erosion as a source of sediment in the United States has received scant attention.

In Britain, measurements of bank erosion have revealed that this can become the major source of sediment in some catchments (Potter 1973, Hill 1973, Lewin & Brindle 1977, McGreal & Gardiner 1977). Bank erosion is also likely to be an important source of sediment in the Narrator catchment, since there is evidence of rapid erosion of channel banks along the lower course of the Narrator Brook. In the British Isles soil erosion is generally regarded to be of minor significance, although, as Evans (1971) points out, this is far from the truth. Even on non-agricultural land in Britain, sheet erosion cannot be excluded as a source of sediment. Large rates of sheet erosion have been observed in Britain, particularly in moorland regions including the Pennines (Tallis 1964), Mid-Wales (Slaymaker 1972) and the North York Moors (Imeson 1971b). Since the greater part of the Narrator catchment is moorland, sheet erosion may also likely be an important source of the sediment transported by the Narrator Brook.

Establishing the relative contribution from each of the sources for sediment and solutes is important for three reasons. First, the rate of supply of material from each of these sources is governed by differing controls. Information concerning the relative importance of sources in the catchment can be a considerable aid to explanation and interpretation of the pattern of significant controls which
emerges from analysis of fluvial transport dynamics. It can be expected, for example, that if catchment slopes were the major source of suspended sediment, precipitation characteristics would impose more influence upon rate of stream transport of suspended sediment than if the stream channel were the major source. Second, determination of denudation rates from rates of fluvial transport also requires some estimate of supply from the various sources of sediment and solutes. Atmospheric input of solutes has first to be deducted from stream solute yields before rates of chemical denudation in the stream catchment can be assessed (Goudie 1970). In the case of sediment, only a proportion is generated by erosion in the catchment and discharged at the catchment outfall; the remainder is re-deposited in the catchment. This proportion has first to be estimated before rates of transport of sediment can be converted to rate of catchment erosion. It depends to some extent upon sources of sediment within the catchment. For silt originating within the channel the proportion delivered to the catchment exit is virtually 100%. For silt supplied from sheet erosion on catchment slopes the proportion is generally much smaller (Onstad et al 1977). Douglas (1972 p. 49) comments: "As sources of streamflow solutes and fluvial sediments becomes better known, geomorphological processes will be better understood and evaluation of landform evolution will be better founded". Finally, from a practical standpoint, knowledge of the relative supply from specific sources is required before effective measures can be implemented to limit sediment or solute yields. Lewin et al (1974) report that the bulk of sediment discharged from a Mid-Wales catchment originates from erosion of stream bank bluffs. In this situation efforts to protect catchment slopes by various conservation practices would achieve relatively little success in reducing stream sediment yields.
1.3 Temporal variations in stream sediment and solute transport

Rate of fluvial transport in all natural streams varies over the short term in response to changing weather conditions and variations in streamflow. Variations in the transport of sediment and solutes are most pronounced during flood periods. Two groups of factors can be identified which control these variations. These two groups include streamflow characteristics on the one hand and precipitation characteristics, catchment wetness and season on the other. The relative importance of these two groups depends upon the type of fluvial transport and the source of material transported.

Bedload refers to sediment particles which maintain close contact with the stream bed during transport. The immediate source for these particles is bed material although they may have originated initially from bank erosion. Bedload is governed by stream flow which determines the efficiency of the stream to entrain particles on the stream bed and sustain their transport. Stream power, a parameter commonly used as the basis for modelling bedload dynamics (e.g. Bagnold 1966, 73, Leopold & Emmett, 1976, Gomez 1979) is the product of depth, velocity, water surface slope and water density of the stream. In contrast to bedload, dissolved material transported by streams is derived from beyond the confines of the channel system. Factors other than streamflow characteristics assume importance in determining rate of solute transport. The results of several studies have demonstrated the importance of precipitation characteristics, catchment wetness and season with respect to stream solute transport (Imeson 1973, Cryer 1976, Foster 1978a). The degree of influence exerted by the two groups of factors upon suspended sediment transport is related to the particle size of suspended sediment. Depending upon the catchment, a proportion of suspended sediment, incorporating the coarse end of the particle size...
range, is derived from bed material. The transport of bed material in suspension is governed exclusively by streamflow characteristics. The remaining finer sediment in suspension originates, at least in part, from sheet wash on catchment slopes. Rate of transport of this sediment is influenced to some extent by precipitation characteristics, catchment wetness and season.

Precipitation characteristics, catchment wetness and season are interrelated but each has some individual significance with respect to suspended sediment and solute transport. The effect of precipitation characteristics is most clearly defined. Precipitation provides the energy for erosion of soil particles and also the transporting medium in the form of overland flow. Gregory and Walling (1973 p. 210) remark "...the output of sediment (from a catchment) is primarily governed by the character of the precipitation input". With respect to stream solutes, for catchments in which the atmosphere is a major source of these solutes, variations in stream solute transport may be governed to some extent by variations in the input of dissolved solids in precipitation. Cryer (1976), for example, found a very close correspondence between the solute concentrations of quickflow and precipitation in a Mid-Wales catchment. Since the Narrator catchment is close to the coast it might be expected that a similar situation would exist. For this reason the solute concentration of precipitation was monitored in the Narrator catchment as well as precipitation amounts and intensities.

The affect of the other two factors, catchment wetness and season upon rates of suspended sediment and solute transport is more subtle. Both these factors relate to the condition of the catchment surface in terms of soil moisture and also in terms of vegetation cover, rates of evapotranspiration, and other aspects of catchment condition that may vary to any extent with season. The manner in which these influence sediment and solute transport is not altogether understood and because of this gap in under-
standing the results of studies which attempt to isolate factors controlling sediment and solute dynamics are difficult to interpret. Morgan (1979), for example, points to the uncertainty that exists regarding the significance of catchment wetness in relation to soil loss and stream sediment production. Results of research by Fournier (1972) on experimental erosion plots in Ohio led him to conclude that wet soil is more susceptible to erosion, while Heede (1975) concluded from his investigations in small catchments in the western United States that soil erosion proceeds at a faster rate when the soil is dry. Richter & Negendaile (1977), on the other hand, were unable to detect any effect of wetness upon rates of soil loss in the Moselle region of West Germany. Similar uncertainty surrounds the significance of season. In a small Mid-Wales catchment where atmospheric fallout is the major source of stream solutes, Cryer (1976) observed strong seasonal variations in stream solute concentrations which he attributed to seasonal variation in atmospheric fallout. Foster (1978a) working in a small Devon catchment in which atmospheric fallout was also established as the predominant source, also found a strong seasonal variation in stream solute concentration but could find no corresponding seasonal variation in atmospheric fallout. No significant seasonal variation in stream solute concentration was encountered by Imeson & Ward (1971) in an East Yorkshire catchment.

Although they may have separate effects upon stream sediment and solute dynamics, probably the most influential part played by catchment wetness and season, is that in combination with precipitation characteristics they determine the pathways by which precipitation falling upon catchment slopes finds its way to the stream. Overland flow is the critical pathway for suspended sediment production. Copeland (1965), for example, has amply demonstrated the very close correspondence between rate of overland flow and rate of both soil loss and stream sediment transport. In an effort to assess the relative impact of precipitation
characteristics, catchment wetness and season upon rates of overland flow in the Narrator catchment, crest stage soil well observations were made at 20 sites. These soil wells were designed to record the frequency of overland flow. Armed with understanding of the controls of overland flow, more meaningful interpretation of the pattern of controls governing sediment and solute dynamics in the Narrator Brook can be achieved.

This task, to interpret the controls of sediment and solute dynamics in the Narrator catchment in terms of sources and pathways, is complicated by interrelationships between controls, for example between precipitation and streamflow characteristics. A strong correlation between rate of sediment or solute transport and any one of the controlling factors inevitably means that strong correlations must also exist with the other factors, even though ordinarily these other factors may have little or no direct effect. To get round this obstacle some multivariate technique which filters out only the independent effect of each factor tested must be used. In this study multiple regression is adopted for this purpose. This technique has previously been used successfully for the same purpose by several workers including Guy (1964) and Walling (1971a) for suspended sediment and Foster (1978b) for dissolved solids. It is important to include in the multivariate analysis variables representing all four factors known to influence fluvial transport rates, precipitation, streamflow, catchment wetness and season. Failure to do this may lead to misinterpretation of the results. Wood (1977), for example, found that sediment concentrations in the river Rother are significantly higher during summer and attributed this to a drier catchment at this time of year increasing the availability of sediment on catchment slopes. He arrived at this conclusion without including catchment wetness and precipitation characteristics in his multivariate analysis. Higher summer concentrations could equally well be a result of higher precipitation intensities during
summer months. This can only be resolved by testing the independent affects of both catchment wetness and precipitation intensity.

Multiple regression in this study is also intended as a predictive tool. By defining fluvial transport rates in terms of precipitation, streamflow and other controlling factors, short term periods of fluvial transport record can be extended by reference to long term precipitation and runoff records where these exist. As a result of the variability in fluvial transport rates, several years of record are normally required to obtain values which can be considered representative of the long term, particularly for suspended sediment. A.S.C.E. (1973) recommends a period of sediment record of at least thirty years for reliable estimates of mean annual yield. For some streams fluvial transport rates have been calibrated against streamflow alone with a certain amount of success. These so called sediment and solute rating curves are then combined with flow duration curves to derive long term yields (Miller 1951, Piest 1964, Loughran 1976). Poor rating curves can be improved to some extent by correcting for season and other factors (Hall 1967, Temple & Sundborg 1972, Oxley 1974). Douglas (1969) also tested several polynomial expressions in addition to the usual power functions but was forced to the conclusion that multiple regression offers the best solution for practical prediction.

1.4 Spatial variations and controls

The third major objective of the study is to investigate the influence of catchment characteristics upon rates of sediment and solute transport. This is approached by separating the Narrator catchment into a series of three nested sub-catchments each with differing catchment characteristics. Differences in unit area sediment and solute yields from the three sub-catchments can thus be interpreted in terms of differing catchment characteristics. This task is greatly facilitated by the uniformity of rock type and gross
climate over the Narrator catchment. These two factors are thus held constant permitting evaluation of the other factors which vary spatially over the catchment, and which include vegetation, soil type, physiography, and channel characteristics.

Previous research has revealed that both vegetation and soil characteristics have a profound influence upon sediment and solute yields. Vegetation inhibits soil erosion by protecting the soil surface from the erosive effects of rain drop impact, by imparting coherence to the soil mass with its roots, and by increasing the aggregate stability of the soil through addition of organic matter (Stocking & Elwell 1976). It also improves the surface infiltration capacity of the soil thereby reducing the surface runoff which is responsible for removing eroded soil particles (Morgan 1979). The most convincing demonstration of this protective role of vegetation is the dramatic acceleration in sediment transport rates that have been observed following damage or destruction of vegetation cover by burning (Sinclair 1954, Imeson 1971b, Brown 1972) timber harvest (Lull & Rheinhart 1963, Hornbeck & Rheinhart 1964, Fredriksen 1970) and construction activities (Wolman & Schick 1967, Vice et al 1968, Walling & Gregory 1970, Walling 1974a). Conversely, adoption of soil conservation measures, principally involving improvement of vegetal cover, has been shown to reduce sediment yields from experimental catchments (Bailey & Craddock 1948, Baird 1964, Noble 1965, Hadley 1974). The degree of protection afforded by vegetation is dependent upon its type and density. Agricultural catchments generally sustain highest sediment yields, followed by grassland catchments, while forested catchments are associated with very low yields (Ursic & Dendy 1965, Douglas 1969).

There is a continuous cycling of solutes between the vegetation cover and the soil beneath, both of which can be regarded as mutually compensating reservoirs of soluble material. While the biomass in a stream catchment remains
relatively stable there is no net long term loss or gain of soluble material from vegetation storage, although short term inbalances may occur especially on a seasonal basis. In this situation the type of vegetation in a catchment exerts little influence upon solute yields. Any reduction of vegetation cover, however, results in a release of dissolved solids from the soil corresponding to the reduction of vegetation solute storage. Up to 15-fold increases in solute yields have been reported following removal of forest vegetation in small catchments (Bormann et al 1968, Pierce et al 1970, Fredriksen 1971). Vegetation type can exert some influence upon stream solute yields by differential adsorption of atmospheric solutes during dry periods. Results of some studies suggest that coniferous forest vegetation is particularly effective in filtering salt particles from the atmosphere (Erikssen 1955, Juang & Johnson 1967, White et al 1971). Coniferous forest plantation covers 11% of the Narrator catchment and from the above discussion marked contrasts can be expected in both sediment and solute production between forested and non-forested parts of the catchment. Vegetation, above all other environmental factors governing rates of fluvial transport, can be most readily manipulated by man. Relating sediment and solute yields to vegetation types thus has an important practical significance for land management aimed at conserving soil and preserving water quality.

The susceptibility of soil to erosion is a very elusive property. It is dependent upon a combination of several soil characteristics in a complex manner. Several established indices of soil erodibility have been tested in laboratory experiments by Bryan (1976; 1977) and it appears from these analyses that none can be considered entirely satisfactory. However, data from erosion plots reveal that texture, organic content and permeability are the most significant soil characteristics with respect to erodibility (Wischmeier 1977). These three factors have been combined by Wischmeier et al (1971) into a nomograph for estimating the erodibility factor in the Universal Soil Loss Equation.
In terms of all of these three soil characteristics, there are sharp contrasts between peaty and non-peaty soils in the Narrator catchment.

With respect to physiography, a considerable volume of research on erosion plots and in the laboratory has established conclusively that rates of soil erosion increase with both slope angle and slope length (Zingg 1940, Smith & Wischmeier 1957, Meyer and Monke 1965). Channel characteristics can also be expected to influence sediment yields particularly for catchments where the channel forms an important source of sediment. Both physiography and channel characteristics vary appreciably over the Narrator catchment and undoubtedly contribute, to some extent, to variations in sediment yield between sub-catchments.

With only three catchments interpretation of differences in yields would be virtually impossible without elimination of rock type and macro-climate as variables. Imeson (1969), however, compared yields from three widely separated catchments in East Yorkshire which differ in gross climate and rock type as well as vegetation, soil type, physiography and channel characteristics. In this situation, conclusions reached regarding the individual influence of any one of these factors cannot be considered entirely reliable.

In addition to comparing sediment and solute yields from three sub-catchments, downstream variations in sediment and solute concentrations were also investigated. Samples were collected periodically at 30 sites along the 3.4 km of the Narrator Brook. Sampling was restricted to baseflow periods since during floods temporal variations in sediment and solute concentrations at a site render any spatial analysis impossible. Detailed investigations of downstream variations in sediment and solute concentrations such as performed in this study have been neglected in hydrogeomorphological research. Downstream variations in channel geometry, channel gradient and bed material have received much more attention in Britain (e.g. Gregory & Park
Analysis of downstream variations in sediment concentration can reveal something of the manner in which sediment is transported in the stream channel and how this is influenced by channel characteristics. Analysis of downstream variations in solute concentration can reveal much concerning the impact of vegetation upon the catchment solute system.

1.5 Rate of denudation

The fourth objective of the study is to determine a representative rate of denudation for Dartmoor Granite from the sediment and solute yields of the Narrator catchment. Establishing rates of denudation is of crucial significance in geomorphology. Directly, denudation is very difficult to measure, but can be conveniently estimated indirectly from catchment sediment and solute yields (equation 1.1)

\[ D = \frac{Y}{A G_s} \]  

\[ D \] rate of denudation (mechanical, chemical, or both), \( \text{m}^3/\text{km}^2/\text{yr} \) or \( \text{mm}/1000 \text{ yr} \)

\[ Y \] annual yield, in tonnes, of sediment or dissolved solids, or both

\[ A \] stream catchment area, \( \text{km}^2 \)

\[ G_s \] specific gravity of catchment rocks, generally taken to be 2.65

A distinction is commonly made between mechanical denudation and chemical denudation computed from sediment yields and solute yields respectively (e.g. Douglas 1973, Walling & Webb 1978, Waylen 1979). This distinction may be somewhat artificial and it is probably more meaningful to combine sediment and solute yields to obtain total denudation. Denudation rates determined from contemporary
catchment sediment and solute yields have been extrapolated back through time to assess rates of landscape evolution (e.g. Gilluly et al 1951, Schumm 1963a, Judson & Ritter 1964, McArthur 1977). Spatial variations in denudation rates have also been investigated to evaluate the affect of climate and rock type (e.g. Fournier 1960, Corbel 1964, Strakhov 1967, Walling & Webb 1978).

Work of this kind is potentially very valuable, providing care is taken to avoid catchments in which rates of sediment and solute transport have been accelerated as a result of disturbance. For example, contemporary rate of denudation for the Tugela River Basin in N.W. Natal, calculated from sediment and solute yields, exceeds the geologically normal rate of denudation, estimated from geomorphological evidence, by a factor of 30 (Murgatroyd 1979). In disturbed catchments, temporal extrapolation of contemporary denudation rates can be very misleading and spatial variations in denudation rates cannot be interpreted in terms of natural controls such as climate and rock type. Judson & Ritter (1964) estimated average rate of denudation for the United States based upon the sediment and solute yields of selected major rivers, and extrapolated this back through time to determine the period required to reduce the United States to ultimate base level. Their estimate of 11 to 12 million years, however, differs appreciably from that of Gilluly et al (1951) at 23 million years, based on the sediment and solute yields of other rivers. Schumm (1963a), more mindful of the problem of contemporary acceleration of stream sediment and solute transport, was more cautious and judged the period to be anywhere from 15 to 110 million years. McArthur (1977) extrapolated back through time an assumed rate of denudation for the Pennines of 1mm/yr. In so doing he attempted to demonstrate that erosion surfaces in the Pennines were very much younger than previously imagined and landscape evolution much more rapid. However, 1mm/yr is probably a considerable overestimate of the
natural rate of denudation for the Pennines. Rates of denudation for small catchments in Mid-Wales (Oxley 1974) and in the Mendips (Waylen 1979), for example, are only 0.0022 and 0.0026 mm/yr respectively. This last example illustrates very clearly the need for reliable denudation rates. Rate of denudation for Dartmoor is of particular significance since Dartmoor has emerged as a key region for deciphering the physiographic history of Southern England as a whole. Preserved in the Dartmoor physiography are details of geomorphic events in the past which have enabled geomorphologists to piece together a sequence of landscape changes (Orme 1964, Waters 1964, Brunsden 1964a). A rate of denudation for the Narrator catchment could provide an insight into the speed at which these landscape changes have occurred. A possible obstacle in this regard arises from vegetational changes in the catchment which may have affected rates of sediment and solute transport. This affect has to be evaluated before rate of denudation for Dartmoor, determined from the sediment and solute yield of the Narrator Catchment, can be meaningfully employed to assess rate of landscape change on Dartmoor. Evaluating the affect of vegetation upon sediment and solute transport by comparison of yields from three sub-catchments of the Narrator Brook, constitutes one of the other major objectives of this study as outlined in section 1.4.

Attempts have been made by Fournier (1960), Corbel (1964) and Strakhov (1967) to relate spatial variations in contemporary rates of denudation to climate on a World scale. These studies have produced markedly conflicting results. Stoddart (1969) attributes the inconsistencies in these studies to the use of sediment and solute yields from large drainage basins many of which are characterised by accelerated erosion. Smaller scale studies have clearly revealed the influence of rock type upon rates of denudation (Miller 1961, Bauer & Tille 1967, Walling & Webb 1978). Walling & Webb (1978), for example, report a very close
correspondence between the pattern of rock outcrops in the Exe River Basin and the spatial variation in chemical denudation. Studies of this kind are particularly valuable because differences in denudation among rocks has an important impact upon the landscape. Comparing the rate of denudation for the Narrator Catchment with published rates for other small catchments in Great Britain will give some indication of the relative rate of denudation of granite under a humid temperate climate in comparison to other rock types.

1.6 Practical implications

Fluvial processes when undisturbed pose relatively little threat to man. Sediment and solutes transported by streams represent a loss of soil and nutrients from the stream catchment. In the natural situation, if environmental conditions are relatively stable, this loss is balanced by renewed supply from rock weathering so that denudation involves little overall change in the soil mass even though the landscape is actively undergoing modification. Catchments affected by accelerated erosion resulting from poor land use management experience net depletion of soil and nutrients and consequent reduction in potential productivity. As well as soil erosion on catchment slopes, stream channel erosion is also subject to acceleration through disturbance of channel equilibrium, by human activity of various kinds. Problems resulting from accelerated fluvial processes are not limited to accelerated erosion although this may appear the most pernicious. Increased rates of fluvial transport resulting from accelerated soil or channel erosion cause deterioration of stream water quality. This can severely restrict full utilisation of water resource potential and can also have an adverse effect upon fresh water ecology. Increased influx of nutrients to lakes and reservoirs can lead to eutrophication, while sediment entering these water
bodies results in siltation and storage reduction. Siltation in stream channels reduces their capacity leading to greater frequency of overbank flooding.

In certain parts of the world these problems arising from interference and consequent acceleration of fluvial processes appear to be particularly severe. It has been estimated that accelerated soil erosion has ruined or seriously damaged for agricultural use some 282 million acres in the United States; a much larger area, possibly as much as three-quarters of a billion acres, has suffered net loss of some portion of its top soil (Foth & Turk 1972). In Natal, South Africa, cultivation of land adjacent to stream channels has resulted in accelerated bank erosion (Alexander 1978). A decline in fish catches off the Natal coast has been traced to siltation of estuaries; several marine fish require an estuarine environment in the early stages of their life cycle (Heydorn 1978).

Accelerated erosion due to construction activities was responsible for a 98% reduction in the size and number of trout in the Clark Fork River, Montana (U.S. Senate 1963). In Tanzania the life of several existing reservoirs with respect to siltation has been cut to less than 30 years as a result of accelerated erosion due to overgrazing in the reservoir catchment areas (Rapp et al 1972). Siltation of canals and river channels has long been a problem in India (Dominy 1966). The Kalagah Bridge, for example, at the time of its construction was 36.6m above the river bed but this has since been reduced to 0.6m as a result of sedimentation in the river channel (Lal & Bannerji 1974).

Eutrophication of lakes and reservoirs as a result of pollution and depletion of nutrients from stream catchments is a major problem in many parts of the world. The recreational potential of Lake Balaton which is the focus of Hungary's tourist industry is gradually being reduced by eutrophication which has resulted in infestation by water hyacinths (Lang 1978).

The popular misconception still prevails that Britain,
as a result of its temperate climate lacking extremes in both precipitation and temperature, has been spared the problems arising from disturbance of fluvial processes (Evans 1971). However problems of soil erosion, accelerated sediment transport, siltation and eutrophication are also prevalent in Britain. Serious soil loss has occurred in several parts of Britain as a result of poor agricultural practices (Thomas 1965, Bridges & Harding 1971, Slaymaker 1972, Evans & Morgan 1974). Active gullying has been reported from some areas (Thomas 1956, Tuckfield 1965, Imeson 1971b, Harvey 1974, Gregory & Park 1976). One of the few studies of erosion potential in Britain revealed that 58% of the soils of the Derbyshire Peak District are liable to serious erosion if vegetation cover is reduced (Bryan 1969). Stream sediment concentrations in a small south Devon stream increased by as much as 11 times following construction in the catchment area (Walling & Gregory 1970). Jee (1932) has recorded that a cloud burst in the Upper Eden Valley in 1930 caused sediment concentrations in the river sufficient to kill large numbers of trout. Thoresby lake, Nottinghamshire, created in 1720, is now almost completely filled with silt (Potter 1973). Large net losses of nutrients have been reported from a Pennine catchment following burning of the moorland vegetation to improve grazing (Crisp 1966). Owens (1970) draws attention to the dangers of eutrophication as a result of accelerated transport of nutrients in British streams.

Douglas (1969) warns of "far reaching deleterious effects" if land use changes are made in Britain in ignorance of possible repercussion upon erosion and sediment yield. Research relating vegetation and land-use to catchment sediment yields is lacking in Britain (Douglas, 1969, Imeson, 1974). The need for this type of research is most urgent for management of reservoir catchments where damage to water quality, eutrophication and reservoir sedimentation are possible hazards (Kirby & Rodda, 1974). Afforestation for example, is a common practice in
reservoir catchments and is based upon the belief that forest cover offers greater protection against soil erosion by intercepting direct rainfall and thereby nullifying its erosive potential (Leyton, et al 1967). This contention derives support from the results of experimental catchment research projects undertaken in several countries including Russia (Nikolayenko 1974), Italy (Gazzalo & Bassi 1964), and the United States (Gottschalk 1962), all of which report reduction in sediment yields following afforestation. Although afforestation may reduce supply of sediment from sheet erosion, Painter et al (1974) describe a 200-fold increase in sediment yield from a moorland catchment in Wales as a result of accelerated channel erosion which they attribute to afforestation of the catchment. Clear signs of rapid bank erosion in the part of the Narrator Brook which passes through forest plantation may perhaps support the conclusions reached by Painter et al (1974). The Narrator catchment is used for grazing cattle and sheep. Research by Imeson (1974) on the North Yorkshire Moors has shown that grazing and associated management practices, including heather burning, can lead to a marked acceleration of fluvial transport. The possible impact of both afforestation and grazing in the Narrator catchment are investigated in this study.

1.7 Relative importance of sediment and solute loads

The final objective of the study is to assess the relative contribution of the different forms of fluvial transport to total load in the Narrator catchment. Brown (1979), in his presidential address to the Institute of British Geographers, singles out the determination of the relative importance of sediment and solute transport by streams as one of the prime areas of interest for future geomorphological research in Britain. The relative proportion of sediment and solutes discharged from a catch-
ment depends upon the several factors which govern each form of transport individually. However, on a continental scale, spatial variation in the relative importance of sediment and solute yields is related to mean annual precipitation. Research by Langbein & Schumm (1958), Rango (1970) and others has shown that unit area sediment yield decreases with increasing mean annual precipitation from a peak in semi-arid climates. According to Livingstone (1963) and Langbein & Dawdy (1964) unit area solute yield displays the opposite trend increasing with mean annual precipitation. A point is thus reached as the climate becomes wetter when sediment yield, which is normally dominant in dry climates, is overhauled by solute yield. This occurs when mean annual runoff reaches around 500 mm according to Statham (1977) and around 600 mm according to Gregory & Walling (1973). Since runoff on Dartmoor exceeds 1 000 mm (Rodda et al 1976) it can be expected that solute yield will predominate in those areas unaffected by human activity. Upon disturbance of the stream catchment suspended sediment transport is generally subject to more rapid acceleration than solute transport. In catchments affected by human activity, therefore, sediment yields are likely to greatly outweigh solute yield, even under wet climates, and this perhaps can be used to help diagnose a disturbed catchment.

A proportion of total sediment transported, known as bedload, moves by rolling and sliding in close contact with the stream bed, in contrast to the finer particles which are transported in suspension within the stream. The contribution of bedload transport to total sediment transport varies considerably from catchment to catchment and no broad trends are apparent. Very few observations of bedload have been made in small streams in Britain in comparison to other forms of fluvial transport, but the majority of those observations that have been made indicate that generally bedload is relatively unimportant. In the Catchwater Drain, Yorkshire, bedload is only 0.5% of total
sediment load (Imeson & Ward 1972), and in five east Devon catchments this proportion varies between 0.5 and 2.5% (Walling 1971a). No generalisations are possible, however, since Painter et al (1974) report that in a small Mid-Wales catchment, as a result of afforestation and the creation of drainage ditches, bedload exceeds suspended load. Bedload transport in Lake District streams is of a rate sufficient to create severe problems of channel aggradation leading to reduction in channel capacity and increased frequency of flooding (Clayton 1951). Since in some catchments bedload can apparently form an appreciable proportion of total sediment in transport it should not, as is often the case, be ignored in studies of catchment denudation, but necessitates some form of measurement or estimation.
CHAPTER 2
THE NARRATOR CATCHMENT

2.1 Introduction

The Narrator Brook, which forms the focus of the present study, is a tributary of the Meavy River, situated close to the south western margin of Dartmoor (fig 2.1; plate 2.1). It is one of three major streams draining to the Burrator Reservoir and its catchment area of 4.68 km² comprises 22% of the total drainage area of the reservoir. Choice of the Narrator catchment represents a compromise between two conflicting requirements of the study. It is representative of the surrounding region and yet sufficiently uncomplicated to permit relation of fluvial transport rates to environmental controls. In smaller catchments which are relatively homogenous with respect to physical characteristics interpretation of sediment and solute output is simpler, but larger heterogeneous catchments are more representative of broader regions. The Narrator catchment is underlain by a single rock type while vegetation and soils display marked contrasts. Although somewhat larger than most research catchments it is small enough that hydrometeorological conditions can be considered sufficiently uniform not to cause significant problems in data interpretation. Human activity in the catchment is limited so that serious acceleration of fluvial transport is unlikely and matching measured transport rates to environmental setting is thus more reliable than would otherwise be the case. Results from the catchment can be regarded as fairly representative of the 600 km² of Dartmoor granite, and possibly in a more general way of all highland regions underlain by granite rocks in a moist temperate climate.

The Narrator catchment also fulfils several practical requirements. Reservoir catchments offer certain important advantages for hydrological research. They are
Fig. 2.1 Location of the Narrator catchment
Plate 2.1 Overall view of the Narrator catchment looking south-east. The coniferous forest plantation is clearly visible in the western region of the catchment.

Plate 2.2 Upper regions of the Narrator catchment looking north-east. Note the extensive clutter surrounding Combeshead Tor at the left of the picture and the contrast this provides with the smooth clutter free slopes in the foreground.
afforded maximum protection from human interference of hydrological processes in order to preserve water quality. The catchment area of the Burrator Reservoir is owned entirely by the South West Water Authority which ensures freedom of movement throughout the catchment together with permission for installation of all the necessary instrumentation. A valuable existing body of data accumulated by the South West Water Authority relating to the Burrator Reservoir and its catchment is also available. These data includes long term rainfall and runoff records, chemical water analyses, and a survey of sediment deposition in the reservoir. Accessibility is another important practical consideration. The establishment of the reservoir with associated commercial forest plantations has necessitated the provision of access roads. A tarmacadamed road passes the mouth of the Narrator Brook and two unsurfaced tracks passable by Landrover extend into the catchment.

For many hydrological research purposes such as nutrient budget or water balance studies it is essential that the catchment be water-tight. The uniformity of geological structure on Dartmoor means that topographic divides and phreatic divides are probably near coincident, which is a distinct advantage. Dartmoor is, however, characterised by a complex system of leats which transfer water across catchment divides. Of the three major sub-catchments of the Burrator Reservoir, only the Narrator catchment is free from leats.

2.2 Geology

The entire area of the Narrator catchment is underlain by Dartmoor Granite which was emplaced, along with several other smaller plutons in Cornwall, during the Hercynian Orogeny, 280 million years ago. Although there are slight textural and mineralogical differences between Blue Granite and Giant Granite, both of which are represen-
ted in the catchment, these differences are unlikely to have measurable impact upon catchment processes, and in this respect the lithology of the catchment can be considered uniform. The granite is coarse grained, porphyritic and schorlaceous (Brammall & Harwood 1923). Othoclase is the dominant felspar thus placing the Dartmoor Granite within the class of alkali granites. Phenocrysts of microperthitic orthoclase in the rock measure up to 20 cm in length. The remainder of the rock is composed mainly of orthoclase, plagioclase, biotite and quartz. Locally biotite has been replaced by tourmaline as a result of metasomatic activity during crystallisation. Accessory minerals, in common with most granites, include magnetite and apatite. In addition, as a result of an unusual frequency of inclusions and intrusions, there is a rich diversity of trace minerals not often found in granite rocks. Some of these are concentrated into veins or lodes and have in the past been exploited commercially on a large scale. Tin mining on Dartmoor was particularly important in the 18th and 19th centuries. Since rock weathering is a major source for stream solutes, the chemical composition of stream water can only be interpreted by reference to geochemical analysis of catchment rocks. Analysis of a sample of Dartmoor Granite from the Princetown Quarry, 5 km from the Narrator catchment is presented by Brammall & Harwood (1923) (table 2.1). Of note is the high proportion of K₂O reflecting the dominance of orthoclase which is diagnostic of alkali granite.

Granite bedrock outcrops at the tors which lie within or at the margins of the catchment, but over most of the catchment it is buried under a large thickness of superficial deposits. The valley fill consists of an upper layer of periglacial head deposits overlying rotted granite. The head deposits represent an accumulation of material transported from the higher margins of the catchment by solifluction during the Pleistocene period and this may have been responsible for exposure of the tors
Table 2.1 Geochemical composition of granite from Princetown Quarry, Dartmoor (Data from Brammall & Harwood 1923 - figures in percent).

<table>
<thead>
<tr>
<th>Chemical</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO₂</td>
<td>70.5</td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>14.4</td>
</tr>
<tr>
<td>K₂O</td>
<td>5.0</td>
</tr>
<tr>
<td>Na₂O</td>
<td>3.0</td>
</tr>
<tr>
<td>FeO+Fe₂O₃</td>
<td>3.0</td>
</tr>
<tr>
<td>CaO</td>
<td>1.5</td>
</tr>
<tr>
<td>H₂O</td>
<td>1.0</td>
</tr>
<tr>
<td>MgO</td>
<td>0.7</td>
</tr>
<tr>
<td>TiO₂</td>
<td>0.4</td>
</tr>
<tr>
<td>P₂O₅</td>
<td>0.2</td>
</tr>
<tr>
<td>MnO</td>
<td>0.1</td>
</tr>
<tr>
<td>Others</td>
<td>0.2</td>
</tr>
</tbody>
</table>

(Waters 1964). Boreholes put down by the Geology Department of Plymouth Polytechnic through the valley fill in the central part of the Narrator catchment failed to reach bedrock at a depth of 35 metres. Excavations, at the time of construction of the Burrator Dam, 1 km west of the Narrator catchment, revealed depths of at least 40 metres (Sandeman 1900).

On the higher margins of the catchment periglacial deposits appear less important. A deep exposure in superficial deposits is provided by a gully, on the edge of the adjacent Newleycombe Lake catchment. Here undisturbed rotted granite immediately underlies surface peat. The rotted granite or growan pre-dates the head deposits. The origin of the growan is undecided. According to Linton (1955) and Brunsden (1964b) it originated from deep weathering under a tropical climate during the Tertiary period. Analysis of quartz grain textures within the growan by Doornkamp (1974) using electron microscopy reveals evidence for tropical weathering, although this does not necessarily confirm that the growan originated in this
way. Te Punga (1957) and Palmer & Neilsen (1962) favour mechanical disintegration in a periglacial climate during the Pleistocene. Eden and Green (1971) from textural and mineralogical analysis of Dartmoor growan discovered that its clay content is lower than in present soil cover developed upon growan while its felspar content is somewhat higher. Since weathering of felspar to clay is more rapid in tropical climates, Eden and Green (1971) conclude that the Dartmoor growan formed under a climate similar to that at present.

These superficial deposits provide a large potential storage for groundwater in the catchment and thereby exert a profound influence upon catchment hydrology. These deposits are also a ready source of material for fluvial transport where it becomes exposed at gully sites and stream bank bluffs. The growan has a particularly sandy texture which renders it friable and susceptible to erosion. Particle size analysis of growan samples from the bank of the Sheepstor Beck within the Narrator catchment and from the Newleycombe Gully 1 km to the north of the catchment, reveal that particles of sand size and larger account for between 86% and 96% of the samples. This compares with figures reported by Eden & Green (1971) for Dartmoor Growan which range from 87% to 72%. Locally, however, clay lenses occur in the growan, which are exposed in stream bank bluffs and have also been encountered in boreholes (J. Alexander - pers. comm.)

2.3 Physiography

The catchment ranges in elevation from 222 m above O.D. at its exit to 456 m at its summit at Eylesbarrow yielding a total relief of 234 m (fig 2.2). Slopes generally are moderate. Most commonly slope angles vary between 5° and 10°; slopes in this range account for 52% of the catchment area (fig 2.3). Low angle slopes less
Fig. 2.2 Topography of the Narrator catchment
than $5^\circ$ occur in the floor of the valley and on the higher margins of the catchment with steeper slopes between (fig 2.4). This distribution of slopes reflects the predominance of convexo-concave slope profiles in the catchment which are characteristic of Dartmoor (fig 2.5). Profiles in the lower western end of the catchment, particularly below tors, are interrupted by several breaks of slope. These breaks of slope may represent solifluction terraces which originated during the periglacial conditions of the Pleistocene. The importance of the Pleistocene legacy to the geomorphology of Dartmoor has been stressed by Waters (1964). The tors, surrounded by extensive fields of coarse clitter which constitute perhaps the most characteristic features of Dartmoor, owe their origins, at least in part, to Pleistocene morphogenesis (plate 2.2).

The Narrator Brook flows in a westerly direction and slopes in the source region of the catchment are predominantly of westerly aspect (fig 2.6). Towards the western end of the catchment where valley form becomes pronounced

![Frequency distribution of slopes in the Narrator catchment](image)
Fig. 2.4 Slope map of the Narrator catchment
Fig. 2.5 Cross valley profiles of the Narrator catchment. See Fig 2.2 for profile locations.
Fig. 2.6  Slope aspect in the Narrator catchment
north and south facing slopes predominate. These valley side slopes, which average $11.0^\circ$ are steeper than the west facing headwater slopes, which only average $6.2^\circ$ (table 2.2). The valley itself is markedly asymmetrical. The mean area weighted angle of north-facing slopes is $13.1^\circ$ in comparison to $9.6^\circ$ for south-facing slopes. This may be yet another physiographic legacy of the Pleistocene. Valley asymmetry in many parts of the World has been ascribed to periglacial conditions, although the precise mechanisms responsible probably vary (Embleton & King 1975).

Table 2.2 Slope angle and slope aspect in the Narrator catchment.

<table>
<thead>
<tr>
<th>Aspect</th>
<th>Area(% of catchment)</th>
<th>Mean Area Weighted Slope ($^\circ$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Western quadrant</td>
<td>54</td>
<td>6.2</td>
</tr>
<tr>
<td>Eastern quadrant</td>
<td>7</td>
<td>4.8</td>
</tr>
<tr>
<td>Southern quadrant</td>
<td>23</td>
<td>9.6</td>
</tr>
<tr>
<td>Northern quadrant</td>
<td>16</td>
<td>13.1</td>
</tr>
</tbody>
</table>

The pre-Pleistocene tectonic and denudational history of Dartmoor has also left its imprint on the Dartmoor landscape and several erosion surfaces at various elevations have been recognised (Orme 1964, Balchin 1964). There is no real evidence in the physiography of the Narrator catchment to support the existence of erosion surfaces which can be matched with those established for Dartmoor as a whole.

In addition to the natural processes of land sculpture the catchment has also been scarred by mineral exploitation in the past. Mining was largely, though not entirely, by surface excavation resulting in pits, trenches and spoil heaps all of which have since acquired a protective cover of vegetation equivalent to that of unaffected areas. Tin streaming was also important and may have been partly responsible for irregular lower slope profiles in the Narrator
catchment (Ternan & Williams 1979). At least four mine
shafts in the catchment bear witness to underground opera-
tions as well as surface excavations.

2.4 Soil characteristics

The nature of the soil cover has an important influence
upon catchment hydrology since it largely determines the
pathways of storm runoff. Soils which are subject to rapid
saturation transmit a large proportion of runoff upon the
surface. Properties which govern the susceptibility of
soil to become saturated include texture and organic matter
content. These properties also influence soil erodibility
and hence supply of soil particles to surface runoff.

Clayden & Manley (1964) recognise three major soil
types upon Dartmoor Granite: peaty gley, peaty podsol and
brown earth. All are present within the Narrator catchment.
A more recent survey of soil on Dartmoor Granite (Harrod
et al 1976) distinguishes between six soil series: Laployd,
Princetown, Hexworthy, Rough Tor, Moretonhampstead and Moor
Gate.

Peaty gley soils which correspond to the Laployd and
Princetown series consist of a thick black surface layer of
peat commonly exceeding a metre in depth overlying a sandy
textured mineral sub-soil which varies in colour from grey
to brown. They occur in permanently saturated areas both
in valley bottoms and also in regions of blanket bog on
hill summits. The major difference between blanket bog
and valley bog soils is that in the latter, soil saturation
is maintained by groundwater rather than by direct pre-
cipitation and consequently dissolved mineral species are
more diverse. Permanently saturated areas are not ex-
tensive in the Narrator catchment occupying only 2% of its
area (fig 2.7; table 2.3). To some extent, delimitation
of permanently saturated areas is arbitrary since saturated
areas expand during wet periods and contract during dry
Permanently Saturated Ground
Bracken Infestation
Deciduous Forest

Moorland / Peaty podsol
Coniferous plantation / brown earth
Grassland / brown earth

Fig. 2.7 Vegetation and soil types in the Narrator catchment
Table 2.3 Areal cover of soil and vegetation types in the Narrator catchment.

<table>
<thead>
<tr>
<th>Soil Type</th>
<th>Area (km²)</th>
<th>Percent of Catchment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moorland with stagnopodsols</td>
<td>3.18</td>
<td>68.0</td>
</tr>
<tr>
<td>Brown earth (brown podsolic soils)</td>
<td>1.40</td>
<td>29.9</td>
</tr>
<tr>
<td>Grassland (improved pasture)</td>
<td>0.87</td>
<td>18.6</td>
</tr>
<tr>
<td>Coniferous plantation</td>
<td>0.53</td>
<td>11.3</td>
</tr>
<tr>
<td>Permanently saturated ground (gley soils)</td>
<td>0.10</td>
<td>2.1</td>
</tr>
<tr>
<td>Bracken (<em>Pteridium aquilinum</em>) infestation</td>
<td>0.83</td>
<td>17.7</td>
</tr>
</tbody>
</table>

Total catchment 4.68 km²

periods (Dunne & Black 1970). The area mapped in fig 2.7 remained wet throughout the very dry summer of 1976 and so can be reasonably regarded as permanently saturated.

Stagnopodsols (peaty podsols) of the Hexworthy and Roughtor series cover 68% of the catchment area of the Narrator Brook. They occur on moderate slopes and high altitudes around the margins of the catchment (fig 2.7). The black surface layer of peat is thinner than in the case of the peaty gley soils, ranging in thickness from 10 to 30 cm. In the Hexworthy series a thin iron pan underlies surface peat but in the Roughtor series it is absent. The sub-soil is coarse in texture and brown to ochreous in colour. Drainage in these soils is poor and they are subject to temporary saturation during wet periods. Saturation overland flow on these soils is likely to be frequent with implications for both sediment and solute production.

The brown earth soil type, comprising the Moretonhampstead and Moor Gate series, accounts for the remaining 30% of the catchment area. This soil type differs
fundamentally from stagnopodsol in the absence of a surface layer of peat. The A horizon varies in colour from brown to black depending upon humus content and averages 40 cm in depth. Weight loss recorded from ignition of nine samples of the A horizon in the brown earth soil type ranged from 9% to 17%; corresponding values for eleven samples of stagnopodsol all exceeded 40%. The texture of the A horizon in the brown earth soil type is variable but predominantly sandy; the proportion of sand and coarser particles for nine samples tested varied between 48% and 68%. As a result of their coarse texture, and comparatively low organic content it is better drained than the stagnopodsol. Saturation overland flow is likely to be less frequent on this soil in comparison to stagnopodsol.

The boundary separating the two major soil types in the Narrator catchment, stagnopodsol and brown earth, is sharp and well defined (fig 2.7). It coincides for the most part with the limits of formerly enclosed land marked by the remains of dry stone walls. This could indicate that the brown earth soil type, in this region of Dartmoor at least, has originated from cultivation of stagnopodsol.

2.5 Vegetation and land use

Vegetation characteristics influence catchment processes in several important ways. Firstly through interception and evapotranspiration vegetation affects runoff volume, while through its effect upon infiltration rate vegetation also determines to some extent the proportion of storm runoff which is transmitted upon the surface. Secondly vegetation acts to protect the soil surface from sheet wash thus regulating supply of suspended sediment for stream transport. Thirdly since vegetation represents a large fluctuating store of potential stream solutes, acquired either by uptake of nutrients from the soil or
entrapment of atmospheric salts, rate of stream solute transport is also affected by vegetation characteristics.

Excluding areas of permanently saturated ground, vegetation in the Narrator catchment can be separated into three broad contrasting types: Moorland (rough pasture), grassland (improved pasture) and coniferous forest. Marsh communities, dominated by species of Sphagnum and Juncus, which colonise permanently saturated ground, cover only 2% of the total area of the catchment.

Moorland occurs as a broad crescentic belt around the higher margins of the catchment and accounts for 68% of the total area (fig 2.7). It is characterised by a discontinuous cover of low shrubs including Calluna vulgaris, Erica tetralix and Vaccinium myrtillus with an understorey of grass and herbs. Prominent among the moorland grass species are Agrostis setacea and Molinia caerulea. The latter dies away in winter exposing the bare peat surface in patches.

Grassland on Dartmoor is considered by Ward et al (1972) to have its origin in burning, grazing and cultivation of moorland and is restricted to the lower western and central parts of the catchment. Grass is dominated by Agrostis tenuis and Festuca ovina which form a thick protective turf and which provide a continuous all year round cover. Large areas of grassland have been invaded by bracken (Pteridium aquilinum) which rises in May and dies back in October (fig 2.7; Table 2.3). In places, during late summer, it reaches two metres in height and becomes exceedingly dense forming a complete canopy. Bracken litter also forms a thick carpet persisting in some areas throughout the dormant season. Bracken does not, however, exclude ground surface vegetation or reduce the thickness of turf. Bracken has also succeeded in colonizing the better drained areas of moorland in the catchment, but here does not become quite as dense. The grassland region contains scattered deciduous trees which do not form any continuous cover ex-
cept in a restricted area close to the stream channel in the central part of the catchment (fig 2.7). Common species are Oak (*Quercus robur*), Beech (*Fagus sylvatica*) and Sycamore (*Acer pseudoplatanus*).

The third major vegetational type present in the Narrator catchment is a coniferous forest plantation established in the inter-war period and covering 0.53 km$^2$ at the western end of the catchment. The major species is Sitka Spruce (*Picea sitchensis*) but Norway Pine (*Pinus resinosa*) and Japanese Larch (*Larix leptolepis*) are also present together with a few deciduous trees which pre-date the forest plantation. In places tree density is such that the canopy is complete and ground surface vegetation is almost entirely excluded, although the soil surface is protected from rain splash by a natural mulch of spruce needles. Even where the canopy is not complete the turf cover is invariably thin.

There exists a very close spatial association between vegetation and soil types in the catchment. Moorland vegetation is confined to stagnopodsol and grassland to brown earth. Afforestation has been entirely restricted to former areas of enclosed grassland. The most significant vegetational contrast in terms of hydrological processes in the Narrator catchment is between forested and non-forested areas (moorland and grassland). Forest vegetation is likely to differ substantially from grassland or moorland in terms of evapotranspiration, interception, soil protection, cycling of nutrients and entrapment of atmospheric salts. The principle corresponding pedological contrast is between peaty and non-peaty soils. These two soil types are likely to differ markedly with respect to frequency of overland flow, and supply of fines for stream sediment transport. Since soil and vegetation types are closely associated in the Narrator catchment they can be combined into three major vegetation/soil units: forest/brown earth (11.3% of total catchment area), grassland/brown earth (18.6%) and moorland/stagnopodsol (68.0%)
The remaining 2.1% of the catchment area consists of hill and valley marshes.

At present the most widespread land use on Dartmoor as a whole, as within the Narrator catchment, is stock rearing (Roberts 1970). Livestock includes hardy black-faced sheep and Galloway cattle together with Dartmoor ponies. Arable farming, although at one time important around the lower margins of Dartmoor, declined from the turn of the century and almost disappeared altogether with the establishment of the National Park in 1954. Arable farming was excluded from the area of the Narrator catchment following purchase of the land by the then Plymouth Water Corporation in 1916. The grazing in the catchment is free range. Despite this, the intensity of grazing varies considerably from place to place. Cattle and sheep rarely venture into the areas which have been invaded by bracken. Grass in areas which are preferentially grazed can become very thin. Greatest damage to vegetation cover is through concentrated trampling at specific sites such as gaps in walls and stream crossings but these are small in extent and few in number. However, according to Lusby (1963) grazing can promote higher sediment yields through reduction in soil infiltration capacity and corresponding increase in overland flow even without any appreciable damage to vegetation cover. The practice of firing the moorland to improve the quality of the grazing can also have severe repercussion upon rates of soil loss and catchment sediment yield. These effects have been documented, for example, in the North Yorkshire Moors (Imeson 1971b). Burning last occurred in the Narrator catchment in 1969 over a small area in the north eastern corner of the catchment. At the time of the present research, the moorland vegetation in this area was completely regenerated.

The expansion of forestry on Dartmoor in the inter-war period was based upon a belief in Dartmoor's importance as a softwood growing area (Roberts 1970). Afforestation is closely linked to exploitation of water resources on
Dartmoor and to the supposed beneficial effects of coniferous forest upon water quality (Leyton et al 1967). The greater part of commercial forest on Dartmoor lies within reservoir catchments. Associated with afforestation has been the creation of drainage channels and forestry roads which can be expected to have some impact upon catchment processes, particularly in relation to runoff generation and sediment supply. Painter et al (1974) report a large increase in sediment yield from a Mid-Wales catchment following afforestation, which they attribute primarily to creation of forest drainage channels.

Dartmoor is growing in importance as a recreational area. Recreational activities tend to be confined to specific areas; pedestrian movement away from roads is very low (Roberts 1970). The Burrator Reservoir is a major attraction since it is close to Plymouth and is readily accessible. Nevertheless, relatively few visitors stray into the Narrator catchment and their combined influence upon catchment processes is probably very small.

2.6 Climate and period of observation

Dartmoor is characterised by high rainfall, generally high humidity, moderate temperature, high amounts of cloud cover, and frequent hill fog (Perkins 1970). The 50 year mean annual precipitation recorded at the Redstone rain gauge site maintained by the South West Water Authority 1 km to the S.W. of the catchment is 1568 mm. Distribution of precipitation through the year displays a marked seasonality. The wettest period is in autumn and early winter when mean monthly totals exceed 150 mm and the driest period is in spring and early summer with mean monthly total less than 100 mm. Snowfall occurs on average over Dartmoor on about 15 to 20 days in the year (Perkins 1970).
Observations were undertaken in the Narrator catchment over an uninterrupted period from the 26th May 1975 to 13th December 1976 totalling 81 weeks. This period as a whole witnessed a marked departure from the climatic norm for Dartmoor. It was very much drier than normal constituting an unprecedented drought over much of the period. Total precipitation over the area of the Narrator catchment for this period of approximately a year and a half is 1 907 mm. This does not fall greatly short of the expected precipitation of around 2 550 mm for a period of this duration. Total period precipitation, however, hides shorter periods which experienced extreme deficits in expected precipitation (fig 2.8). Precipitation during the period as a whole represented a marked accentuation of the seasonality in precipitation which characterises Dartmoor in normal years. While autumn precipitation in 1975 and 1976 was close to the 50 year average, summer precipitation dropped considerably below the 50 year average (fig 2.8). Although incursion of sub-tropical pressure systems lasting for periods of up to several days is a characteristic feature of summer weather in South West England, in the summers of 1975 and 1976 sub-tropical highs over Britain as a whole became extraordinarily persistent (Kelly & Wright 1978). During these two summers long periods elapsed without any measurable rainfall. No rainfall was recorded, for example, over the period 20/7/76 to 28/8/76. The drought opened in the South West in the early summer of 1975 following a wetter than average winter. Total precipitation for the months of May and June 1975 was only 34.5% of the 50 year average for these months. By July stream water levels in the South West had dropped to their lowest on record and several ran dry for the first time in living memory. In late summer and early autumn precipitation recovered to near normal but this was short-lived and overall the winter of 1975/76 turned out to be an unusually dry one.
Fig. 2.8 Precipitation during May 1975 to Dec. 1976 in comparison to the 50 year average.
Total precipitation for the 6 month period October 1975 to March 1976 was only 54.1% of the 50 year average for this period. The summer of 1976 which followed proved to be even drier than the previous summer. Total precipitation for the 5 month period April to August 1976 was equivalent to only 32.6% of the 50 year average for this period. The recurrence interval of a drought of such sustained intensity is less than one in a thousand years (C.W.P.U. 1976).

The drought ended in the autumn of 1976 as suddenly as it arrived with the highest autumn falls in Great Britain since records began in 1727 (Walling 1978). Total rainfall for the two months September and October 1976 in the Narrator catchment was 57.9% above the 50 year mean. This whole period of meteorological extremes also included some unusually intense rain storms resulting from convective activity associated with the sub-tropical weather systems which predominated during this period. For one such event, on the 7th July 1975 more than 25 mm fell in a single hour, again breaking all previous records.

Snowfall during the period of observation was less than usual. Moderate falls in late January and early February 1976 resulted in a covering of snow on the catchment, averaging about 10 cm in depth. Total contribution by snow-melt to runoff over the period as a whole is less than 1%.

Although the Narrator catchment may be regarded as broadly representative of the region of Dartmoor Granite, the question inevitably arises as to what extent the period of observation can be regarded as representative of the long term. Input and output totals for this period clearly cannot be realistically equated with long term means. On the positive side, the extreme weather conditions over the period of observation ensured a wide range in values for hydrometeorological variables including storm period precipitation totals, precipitation intensity and catchment wetness. Few storm events in the recent past
or near future are likely to have values for these variables outside this range. Consequently, empirical equations relating hydrometeorological variables to sediment and solute transport during the period of observation can be employed with confidence to predict sediment and solute transport from rainfall and runoff records beyond this period of calibration. In this way long term rainfall and runoff records for the Narrator catchment can be used to determine long term mean fluvial transport rates, when such records become available.

2.7 Channel characteristics

The extent and composition of the channel network in a catchment can have an important influence upon yield of sediment. Ephemeral channels, which in the Narrator catchment include drainage ditches and landrover tracks as well as natural channels, can become an important source of sediment when they are occupied by stream flow.

All tributary channels of the Narrator Brook, both perennial and ephemeral, were surveyed in the field during baseflow in the summer of 1975. The channel network of the Narrator catchment which emerges from field survey is more extensive and varied in composition than appears on large scale topographic maps of the catchment. On the 1:10 560 Ordnance Survey map of the Narrator catchment, which is the largest scale topographic map available, the Narrator Brook appears as a second order stream with 8 first order tributaries. Field survey lifted the Narrator Brook to fourth order with 4 third order tributaries, 14 second order tributaries and 44 first order tributaries (fig 2.9).

It became clear from the field survey that the channel network has been greatly influenced by human activity, particularly mineral exploitation and afforestation. Springs issuing from two of the mine shafts in the catch-
Fig. 2.9 Drainage net in the Narrator catchment
ment nourish tributary streams (South Fork and Deancombe Brook - fig 2.9). At two locations, between Sts 19 and 20, the main stream divides and rejoins. These may be diversions made by prospectors to facilitate tin streaming operations. The channel network has been expanded by the excavation of several artificial tributary channels, together totalling 1 km in length, to improve drainage in the area of the catchment under coniferous forest plantation. For the final 250 m of its course the Narrator Brook itself flows through an artificial channel. The purpose of this is to divert the Narrator Brook through the Head Weir gauging site which is run by the South West Water Authority to monitor inflow to the Burrator Reservoir. Some sections of the landrover tracks which run through the forest plantation in the Narrator catchment support surface runoff during wet periods and become incorporated into the drainage net. From field evidence, including rills and sand bars, these sections of forest track were mapped and are included in fig 2.9.

A large proportion of the drainage net (27%) is ephemeral including all the forestry tracks and the majority of the artificial channels (table 2.4). Ephemeral channels can become an important source of stream sediment. Fine material which accumulates in the channels during dry periods is flushed out when next the channels are occupied by water.

Table 2.4 Composition of the drainage net in the Narrator catchment (figures in Km).

<table>
<thead>
<tr>
<th></th>
<th>Perennial</th>
<th>Ephemeral</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Natural channels</td>
<td>6.45</td>
<td>1.05</td>
<td>7.50</td>
</tr>
<tr>
<td>Artificial channels</td>
<td>0.75</td>
<td>1.04</td>
<td>1.79</td>
</tr>
<tr>
<td>Tracks</td>
<td>0</td>
<td>0.59</td>
<td>0.59</td>
</tr>
<tr>
<td>Total</td>
<td>7.20</td>
<td>2.68</td>
<td>9.88</td>
</tr>
</tbody>
</table>
Ephemeral streams included in fig 2.9 are limited to recognisable channels which have breached the turf, although it has been observed that during prolonged heavy rain streams of water flowing on turf also contribute to tributary channels. The distinction between ephemeral and perennial channels is transient since stream networks expand and contract according to hydrometeorological conditions (Gregory & Walling 1968). During the dry summer of 1975 when the field survey was conducted discharge from the Narrator catchment was even lower than at the height of the record breaking summer drought in August 1976. Streams still running at the time of the survey, therefore, can be regarded for all practical purposes as being truly perennial.

In addition to channels, the drainage net also includes several marshes which support tributary streams (fig 2.9). Research in other catchments has revealed that marshes have an important influence upon both stream runoff (Bay 1969) and stream solutes (Keller 1973). Also included in fig 2.9 are major cattle crossing points which occur at ten locations within the channel network. At these locations damage to stream banks and disturbance of stream bed may provide a source of sediment.

Channel characteristics are closely interrelated with both sediment supply and transport efficiency. The channel profile, planform and geometry of the entire main stem of the Narrator Brook were surveyed in detail. Results are summarized in Appendix 1, table 2.5, and figs 2.10, 2.11 and 2.12. The main stream channel is 3.46 km in length of which 0.19 km is ephemeral. The long profile of the Narrator Brook can be divided into five clearly defined sections of unequal length, three sections of gentle gradient (1,3 and 5) separated by two steeper sections (2 and 4) (fig 2.10). Changes in planform and geometry along the Narrator Brook correspond quite closely to gradient so that in terms of these characteristics also the five
Fig. 2.10 Long profile of the Narrator Brook
Fig. 2.11 Plan of the main channel of the Narrator Brook showing channel bars, eroding banks and stream sampling stations
Fig. 2.12 Stream channel cross sections at 41 locations along the Narrator Brook. Dashed line indicates normal baseflow stage. Location of sections is shown in Fig. 2.11. (View upstream)
Table 2.5 Channel characteristics of the Narrator Brook divided into six stream sections (see fig 2.10).

<table>
<thead>
<tr>
<th>Section</th>
<th>Stream Length(m)</th>
<th>Mean Stream Gradient(m/km)</th>
<th>Mean Stream Sinuosity</th>
<th>Mean Stream Width/Depth Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>630</td>
<td>26.9</td>
<td>1.12</td>
<td>3.9</td>
</tr>
<tr>
<td>2</td>
<td>890</td>
<td>84.5</td>
<td>1.07</td>
<td>7.5</td>
</tr>
<tr>
<td>3</td>
<td>360</td>
<td>27.6</td>
<td>1.13</td>
<td>7.3</td>
</tr>
<tr>
<td>4</td>
<td>240</td>
<td>52.5</td>
<td>1.03</td>
<td>10.2</td>
</tr>
<tr>
<td>5 A</td>
<td>350</td>
<td>17.9</td>
<td>1.29</td>
<td>6.2</td>
</tr>
<tr>
<td>B</td>
<td>1000</td>
<td>15.9</td>
<td>1.08</td>
<td>18.5</td>
</tr>
</tbody>
</table>

Stream source

sections are quite distinct, except for the lower part of section 5 (section 5B) which appears anomalous (table 2.5). Sections 1, 3 and 5A have low gradients; 26.9, 27.6 and 17.9 m/km respectively, compared to 84.5 and 52.5 m/km for sections 2 and 4. These low gradient channel sections are characteristically narrow and sinuous. Average sinuosity values for the sections 1, 3 and 5A (1.12, 1.13 and 1.29 respectively) all exceed corresponding values for the two steep sections (1.07 and 1.03). Similarly average width/depth ratios for the three low gradient sections (3.9, 7.3, and 6.2) are lower than for the two steep sections (7.5 and 10.2). This tendency towards a narrow sinuous channel form in the low gradient sections is accentuated in section 1 by the marshy conditions bordering the channel (fig 2.11). The channel is lined by Sphagnum which protects the banks from erosion and maintains a narrow deep cross-section. The steeper sections (2 and 4) are characterised by wide channels of low sinuosity. These channel sections are typically littered with boulders ranging up to over a metre in diameter and waterfalls over a
metre in height are common.

Section 5B coincides with the coniferous forest plantation in the Narrator catchment. Although this section has a very similar gradient to section 5A (15.9 m/km compared to 17.9 m/km), there are marked contrasts in planform and geometry (table 2.4). Section 5B has a lower sinuosity than section 5A (1.08 compared to 1.29), combined with a higher width/depth ratio (18.5 compared to 6.2). There is also an unusual frequency of eroding banks and gravel bars along section 5B compared with other sections (fig 2.11). These anomalies are related and can be directly attributed to the affects of afforestation. This is discussed in further detail in Chapter 4.
CHAPTER 3
RESEARCH METHODS

3.1 Field methods

3.1.1 Precipitation Measurements

Precipitation input to the Narrator catchment is monitored by a network of four autographic rain-gauges (fig 3.1). Number 1 gauge (Head Weir) is located close to the catchment outfall; number 2 (Combeshead) is in the valley bottom near the centre of the catchment; and numbers 3 (Down Tor) and 4 (Yellowmead) are respectively on the higher northern and southern flanks of the catchment. In addition to precipitation totals, since the gauges are autographic they also provide data relating to the timing of storm events together with their durations and intensities. All four gauges function on the siphon principle; number 1 is a tilting siphon gauge while the remaining three are natural siphon gauges (plates 3.1 and 3.2). The natural siphon gauges, numbers 2, 3 and 4, siphon at intervals of 25 mm precipitation which permits estimation of catches to within 0.5 mm. Number 1 gauge has a greater siphon frequency (every 5 mm) and accuracy to 0.1 mm precipitation catch is possible. All operate on a weekly cycle and whilst this is the most convenient arrangement for the changing of charts it results in some loss of detail. Obtaining storm period totals or mean intensities presents no problems, but totals for periods less than two hours cannot be reliably abstracted and this imposes some limitations particularly in relation to detailed modelling of catchment sediment dynamics. The dense rain-gauge network in the Narrator catchment was considered necessary in order to determine the extent to which precipitation varies spatially within the catchment, and also to provide a safeguard against malfunction or non-operation of one or more of the gauges. The gauges are vulnerable to adverse weather conditions. During
Fig. 3.1 Instrumentation in the Narrator catchment

- Manual sampling site with staff gauge
- Autographic rain gauge
- Automatic gauging and sampling station
- Crest stage soil well
- Bedload trap

--- Sub-catchment boundary

oom hectikometre
Plate 3.1 Rain gauge site 1 (Head Weir). Adjacent to the raingauge is the bulk fallout collector, complete with nylon mesh.

Plate 3.2 Rain gauge site 4 (Yellowmead) with fenced enclosure. In the background, beneath a thin covering of snow, are Down Tor on the left and Combeshead Tor on the right.
winter months, a prolonged period of rain diluting the antifreeze in the float chamber, immediately followed by freezing temperatures, has temporarily put rain-gauges out of action on more than one occasion. Vandalism by visitors to the catchment also proved to be a problem. For two of the total of 81 weeks of observation only one rain gauge was operative and if there had been any less than a total of four gauges a break in the precipitation record could have been incurred.

Measurement of rainfall is subject to many diverse errors arising largely from siting and installation of gauges so that there may be a large discrepancy between gauge catch and actual precipitation (Rodda 1967, Neff 1977). Despite this, even though the degree of exposure varies considerably at the gauge sites in the Narrator catchment, records for the four gauges displayed a marked degree of consistency. Total catch for each of the gauges for the period of observation as a whole deviated by no more than 8.5% from the mean for the four gauges (table 3.1). A large proportion of this variation is undoubtedly due to measurement errors. These results suggest that precipitation in the Narrator catchment is relatively uniform and does not vary in any systematic way with altitude, although exposure differences may be giving an underestimate of precipitation at upland sites (sites 3 and 4). From

Table 3.1 Precipitation received at four gauges within the Narrator catchment for the period 26/5/75 to 13/12/76 (See fig 3.1 for gauge locations).

<table>
<thead>
<tr>
<th>Gauge No.</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total catch (mm)</td>
<td>1876</td>
<td>2070</td>
<td>1880</td>
<td>1801</td>
<td>1907</td>
</tr>
<tr>
<td>Percentage deviation from mean</td>
<td>1.6</td>
<td>8.5</td>
<td>1.4</td>
<td>5.6</td>
<td></td>
</tr>
<tr>
<td>Gauge altitude (m)</td>
<td>220</td>
<td>271</td>
<td>328</td>
<td>294</td>
<td></td>
</tr>
</tbody>
</table>
these considerations an areal weighting method of computing total catchment precipitation input was not considered necessary and instead a simple mean of records at the four sites was adopted. Mean storm period intensities and other hydrometeorological parameters were also obtained by a mean of the four gauge records.

3.1.2 Stream Gauging

The main gauging site, located at the catchment exit, was equipped to monitor runoff, together with yield of sediment and solutes from the Narrator catchment as a whole. Although geology and gross climate are relatively uniform over the Narrator catchment, there are three contrasting vegetation/soil types present: coniferous forest/brown earth, grassland/brown earth and moorland/stagnopodsol. In order to evaluate the individual effect of each of these upon catchment hydrology, the Narrator catchment was divided into a series of three nested sub-catchments by establishing two additional autographic gauging sites on the Narrator Brook at intervals of 900 m and 2213 m upstream from the catchment exit (Sts 11 and 21 - fig 3.1). It could not be expected that sub-catchment divides would coincide exactly with vegetation and soil boundaries. This rules out the unit source area approach advocated by Doty & Carter (1965) in which individual catchment areas are chosen to be uniform in terms of physical characteristics in order to facilitate interpretation of inter-catchment variations in runoff and sediment yield. However each sub-catchment of the Narrator Brook contains a differing proportion of the three major vegetation/soil types identified in the Narrator catchment and results can be interpreted on this basis (fig 2.7, table 3.2). This approach is facilitated by the sharp boundaries between vegetation and soil types in the catchment and also by their distribution. They succeed each other from east to
Table 3.2 Physical characteristics of three nested sub-catchments of the Narrator Brook.

<table>
<thead>
<tr>
<th>Catchment Area Above</th>
<th>St 21</th>
<th>St 11</th>
<th>St 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drainage Area (Km²)</td>
<td>1.56</td>
<td>3.67</td>
<td>4.68</td>
</tr>
</tbody>
</table>

MAJOR VEGETATION/SOIL TYPES

<table>
<thead>
<tr>
<th></th>
<th>St 21</th>
<th>St 11</th>
<th>St 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moorland/stagnopodsol (%)</td>
<td>99.0</td>
<td>81.7</td>
<td>69.8</td>
</tr>
<tr>
<td>Grassland/brown earth (%)</td>
<td>1.0</td>
<td>16.4</td>
<td>18.7</td>
</tr>
<tr>
<td>Coniferous forest/brown earth (%)</td>
<td>0</td>
<td>1.9</td>
<td>11.5</td>
</tr>
</tbody>
</table>

PHYSIOGRAPHY

<table>
<thead>
<tr>
<th></th>
<th>St 21</th>
<th>St 11</th>
<th>St 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean Altitude (m)</td>
<td>388</td>
<td>350</td>
<td>334</td>
</tr>
<tr>
<td>Mean Slope (°)</td>
<td>5.8</td>
<td>7.6</td>
<td>8.0</td>
</tr>
<tr>
<td>Drainage Density (m/Km²)</td>
<td>89</td>
<td>150</td>
<td>206</td>
</tr>
<tr>
<td>Aspect: Western quadrant (%)</td>
<td>82</td>
<td>67</td>
<td>52</td>
</tr>
<tr>
<td>Eastern quadrant (%)</td>
<td>10</td>
<td>8</td>
<td>7</td>
</tr>
<tr>
<td>Northern quadrant (%)</td>
<td>0</td>
<td>12</td>
<td>18</td>
</tr>
<tr>
<td>Southern quadrant (%)</td>
<td>8</td>
<td>13</td>
<td>23</td>
</tr>
</tbody>
</table>

west down the axis of the catchment so that the Narrator Brook passes through each in turn. By placing the two additional gauging stations as close as conditions allow to the intersection of the boundaries of the three vegetation/soil types with the stream, variation in the proportion of each among the sub-catchments is maximised. In addition to variations in the relative proportion of soil and vegetation types between sub-catchments, there are also appreciable physiographic variations which complicate interpretation to some degree (table 3.2).

One considerable advantage of instrumenting several small catchments within a confined area is that hydrometeorological conditions and catchment inputs can be assumed to be uniform and consequently outputs from each catchment can be directly compared even over single flood events (Parsons et al 1964). Ordinarily, comparisons can only be made on the basis of mean annual outputs, or else by long term cali-
brations of outputs against selected hydrometeorological variables. With this system of nested sub-catchments any downstream changes in runoff, sediment and solute yields recorded at the three gauging sites along the Narrator Brook, may be referred directly to varying vegetation, soil and topographic characteristics between sub-catchments.

While the gauging stations were located as close as possible to the intersection of vegetation and soil boundaries with the stream, the precise locations were governed by the practical requirements of stream gauging with respect to availability of suitable channel sections. Channel sections at all three sites are straight and free from obstructions so that velocity distributions within the sections are regular, thus facilitating accurate discharge determinations by the area-velocity method. Hydraulic geometry at the chosen section is such that even at the lowest flows both depth and velocity are sufficient to permit current meter measurements. At each site sheets of fibre glass or marine plywood were erected vertically against the stream banks to create flume-like structures (plates 3.3 - 3.8). This stabilizes the channel by preventing bank erosion and also maintains a rectangular cross-section throughout the range of flows. In this way the stage/discharge relation or rating curve is improved so that prediction of stream discharge from stage records becomes more reliable. Providing channel width remains constant with changing stage, the relation between stage and discharge is linear when both are log-transformed and this permits tentative extrapolation of the relation in order to estimate flows beyond the range of field ratings (Linsley et al 1949). Despite regularization of the cross-sections, rating curves for the three gauging sites still display some degree of scatter which could be the result of varying scour and fill on the stream bed, disparities in water surface slope and discharge for a given stage between rising and falling limbs of the hydrograph, or to the changing character of bed material affecting channel roughness and stream velocity.
Plate 3.3 Main gauging site at St 1, showing glass-fibre flume walls and hut containing recording equipment (view downstream).

Plate 3.4 Recording equipment at St 1, including Ott water level recorder and automatic vacuum operated stream sampler.
Plate 3.5 Gauging site at St 11 (view upstream).

Plate 3.6 Recording equipment at St 11, including Ott water level recorder and automatic vacuum operated stream sampler.
Plate 3.7 Gauging site at St 21 (view downstream).

Plate 3.8 Recording equipment at St 21 including pressure bulb type water level recorder and automatic vacuum operated stream sampler.
The relatively large standard errors of the rating regressions, 0.08, 0.09 and 0.11 log units for Sts 1, 11 and 21 respectively, mean that estimation of the higher flows by extrapolation is likely to be subject to some degree of error. The proportion of both total runoff and total solute yield passing the gauging sites at discharges greater than the highest field rating is less than 5% in each case so that overall the error incurred in extrapolation is not considered to be serious. For sediment yield however, this proportion approaches 10%. This source of error could not be avoided and impairs to some extent any comparison of sediment yield between sub-catchments, particularly when differences are small. Automatic water level recorders provide a continuous record of stream stage at the three gauging stations. At Sts 1 and 11 the recorders used are manufactured by Ott. These are of the float and pulley type recommended by the United States Geological Survey (Buchanan & Somers 1968). At St 21 a pressure bulb type recorder manufactured by Negretti and Zambra was employed. While this recorder is cheaper to purchase and simpler to install, it proved troublesome and unreliable resulting in the loss of several weeks of data. Estimating baseflow runoff for periods without autographic stage record at St 21 was not a problem since stage changes during baseflow are gradual and progressive. Runoff volumes for those flood periods at St 21 missing from the stage record were obtained by calibration with records at St 11, 1220 m downstream, based on the period over which flow record for both sites were available (fig 3.3). The relation between storm runoff volumes recorded at the two sites displays a surprising degree of scatter considering the proximity of the two stations on the same stream. The ratio of storm runoff for the two stations is not fixed but varies according to changing storm period rainfall characteristics. This can be traced to the differing proportions of stagnopodsol and brown earth soil types in the sub-catchment areas above Sts 11 and 21 and is the subject
Discharge (Q) litres sec\(^{-1}\)

\[ Q = 0.000137 \times S^{3.224} \]

or \( \log Q = 3.224 \log S - 2.826 \)

Standard error 0.078 log units

---

Discharge (Q) litres sec\(^{-1}\)

\[ Q = 0.010 \times S^{2.959} \]

or \( \log Q = 2.959 \log S - 1.999 \)

Standard error 0.086 log units

---

Discharge (Q) litres sec\(^{-1}\)

\[ Q = 0.00000195 \times S^{5.781} \]

or \( \log Q = 5.781 \log S - 4.710 \)

Standard error 0.110 log units

---

Fig. 3.2 Discharge/stage calibrations for three gauging sites on the Narrator Brook. (a) St.1 (b) St.11 (c) St.21.
Fig. 3.3 Relations between quickflow runoff at St. 11 and quickflow runoff at St. 21 for further discussion in Chapter 5.

3.1.3 Stream Sampling Procedure

In order to monitor the export of suspended sediment and dissolved solids from the three sub-catchments of the Narrator Brook, records of variations in sediment and solute concentration at the three gauging sites are required in addition to flow records. For this purpose reliance was placed on a scheme involving stream water sampling coupled with laboratory analysis. The design of such a sampling scheme is critical and hinges firstly upon whether dissolved or suspended solids are being monitored, secondly upon the temporal variability of concentrations, and thirdly upon distribution of concentrations within the
channel cross-section. Sampling programmes have to be tailor-made to suit the situation and no general recommendations are possible (Guy 1970). The present research encompasses both dissolved and suspended solids. Dissolved solids concentration is far less temporally variable than suspended solids and is also uniformly distributed in the cross-section, thus imposing fewer constraints upon the design of a sampling programme. Consequently a sampling programme designed for suspended sediment will automatically accommodate a dissolved solids sampling programme.

Being a small stream the Narrator Brook is characteristically "flashy"; flood periods seldom last more than 24 hours. Since suspended solids concentration always rises markedly during flood events, a large proportion of sediment discharged by small streams may be transported over very brief periods (Piest 1965, Rakoczi 1977). Crisp (1966) reports that 95% of the annual sediment yield of a small Pennine catchment is discharged in less than 5% of the time. This situation demands a high frequency of sampling preferentially concentrated over short flood periods the timing of which cannot be predicted in advance. For the Narrator catchment which is some distance from the centre of operations at Plymouth, this necessitated the adoption of a scheme of automatic remote sampling. For this purpose automatic vacuum bottle samplers, which operate on a weekly cycle, were installed at each of the gauging sites. The sample bottles are evacuated on site by a vacuum pump and a clockwork time mechanism releases the vacuum from each in turn at pre-set intervals so that samples are drawn from the stream into bottles by suction. As well as the units being cheap to buy they are independent of mains supply, robust and simple to maintain. Any minor malfunction can be corrected on the spot thus minimising loss of record. Automatic bottle samplers of one kind or another are standard equipment for water quality monitoring in many research catchments (Witzigman 1962, Hanson 1966,
Doty 1970, Walling & Teed 1971, Painter 1976). The bottle samplers in the Narrator catchment were set to deliver three samples daily during the period of research, one every eight hours. Since the duration of most floods in the Narrator Brook is less than 24 hours, this frequency of sampling is inadequate for defining sediment concentration variations over flood events in sufficient detail to obtain accurate estimates of total transport for each event. For most small streams sediment transport is not distributed evenly over flood events but is concentrated in the rising limb of the hydrograph, which for the Narrator Brook may be no more than four or five hours in duration even for the largest floods. For this reason sampling frequency on the rising limb should be greater than for the falling limb (Guy & Norman 1970). To supplement the sampling programme a series of rising stage samplers were installed at each gauging site. These were constructed from plastic containers and tubing based on a design recommended by the United States Geological Survey (Guy & Norman 1970) (fig 3.4, plate 3.9). During the rising stage of a flood, when the water level reaches the crown of the intake tube, stream water is siphoned into the container expelling air through the exhaust tube. When the level of water within the container reaches the base of the exhaust tube siphoning ceases and the sample is preserved uncontaminated until collection even though the exhaust tube may subsequently become submerged. The sample thus obtained represents stream water at a stage corresponding to the crown of the intake tube, and several samples set at different stages can be used to define concentration variations over the rising stage of floods.

From a combination of the two sampling techniques used at the three gauging stations on the Narrator Brook, a maximum of five samples is obtained for the rising limb of flood events depending on peak stage attained by the flood, together with two or three samples during flood recession which are provided by the automatic bottle sampler. This
scheme proved adequate to define flood concentrations in sufficient detail to derive reliable estimates of total transport of sediment and solutes for individual flood periods. To investigate flood period concentration dynamics in more detail, a high frequency automatic bottle sampler was in service at the main gauging site at the catchment exit in addition to the other sampling equipment described. This sampler is similar in most respects to the other bottle samplers employed in the catchment but the timing mechanism is powered by electricity supplied from a re-chargeable battery rather than by clockwork. It is fitted with a float switch that can be set at any desired stage and is activated when water level in the stream reaches the float. Once activated, samples are drawn at a rate of one every half hour. The markedly asymmetrical form of hydrographs in the Narrator Brook results in far more samples on the falling limb obtained in this way than
Plate 3.9  Array of rising stage samplers at main gauging site. Below the lowest sampler is a submerged container for collecting suspended sediment.

Plate 3.10  Manual sampling site at St 4 with staff gauge.
on the rising limb where sediment concentration variations are greater. For this reason automatic samplers which are designed to sample according to increments of changing stage rather than time intervals have proved more effective for small streams (Beverage & Skinner 1968, Claridge 1973).

In addition to automatic sampling, manual samples were also collected at fortnightly intervals at 30 sampling stations along the Narrator Brook in order to analyse downstream variations in baseflow sediment and solute concentrations (fig 2.9). Each station is equipped with a staff gauge which is read at the time of sampling (plate 3.10). These samples were obtained simply by dipping a wide necked polythene sample bottle into the stream.

Baseflow sediment concentrations in the Narrator Brook are generally below 1 mg/l. At these low concentrations results from automatic bottle samplers proved unreliable due to gradual accumulation of sediment particles in the orifice of intake tubes. This sediment then becomes incorporated in stream samples drawn through the tubes when the sampler is activated, resulting in an over-estimate of true ambient stream concentration. At higher sediment concentrations during flood events the error from this source, in relative terms, is minor.

The sampling programme as a whole thus includes four distinct sampling techniques.

1. Automatic samplers at Sts 1, 11 and 21 sampling at 8 hr intervals with intake set at a fixed level.
2. Automatic sampler at St 1 sampling at 4 hr intervals over flood periods with intake at a fixed level.
3. Rising stage samplers at Sts 1, 11 and 21 with intakes at various levels.

In view of the increase in concentration of suspended sediment with depth in many streams the question arises as
to what extent sediment concentrations derived from these sampling techniques are comparable and to what extent each is a reflection of actual mean concentration in the stream section. Where suspended sediment concentrations vary to any degree in the stream cross-section a velocity weighted depth integrated mean concentration is required before reliable rates of sediment transport can be computed (A.S.C.E. 1969a, Guy & Norman 1970). None of the four sampling techniques adopted for the present study are depth integrating. Moreover, intake velocity in each case differs from contemporary stream velocity. This may give rise to unrepresentative samples, particularly where sand sized particles form an appreciable proportion of total suspended sediment (Guy & Norman 1970). Suspended sediment samplers developed by the United States Geological Survey are designed to overcome both these problems (Guy & Norman 1970). Since these samplers are operated manually, they are generally impractical for small streams where temporal variability of sediment transport is great.

Varying concentration with depth is more pronounced for the larger sediment particles; according to available evidence (Anderson 1942) particles finer than 175 microns appear to be uniformly distributed in natural stream cross-sections. More than 95% of suspended sediment transported during baseflow in the Narrator Brook is finer than 175 microns. In order to test the efficiency of sampling by dipping a bottle into the stream, ten dip samples were collected during baseflow at St 4 together with ten samples obtained using a USDH 48 depth integrating hand sampler (plate 3.11). All samples were collected within a period of 30 minutes. A't' test indicates that there is no difference between the two groups of samples (table 3.3). This endorses results of similar tests carried out in Russian streams (Lisitsyna & Bogolyubova 1965). During storm flow, sediment concentrations in the Narrator Brook increase and particles larger than 175 microns form a larger proportion of suspended load, although this propor-
Plate 3.11  Stream sampling with USDH 48 depth integrating hand sampler.

Plate 3.12  Bedload trap at main gauging site (streamflow is from right to left).
tion generally remains below 10%. Due to the flashy nature of the stream, insufficient data is available from the Narrator Brook to permit a comparative analysis of samples collected automatically with samples obtained from a manual depth integrating sampler. Previous studies, however, have indicated that providing the proportion of particles in suspension larger than 100 microns is below 10%, results from both automatic rising stage samplers and automatic bottle samplers compare satisfactorily with manual depth integrating samplers (Dragoun & Miller 1966, Handa et al 1966, Welborn 1969, Walling & Teed 1971).

Table 3.3 Comparison of suspended sediment concentrations for depth integrated samples with samples obtained by dipping a bottle into the stream. (All samples were collected during baseflow at St 11, Narrator Brook, 2/7/75, 11:00-11:30 am., in the order indicated by the reference numbers. Values are in mg/l).

<table>
<thead>
<tr>
<th>Depth Integrated Samples</th>
<th>Bottle Dipped Samples</th>
</tr>
</thead>
<tbody>
<tr>
<td>1  0.22</td>
<td>11  0.75</td>
</tr>
<tr>
<td>2  0.74</td>
<td>12  0.26</td>
</tr>
<tr>
<td>3  0.57</td>
<td>13  0.66</td>
</tr>
<tr>
<td>4  0.63</td>
<td>14  0.53</td>
</tr>
<tr>
<td>5  0.71</td>
<td>15  0.54</td>
</tr>
<tr>
<td>6  0.89</td>
<td>16  0.25</td>
</tr>
<tr>
<td>7  0.91</td>
<td>17  0.65</td>
</tr>
<tr>
<td>8  0.42</td>
<td>18  0.23</td>
</tr>
<tr>
<td>9  0.54</td>
<td>19  0.28</td>
</tr>
<tr>
<td>10 0.28</td>
<td>20  0.84</td>
</tr>
</tbody>
</table>

Mean 0.59 0.55

\[ t = 0.40 \text{ (not significant)} \]
Possible inadequacies in the sampling scheme described may have adversely affected the accuracy of results, particularly in the case of suspended sediment. Inevitably, possible inaccuracies accrued from sampling and other sources impose some constraint upon interpretation of results. In the case of dissolved solids, interpretation of results is not constrained to the same degree by limitations in sampling techniques. In turbulent streams, solute concentration is uniform through the channel cross-section and a sample drawn from any part is representative of the whole (Glover & Johnson 1974).

3.1.4 Bedload Measurements

In addition to stream sampling for suspended sediment and solutes, transport of bedload was also monitored at the main gauging site. The primary purpose of this was to obtain total output of sediment from the Narrator catchment and to determine the relative importance of bedload transport in comparison to other forms of fluvial transport. As a result of observational difficulties, research into bedload transport has lagged behind suspended sediment and solutes, and there is a dearth of reliable field measurements (Painter 1976).

Several methods have been evolved to measure rates of bedload transport. A recent development is the use of acoustic devices (Johnson & Muir 1969, Anderson 1976). More commonly bedload samplers of varying designs are employed (Hubbell 1963). These are lowered to the stream bed at time of flood to collect bedload sediment in transport. All bedload samplers require manual operation and since rates of bedload transport are subject to very rapid fluctuations, estimating long term yields on the basis of frequent sampling is seldom practical, more especially in small flashy streams. An additional disadvantage is that no matter how well they are designed, the presence of the
sampler on the stream bed disturbs flow patterns to some degree diverting movement of bedload away from the sampler orifice. None of the bedload samplers examined by Novak (1957) in flume tests achieved more than 70% sampling efficiency.

An alternative method is to sink a permanent trap into the stream bed (e.g. Lewin & Brindle 1977, Gomez 1979). In this situation, since there is no protrusion above the stream bed, interference with fluid dynamics and particle movement is minimised and collection of bedload in the trap approaches 100% efficiency. However, one possible source of error is removal of sediment by scour after it has been detained in the trap. Bedload monitoring by this method is automatic in that it does not require the presence of an operator during flood events. With a few exceptions (e.g. Leopold & Emmett 1976) this method is, for obvious practical reasons, generally restricted to small streams. Normally bedload traps furnish only total transport over the period since the trap was last emptied with no indication of variations during the period. This can become a distinct drawback in attempts to model bedload transport dynamics.

The bedload trap installed in the Narrator Brook was specifically constructed for the purpose and consists of three parts (fig.3.5, plate 3.12). A rectangular box of marine plywood 15cm by 40cm was sunk into the stream bed and remained a permanent fixture. The leading edge of the box was flush with the stream bed. This is critical if the lower rates of bedload transport are to be detected. Inside the box was a lining of soft vinyl on a wire frame which could be removed to recover collected bedload. A removable wooden frame in the top part of the box held the inner lining in place and prevented bed material from entering the gap between outer box and inner lining. This frame also supported a raised section at the downstream end of the trap with a supplementary collection bag. This raised section was designed to trap saltating particles
Fig. 3.5 Bedload trap at St. 1, Narrator Brook

which might otherwise have bypassed the trap. Additionally, it reduces the possibility of subsequent removal of bedload from the trap by scour. It was hoped that this structure would be far enough from the leading edge of the trap to avoid serious disturbance of bedload movement in this vicinity.

The width of the trap is 15cm, which, at its location at the main gauging site on the Narrator Brook is 1/14th of the stream width. The only two hydraulic factors affecting bedload transport which vary to any degree across a channel section are stream depth and stream velocity (Colby 1961, Skibinski 1968). Since both these factors vary across the stream section at the main gauging site, so too does bedload transport. If reliable estimates of total bedload transport are to be obtained the trap has to be located where rate of transport is likely to be representative of the cross-section. The bedload trap was positioned at a point where depth and velocity
both approximate mean values for the cross-section as a whole. Here it is likely that rate of bedload transport also approximates a mean value for cross-section and thus multiplying trap catch by 14 yields a reasonable estimate of the total bedload transport through the cross-section. For a limited time towards the end of the period of observation, comparison is possible with results from a bedload trap installed a short distance downstream and covering the entire width of the channel (Gomez 1979, fig. 3.6).

\[ \text{(Catch of 'partial width' bedload trap - Kg)} \times 14 \]

**Fig. 3.6 Relation between catch of partial width bedload trap and catch of full width bedload trap, St. 1, Narrator Brook (Data for full width bedload trap is from Gomez 1979)**
Although the data are sparse a broad measure of agreement is apparent. There are however, short term disparities in recorded bedload by the two traps which may perhaps be attributed to changing location of the stream thalweg or changing composition of bed material across the channel. While this to some degree adversely affects the efficiency of partial width traps for investigating detailed temporal dynamics of bedload transport, providing the trap is carefully positioned these irregularities appear to be averaged out over time so that estimates of long term transport rates by this method are probably quite sound. The trap was emptied at weekly intervals during the period of research except during periods with little recorded change in stream stage. During these periods the trap was left two or more weeks before recovery of collected bedload. Period trap catches were then summed to obtain total catchment output for comparison with other forms of fluvial transport. One problem encountered in bedload measurement was related to its large temporal variability stretching over three orders of magnitude. During a four week period in April and May 1976 total bedload discharge of the Narrator Brook was less than 0.024 kg/m/week, while for 5 of the 81 weeks of observation the bedload trap was completely filled representing a bedload discharge of at least 24 kg/m/week. On these occasions the extent to which the capacity of the bedload trap was exceeded is uncertain and actual discharge of bedload for these times is unknown.

A further difficulty arises in distinguishing between bedload and suspended load. On occasions, as much as 10% of the bedload collected in the Narrator Brook was less than 300 microns in size. During higher flows particles larger than this size on the stream bed become part of the suspended load. There is thus an overlap between the two forms of transport and Einstein et al (1940) maintain that in most streams the distinction is merely one between methods of observation. For the present research all sediment collected in the stream bed trap was regarded as
bedload and all sediment extracted from stream water samples as suspended sediment.

3.2 Laboratory methods

3.2.1 Suspended Sediment

Several standard procedures are available for laboratory determination of the sediment concentration of stream samples which are described in A.S.C.E. (1969b) and Guy (1969). Choice of method depends upon the range of concentrations to be analysed. For the Narrator Brook where concentrations seldom exceed 100mg/l the most suitable method is vacuum filtration. This method involves passing the sample through a pre-weighed filter; maintaining a vacuum within a flask below the filter housing speeds rate of filtration. Filter with filtrate is then dried at 105°C for a period of not less than one hour and allowed to cool in a desiccator before reweighing to determine the weight of filtered sediment. Results are reported in mg/l by making adjustment for the volume of sample filtered where this is not a litre. The volume of sample which should be filtered depends upon the expected concentration, the aim being for samples with low concentration to maximize as far as possible the amount of sediment on the filter in order to reduce weighing errors. Gregory & Walling (1973) recommend that sample volumes for filtration should be at least around 250ml to 500ml. In the present study, for samples from both the rising stage samplers and the storm period automatic vacuum bottle sampler which contain the highest concentrations, volumes filtered varied between 250ml and 350ml. Sample volumes from the three standard automatic vacuum bottle samplers were greater, in the range of 450ml to 550ml, and for the hand samples taken during baseflow when concentrations are generally below 1mg/l, volume filtered was 650ml. The
pore size of filter used affects the amount of particulate matter retained and therefore influences computed sediment concentrations. The division between particulate and dissolved solids is diffuse. Colloids which display physical characteristics of both particulate and dissolved matter occupy a broad transition in the size range 0.5 microns to 0.001 microns. The filter pore size selected for laboratory analysis of sediment concentration in the present study is 0.22 microns recommended by Douglas (1971). This falls in the central part of the colloidal size range; some colloidal material finer than 0.22 microns thus passes through the filter and is not recorded as suspended sediment. During flood periods in the Narrator Brook the stream becomes discoloured with colloidal humus and even after filtration slight discolouration remains. Consequently, as with bedload and suspended sediment, where the distinction depends upon methods of field observation, the distinction between suspended solids and dissolved solids depends upon the method of laboratory analysis (Loughran 1971). For the present study material retained on the 0.22 micron filter was regarded as suspended solids and that passing through as dissolved solids. Filter pore size selected, providing it is within the colloidal size range, is not critical since in most situations gravimetric concentrations of colloids is very small in comparison to both suspended sediment and solutes. In the higher reaches of the Narrator Brook colloidal concentrations are high even during baseflow when concentration of larger sediment particles is very low. In this situation filter pore size may significantly effect sediment concentration determinations.

Although filtration is the most accurate method for laboratory determination of sediment concentration and therefore the most suitable for concentrations in the range 1 to 100mg/l, the method is subject to error from several sources (Douglas 1971, Loughran 1971). With smaller concentrations below 1mg/l these errors have
relatively greater impact rendering results difficult to reproduce (Loughran 1971). Such low concentrations can only be successfully analysed in the laboratory with sample volumes greater than half a litre and also by observing certain precautions. The major source of error arises from a drop in filter weight particularly during filtration and oven drying. This weight loss may be a result of dissolution, during filtration, of glycerol which is present in small amounts in all membrane filters (Winneberger et al 1963). Alternatively it may be due to partial volatilization of the filter during oven drying or else loss of filter paper fragments during handling. These weight losses can be reduced for glass fibre filters by first soaking the filter in distilled water and oven drying, before commencing analysis. Experiments with membrane filters, however, show that weight loss does not decrease substantially even after several wetting and drying cycles so that this precaution is ineffective for membrane filters (Douglas 1971). Filter weight may also be influenced by changing humidity in the laboratory due to absorption of water vapour from the atmosphere; both filter and filtrate are hygroscopic. All filter weight changes were compensated for by the use of the control filter method used previously by Winneberger et al (1963) and Douglas (1971). The control filter undergoes exactly the same treatment as the filter or batch of filters being used for analysis of stream sediment concentration, except that an equivalent volume of distilled water is passed through the control filter in the place of stream water. Any change in weight experienced by the control filter is applied as a correction to the remaining filters in the batch.

Even after other possible sources of error have been tackled, sediment concentrations determined by filtration were subject to random weighing errors amounting to \( \pm 0.3 \text{mg/l} \). As a result, at concentrations below 1mg/l which is usual for the Narrator Brook at baseflow, reproducibility
is poor. However a mean of several values irons out the errors to a large degree. Laboratory determined sediment concentrations for two groups of ten samples, drawn from a single site over a 30 minute period during steady base-flow, range from 0.22 to 0.91mg/l (table 3.3). Mean values for the two groups, however, are very similar. At higher concentrations during storm periods errors incurred in the filtration method become insignificant. Above 100mg/l filtration is unsuitable because the amount of sediment retained on the filter is such that there is a danger of spillage during handling. In addition, if there is an appreciable proportion of clay and colloidal sized sediment, rate of filtration is slowed to such a degree that several days may be required to filter a 250ml sample. This situation is unsatisfactory if a large number of samples need to be filtered.

An alternative method of analysis used in this study for concentrations in excess of 100mg/l, is evaporation of a measured volume of sample in a pre-weighed evaporation dish as described in A.S.C.E. 1969b. The dissolved solids content of the sample has to be estimated and deducted from the weight of residue, and this invariably introduces a measure of inaccuracy into the method. Weighing the residue accurately also presents difficulties since generally its weight is greatly exceeded by the weight of the evaporating dish in which it is lodged. A lower ratio of the weight of the receptacle to the item to be weighed is desirable for more accurate weight determination. Errors in this method were minimised in the present study by first centrifuging the sample, decanting the supernatent liquid, and transferring the slurry to a small crucible for evaporation and weighing.

3.2.2 Solutes

The total solutes content of stream samples was determined indirectly from their specific electrical
conductance; values are recorded in micromhos/cm reported to a standard temperature of 25°C. The conductivity of water is a function of the concentration and proportional representation of electrical charged dissolved constituents and also of the temperature of the solution. At constant temperature, for a given admixture of ions, specific conductance (S.C.) is directly proportional to total dissolved solids (T.D.S.).

\[ S.C. = K \times T.D.S. \quad \ldots \ldots \ldots \ldots \ldots (3.1) \]

The constant of proportionality \( K \) depends upon the relative proportion of ions present. For a pure solution of sodium chloride, which is the major dissolved constituent of precipitation, \( K \) is 0.48, while for a pure solution of calcium bicarbonate, the main chemical product of rock weathering, it is 1.6 (Golterman & Clymo 1969). For all natural streams \( K \) can vary between these two limits depending upon the relative contribution to stream solutes from precipitation and rock weathering, but usually \( K \) lies in the range of 0.55 to 0.90. \( K \) remains constant for a particular stream as long as the relative proportion of dissolved constituents does not vary to any large degree (Paras 1971). The value of \( K \) can be determined by regression of specific conductance with measured total dissolved solids for selected samples, preferably covering as wide a range in concentration as possible. This was done for the Narrator Brook as shown in fig 3.7 with total solute concentrations ranging from 26 to 71mg/ℓ and conductivity from 49 to 104 micromhos/cm. For calibration purposes, total dissolved solids was determined by evaporation of a measured volume of prefiltered sample. The greater part of the scatter in the calibration can be attributed to the large degree of inaccuracy inherent in the determination of total dissolved solids by the evaporation method. Sources of error include volatilisation of certain salts, retention of water of crystallisation,
Fig. 3.7 Calibration of total solute concentration against specific electrical conductance for stream water and precipitation in the Narrator catchment
and absorption of atmospheric water vapour (Hem 1970). Some scatter is also due to the presence of dissolved constituents which are not electrically charged, notably silica. Silica contributes to total dissolved solids but has no effect upon the electrical conductance of the solution (White et al. 1963).

The K value of 0.77 for Narrator stream water is probably equally applicable to all streams draining the Dartmoor Granite; since lithology is uniform the relative proportion of ions present is unlikely to alter appreciably from stream to stream. Other K values in Britain determined by the same procedure include 0.65 for the Exe River Basin (Walling & Webb 1975) and 0.91 for a Mid-Wales catchment (Cryer 1976). The calibration for precipitation over the Narrator catchment, also shown in fig 3.7, has a K value of 0.56, which is rather lower than the 0.77 for Narrator stream water. This reflects the predominance of sodium and chloride in precipitation solutes. Lesser proportions of magnesium, sulphate and other ions are responsible for pushing the K value slightly above that of 0.48 for a pure solution of sodium chloride. The larger negative intercept for the precipitation calibration in comparison to that for stream water may be a result of the relatively low pH of precipitation. Precipitation pH values vary between 3.5 and 5.0 in comparison to the corresponding limits for stream water of 5.0 and 6.0. Ionized hydrogen affects conductivity but does not contribute to the gravimetric concentration of total dissolved solids (Edwards et al. 1975).

Although an indirect method of determining total dissolved solids specific conductance has the advantage of being both rapid and cheap so that large numbers of samples can be analysed. It is also a very sensitive measure and results are reproducible to within 1%. This permits detailed investigations of the small spatial and temporal variations of stream solute concentrations occurring within the Narrator catchment which would not be possible
using the evaporation method.

Total dissolved solids can also be obtained by summation of the major solute constituents determined individually. As well as being time consuming, by summation of individual constituents, inaccuracies in the determination of each are compounded reducing the sensitivity of the method. However, information regarding the composition of total dissolved solids is required for delimiting the major sources of stream solutes. Individual dissolved constituents were analysed for selected samples according to standard methods including flame photometry for sodium and potassium; atomic absorption spectrophotometry for calcium, magnesium and iron; specific ion electrode for chloride; and auto-analyser for silicon and nitrate. As with total dissolved solids, concentrations of major constituents for selected samples may also be calibrated against specific conductance (Steele 1976; fig 3.8).

3.2.3 Bedload

Bedload collected in the Narrator Brook was first dried and organic matter removed before weighing. For the larger samples, over 0.5kg, organic matter, leaves and twigs, were removed by hand. For samples smaller than about 0.5kg, organic matter was removed by heating the sample to 500°C in a furnace for a period exceeding 12 hours as described in Briggs (1977a). After weighing, each sample was subjected to particle size analysis by the dry sieve method (Briggs 1977b). Mesh sizes employed for the particle size determinations of bedload samples, and also samples of bed material collected in the Narrator Brook, ranged from +4ϕ(0.075mm) to -4ϕ (16mm) at intervals of 1ϕ.
3.3 Computational methods

3.3.1 Delimitation of Storm and Flood Events

According to many workers (Collier 1963, Guy 1964, Rendon-Herero 1974, Walling 1977) the flood event is the most logical unit as the basis for investigation of the controls of sediment and solute dynamics. As a result of the variable lag between changing precipitation characteristics experienced at the catchment surface and concentration of sediment or dissolved solids observed in the...
stream, relating instantaneous concentrations to hydro-
meteorological factors is not feasible. Flow records from
the Narrator catchment were separated into discrete flood
events and precipitation records were separated into

corresponding storm events. Mean flood period sedi-
ment and solute concentrations were then subjected to
multivariate analysis. Mean storm period precipitation
parameters and mean flood period streamflow parameters
were included in the analysis as independent variables.

Stream discharge records over the period of observation
were divided into quickflow and baseflow by hydrograph
separation employing the method devised by Hibbert &
Cunningham (1967) and used by Walling (1971b). The method
assumes a uniform increase in baseflow discharge of 0.55
l/s/hr/km² during the flood event (fig. 3.9). It has the

Method assumes that baseflow
increases at a rate of 0.55 l/s/hr/km²
during the flood event.
Drainage area of the catchment is 4.68 km²
Baseflow discharge immediately
prior to flood at point X is 52 l/s
Rising baseflow line intersects
recession limb of hydrograph at Y,
9 hours later, at a discharge of
(0.55 \times 9 \times 4.68) + 52 = 75 l/s

Fig. 3.9 Hibbert and Cunningham's (1967) method
of hydrograph separation applied to a
flood event recorded on the 7th and 8th
of July 1975 at St. 1 on the Narrator
Brook
advantage of being objective, precise and totally reproducible. However, no genetic connotations can be attached to quickflow and baseflow separated in this manner; no pathways can be implied. A flood event, for the purpose of this research, is defined as a rise in stream stage involving some quickflow runoff for at least one of the three gauging stations along the Narrator Brook, and is distinguished from a subsequent event by a return to baseflow. Very small stream rises which do not generate quickflow do not qualify as flood events and were not included in subsequent analysis. Some events are composite including two or more individual rises before a return to baseflow. These are treated as a single event. Seventy-one flood events thus defined occurred during the period of observation with volumes of quickflow runoff at the main gauging site at the catchment exit ranging from 419 m$^3$ (0.09mm) to 87 316 m$^3$ (18.7mm).

Delimitation of individual precipitation or storm events has to be standardized in order to preserve objectivity as in many cases the precise limits of a storm event are not clearly defined. The most suitable scheme depends on the nature of the catchment. For the present study a storm event is defined as consisting of at least 10mm precipitation and is separated from both previous and subsequent storm events by at least eight hours without measurable precipitation. Sixty-three such events occurred during the period of observation with storm period precipitation ranging from 10.0mm to 78.8mm and together amounting to 75.7% of total precipitation for the period as a whole. An eight hour interval between storm events proved the most suitable compromise for matching storm events with flood events in the Narrator catchment. A shorter time interval and separate storm events so designated become merged into a single flood event while a longer time interval results in single storm events encompassing more than one flood event. With an eight hour interval there is very little such overlap. Only three
of the 63 storm events include more than a single flood event, and only two of the 71 flood events are spread over more than a single storm event. Similarly, a minimum requirement of 10mm precipitation for defining storm events proves most suitable for the Narrator catchment although inevitably not all the storm and flood events correspond. During the period of observation, 11 of the 63 storm events are unmatched by flood events while 21 of the 71 flood events were generated by non-storm precipitation events. There are thus a total of 82 events which can be classed as either flood events or storm events or both. This does not include two small flood events which occurred during early February 1976, each of which resulted from rainfall upon melting snow. Since these floods were supplied in part by snow-melt, associated sediment and solute yields cannot be directly related to precipitation characteristics. For this reason these events are not included in multivariate analyses, but are treated separately.

3.3.2 Derivation of Variables

Variables included in multivariate analysis include, besides sediment and solute concentrations, hydrological and precipitation parameters together with indices of catchment wetness and seasonality. A fundamental feature of all indices and parameters used in the present study is simplicity and reproducibility. Gregory & Walling (1973) stress the need to base indices upon readily available data so that they can become standardized thus facilitating comparisons between different studies. Most have been employed in previous studies of sediment and solute dynamics, but some are new. The dependent concentration parameters were derived in the following manner. From concentration of stream samples, together with stream discharge at the time of sampling, mean discharge weighted sediment and solute concentration \( C_{FP} \)
was computed for each of the flood events (equation 3.2).

\[ (C_{FP}) = \frac{\sum_{i=1}^{n} (C_i Q_i)}{\bar{Q}} \]  \hspace{2cm} (3.2)

where \((C_{FP})\) is mean flood period discharge weighted concentration \((\text{mg/} \ell)\)

- \(C_i\) is concentration of individual stream samples obtained during flood period \((\text{mg/} \ell)\)
- \(Q_i\) is stream discharge at the time of sampling \((\ell/\text{s})\)
- \(\bar{Q}\) is mean flood period discharge \((\ell/\text{s})\)

As a result of the dissimilar frequencies of sampling adopted for the rising and falling stages of flood events in the Narrator catchment (see section 3.1.2) it became necessary to determine separate discharge weighted concentrations for rising and falling stages before combining the two into a single value for the flood event as a whole. The disparity in concentrations between rising and falling stages varies according to hydrometeorological conditions and is discussed further in chapter 6.

Guy (1964), Walling (1971a), Herb (1976), and others rely on mean discharge weighted flood period concentrations as dependent variables in multivariate analysis. In this study calculations were carried a stage further by obtaining mean concentration of quickflow (equation 3.3).

Quickflow concentrations are more useful for investigating the controls of flood period sediment and solute dynamics than flood period concentrations since they are likely to be more sensitive to changes in hydrometeorological conditions. This is because baseflow discharge during flood periods, as determined by the method of Hibbert & Cunningham (1967) described in section 3.3.1, is unaffected by storm period hydrometeorological conditions. Even though baseflow sediment and solute concentrations in the Narrator Brook are relatively uniform over time, the changing proportion of baseflow to total flow for different flood
where \( C_{QF} = \frac{(C_{FP}Q_{FP}) - (C_{BF}Q_{BF})}{Q_{QF}} \) (3.3)

Events has a large influence upon flood period concentrations complicating multivariate analysis. Only those events, numbering 37 in all, for which quickflow amounted to at least 20% of total flow were included in multivariate analysis. This restriction was imposed because in cases when quickflow is a very small proportion of total flow, small inaccuracies in the determination of mean storm period concentration, incurred in both stream sampling and laboratory analysis, become greatly magnified when converted to quickflow concentrations.

In order to obtain total yield of suspended sediment and dissolved solids for the period of observation as a whole, mean discharge weighted quickflow concentrations were multiplied by quickflow runoff to give quickflow yield of sediment and solutes for each event. These were then summed and added to the baseflow yield of sediment and solutes for the period of observation (table 3.4). Baseflow yields were obtained by multiplying mean baseflow concentrations by baseflow runoff. Mean baseflow concentration at the three gauging sites were determined on the basis of 27 samples collected at each site during the period of observation (table 3.4). For multivariate analysis concentration is preferable to yield since it is a more independent measure. Yield of sediment and solutes is a product of both concentra-
Table 3.4 The baseflow component of outputs from three sub-catchments of the Narrator Brook, 26/5/75 to 13/12/76.

<table>
<thead>
<tr>
<th>Gauging Station</th>
<th>1</th>
<th>11</th>
<th>21</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean baseflow suspended sediment concentration (mg/l)</td>
<td>0.65</td>
<td>0.54</td>
<td>0.37</td>
</tr>
<tr>
<td>Mean baseflow specific conductance (μmhos/cm)</td>
<td>55.5</td>
<td>50.5</td>
<td>47.5</td>
</tr>
<tr>
<td>Mean baseflow concentration of total dissolved solids (mg/l)*</td>
<td>41.6</td>
<td>37.9</td>
<td>35.6</td>
</tr>
<tr>
<td>Baseflow runoff (m$^3$.10$^3$)</td>
<td>5 385</td>
<td>4 884</td>
<td>1 790</td>
</tr>
<tr>
<td>Baseflow suspended sediment yield (t)</td>
<td>3.50</td>
<td>2.64</td>
<td>0.66</td>
</tr>
<tr>
<td>Baseflow yield of total dissolved solids (t)</td>
<td>87.2</td>
<td>83.3</td>
<td>77.8</td>
</tr>
</tbody>
</table>

* Obtained by reference to fig 3.7

... and stream discharge, and this renders interpretation of interrelationships with hydrological and hydrometeorological variables more difficult (Guy 1964).

The independent variables included in multivariate analyses are listed in table 3.5. Peak discharge and mean discharge are used to represent the transporting power of the stream during the flood event. Quickflow runoff and intensity of flood rise are useful indices which relate to catchment condition and sources of storm runoff in the catchment. When the catchment is wet and overland flow becomes important, a large volume of quickflow runoff can be expected, combined with a steep flood rise. Following Bobrovitskaya (1967) and Walling (1971a) intensity of flood rise is calculated as the difference between peak discharge and preceeding baseflow discharge divided by the time of rise in hours. Total storm period precipitation, precipitation intensity, catchment wetness and season influence runoff generation on catchment slopes and the supply of both sediment and solutes to the stream channel. Total
Table 3.5 Independent variables included in multivariate analysis of sediment and solute dynamics in the Narrator Brook.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Units</th>
<th>Range of variation-Encountered During Period of Observation</th>
<th>Previously Employed in Multivariate Studies of Stream Sediment and Solute Dynamics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak discharge</td>
<td>( l/s )</td>
<td>68-2146</td>
<td>1, 2, 3, 4</td>
</tr>
<tr>
<td>Mean flood period discharge</td>
<td>( l/s )</td>
<td>60-776</td>
<td></td>
</tr>
<tr>
<td>Flood period quick-flow runoff</td>
<td>( m^3 )</td>
<td>0-87316</td>
<td>2, 3, 5</td>
</tr>
<tr>
<td>Baseflow discharge preceeding flood event</td>
<td>( l/s )</td>
<td>52-376</td>
<td>1, 2, 3, 6</td>
</tr>
<tr>
<td>Intensity of flood rise</td>
<td>( l/s/hr )</td>
<td>1.2-405.0</td>
<td>2, 6, 7</td>
</tr>
<tr>
<td>Total storm period precipitation</td>
<td>( mm )</td>
<td>3.8-78.8</td>
<td>1, 2, 3, 5</td>
</tr>
<tr>
<td>Mean storm period precipitation intensity</td>
<td>( mm/hr )</td>
<td>0.3-9.9</td>
<td>1</td>
</tr>
<tr>
<td>Maximum two-hour precipitation</td>
<td>( mm )</td>
<td>1.8-35.5</td>
<td></td>
</tr>
<tr>
<td>Antecedent precipitation (A.P.I.(_{30}))</td>
<td>( mm )</td>
<td>0-59.9</td>
<td>8</td>
</tr>
<tr>
<td>Seasonal index</td>
<td>-</td>
<td>0-1.0</td>
<td>9</td>
</tr>
</tbody>
</table>

1 Guy 1964                                     2 Walling 1974b 3 Herb 1976
4 Foster 1978b                                 5 Walling 1971a 6 Walling & Teed 1971
7 Bobrovitskaya 1967                          8 Spraggs 1976 9 Cryer 1976

precipitation and precipitation intensity determine the kinetic energy of precipitation. Rainfall energy is commonly used to model both soil loss and sediment yield (e.g. Wischmeier & Smith 1858, Dragoun 1962). However, rainfall energy in these studies is computed solely from rainfall depth parameters (Hudson 1971). Tests by Elwell & Stocking (1974) reveal that depth parameters are as equally effective as energy parameters in modelling soil
loss, and are to be preferred since they are more convenient.

Mean storm period precipitation intensity and maximum two hour precipitation are both measures of precipitation intensity. Mean precipitation intensity is computed by dividing the total precipitation of a storm event by its duration. When a storm event includes two or more episodes of precipitation separated by dry periods which may be up to eight hours in duration, mean intensity can become unrepresentative. Maximum short period intensities are more sensitive. Shorter period intensities than the two hour period used in the present study would probably prove more effective. Wischmeier and co-workers employ maximum half-hour precipitation intensities for modelling rates of soil erosion and stream sediment transport (Wischmeier et al 1957, Wischmeier & Smith 1962, Wischmeier 1977) and maximum 5 minute intensity is used by Fournier (1972) for the same purpose. Unfortunately the automatic precipitation gauges employed in the Narrator catchment, which operate on a weekly cycle, do not supply a sufficiently detailed record to permit determination of shorter period intensities than two hours, within acceptable limits of accuracy.

Baseflow discharge and antecedent precipitation are all measures of catchment wetness. Baseflow discharge preceding a flood event has been used by Guy (1964), Walling (1971a) and others for this purpose. In the Narrator catchment baseflow discharge is relatively insensitive to fluctuations in wetness of the catchment surface. Up to 10mm of light rain can fall in the Narrator catchment without any measurable effect upon streamflow. For this reason antecedent precipitation is likely to be a more effective index of catchment wetness. The 30 day decay index, $API_{30}$, first devised by Osborn & Lane (1969), has previously been used as a measure of catchment wetness by Weyman (1974), and Spraggs (1976).
$$\text{API}_{30} = \frac{1}{30} \sum_{i=0}^{30} \text{Pi} \quad \text{..........................(3.4)}$$

where \( \text{Pi} \) is the precipitation on the \( n \)th day preceding the storm event.

This index preferentially weights precipitation for days closer to the storm event.

The seasonal index is that used previously by Cryer (1976) and computed from:

$$D = \frac{183}{183} \left( \begin{array}{c} \text{sign} \end{array} \right) \quad \text{..........................(3.5)}$$

where \( D \) is the number of days since the preceding 1st. of January. This index corresponds closely with seasonal fluctuations in evapotranspiration rates in the catchment, for which it may be conveniently regarded as a surrogate (fig 3.10). Evapotranspiration partly controls catchment wetness, which in turn influences the availability of sediment on catchment slopes. Detailed records of evapotranspiration for the Narrator catchment, however, were unavailable during the period of research.

![Graph showing seasonal index and potential evapotranspiration](image)

**Fig.3.10** Relation between seasonal index and estimated potential evapotranspiration in the Narrator catchment for the period May 1975 to Dec. 1976 (Total monthly potential evapotranspiration in the Narrator catchment, mean altitude 334m above O.D., is estimated from a mean of data at Plymouth, 20m above O.D., and Princetown, 620m above O.D.)
3.3.3 Multivariate Analysis

Multiple regression is without doubt the most popular multivariate technique in the analysis of temporal variations in stream sediment and solute transport (e.g. Guy 1964, Walling 1971a, Walling & Teed 1971, Herb 1976, Wood 1977, Foster 1978b). A major problem facing such studies is multicollinearity. Since hydrological response is determined by hydrometeorological conditions, a high degree of intercorrelation between the independent hydrological and hydrometeorological variables is only to be expected. One of the two principle uses for multiple regression is for prediction. A goal of the present research is to establish predictive equations by multiple regression whereby short term fluvial transport records may be extended by reference to long term hydrological and hydrometeorological records. Multicollinearity does not affect the predictive use of multiple regression. It does, however, seriously impair the physical interpretation of results with respect to deducing the underlying processes and mechanisms. Multiple regression in fluvial transport studies is more commonly used for this purpose than for prediction.

In order to make any meaningful inferences from multiple regression it is necessary to isolate the truly independent controls. For this reason, Imeson (1969) advocates the use of principle component analysis. A major drawback of principle component analysis is that it is not a predictive tool.

In the present study the truly independent controls were isolated from multiple regression analysis by using a "forward elimination technique" described by Mather (1976). The first step is to select among the list of independent variables the one having the highest significant correlation with the dependent variable and enter it in the regression. The remaining variables are then tested by means of a partial F-test, to see which adds most significantly to the regression. This procedure is continued until none of the
remaining variables add significantly to the multiple regression at the 0.01 level. It can then be concluded that any variable which fails to contribute significantly to the regression has no significant independent effect upon the dependent variable. The 0.01 level of significance is adopted as the minimum acceptable level since in regressions with as many as 10 independent variables the 0.05 level is not sufficiently stringent.

It is of critical importance with respect to interpretation of multiple regression results that all possible variables, both hydrological and hydrometeorological, which could logically contribute to variance in fluvial transport rates are included in the analysis. No physical meaning can be attached to a significant contribution to explanation in variance of the dependent variable by an independent variable unless this has been achieved in competition with all other variables that might be expected to have some influence.

Both log transformed and untransformed data were tested in multiple regression analysis. Hydrological data are characteristically skewed in a positive direction. In analysis of both storm period sediment concentrations and bedload transport rates, log transformation, which normalizes positively skewed data, provided marginally better explanation of variance than untransformed data.
CHAPTER 4
SEDIMENT YIELD AND SEDIMENT SOURCES

4.1 General considerations

4.1.1 Sediment source categories

The sediment yield of streams is a reflection of both the nature and location of specific sediment sources in the catchment. Sediment sources in a catchment may be many and varied and sediment yield from the catchment represents a composite of supply from several sources. Not only does each source deliver sediment with differing particle size distribution, but supply from each is controlled by differing dynamics. In order to understand and thereby define stream sediment dynamics in a meaningful way, source patterns in the catchment need first to be identified. Sediment sources are commonly separated into two broad categories. These are sheet erosion of catchment slopes and erosion of stream channels. Within these two groups specific source areas may be identified such as a construction site or an eroding stream bank bluff.

Sheet erosion is the removal of particles from the soil surface by the action of both rain splash and overland flow. Rain splash is generally considered to be primarily an agent of detachment reducing soil aggregates to primary particles by impact, while overland flow is regarded primarily as an agent of transport conveying from the site of erosion the soil particles made available by rain splash (Morgan 1979). It is apparent, however, that these roles are by no means fixed. Although it is often considered that overland flow is ineffective as an agent of erosion in its own right since flow depth is insufficient to generate the turbulence required, observations by Emmett (1978) on erosion plots led him to conclude that overland flow is capable of erosion even though it is within the laminar flow regime. Conversely, when soil particles on a slope are thrown upward by rain splash there
is a net downslope transfer of soil particles due to the influence of gravity, so that soil splash is also able to contribute to the work of transport (Ellison 1945). Sediment supplied from sheet erosion is relatively fine grained. This is due to the inability of overland flow to transport large particles to the stream channel and also reflects the large proportion of available fines in most soils.

The size of particles derived from channel bank erosion is determined entirely by the particle size composition of bank material. Depending upon flow conditions, the finer fraction of sediment eroded from stream banks may enter directly into suspended sediment transport. The coarser fraction falls to the stream bed where it is stored as bed material. Particles in bed material storage are transported, either as bedload or in suspension, when stream power becomes sufficient to entrain them. The process of stream bank erosion involves the detachment of sediment particles from submerged areas of channel banks by the erosive action of the stream, although sub-aerial processes on exposed areas of the bank, particularly frost weathering, may also play a part (Hill 1973, McGreal & Gardiner 1977). Where the top of the banks are reinforced by riparian vegetation undercutting may occur with periodic bank collapse. This situation is common along much of the Narrator Brook, particularly outside the forest area where the turf mat protecting the channel is thick. At some of the channel cross-sections surveyed outside the forest, the extent of undercutting is such that the width of the stream bed approaches twice the water surface width (fig 2.12).

Although in terms of the processes involved there appears to be a clear distinction between channel sources and slope sources, in practice there is considerable overlap. Rain splash, more commonly associated with sheet erosion, may be responsible for detachment of sediment particles from exposed parts of stream banks. In ephemeral channels sediment particles made available for transport by rain splash are flushed from the channel when
it is next occupied by streamflow.

4.1.2 Methods of sediment source analysis

Two broad strategies have been employed in previous studies to determine the relative contribution to stream sediment transport from specific sources in the catchment. The first involves measurement of erosion at source areas. Channel erosion is relatively localised and thus rates of erosion at a site are often sufficiently rapid to permit direct measurement. Techniques that have been employed in Britain to measure channel erosion include periodic resurveys, time lapse photography, and the use of erosion pins (Hill 1973, Potter 1973, Lewin et al 1974, McGreal & Gardiner 1977). Sheet erosion is more widespread than channel erosion and consequently rate of change at a site is small rendering direct measurement difficult. Direct measurement has been attempted in Britain using erosion pins (Bridges & Harding 1971, Imeson 1971b, Haigh 1977). Sediment traps have also been employed for this purpose (Young 1960, Kirkby 1967). However, according to Megehan & Nowlin (1976, p 4-126): "Actual measurements of soil erosion on a watershed scale are fraught with sampling and measurement difficulties that have been insurmountable to date." Although direct measurement of sheet erosion may be unfeasible, sheet erosion can be estimated from soil erosion models such as the Universal Soil Loss Equation.

However, the major drawback with measuring erosion rates at source areas is that these rates cannot be directly compared to sediment yield to assess their contribution. This is because not all sediment released by erosion at source areas is transported from the catchment as sediment yield. A proportion of the sediment, depending upon the location of the source and the particle size distribution of eroded material, may become stored in the catchment. Sediment derived from sheet erosion may be redeposited on
lower slopes before reaching the stream channel. The factors controlling the delivery of sediment from sheet erosion to the catchment outlet include climate, land use, local environment and general physiography (Piest 1970). Empirical equations have been developed to predict delivery rates for sheet erosion (e.g. Maner 1958, Roehl 1962) but Dickenson & Wall (1977) believe that because of the complexity involved, prediction of delivery rates for sheet erosion is never likely to be successful. Sediment derived from both sheet erosion and channel erosion may also be stored within the channel. The most obvious storage of sediment in the channel is bed material which in most streams consists of particles larger than those normally transported in suspension. However, fines can also be stored in the stream channel in large quantity, particularly in streams where debris dams are common. Sediment trapped behind debris dams is released when the dam fails. The importance of debris dams to the sediment regime of small streams has been stressed by Megehan & Nowlin (1976). Small debris dams do appear for short periods at various locations along the Narrator Brook. Debris is provided by deciduous trees close to the channel which shed leaves, twigs and small branches into the stream. These dams may be responsible for regulating transport of sediment in the Narrator Brook to some degree.

The second major approach to establishing the contribution of various sources to stream sediment yield is through comparison of the characteristics of stream sediment and source materials. Mineralogical characteristics have occasionally been used for this purpose (e.g. Wall & Wilding 1976, Wood 1978, Oldfield et al 1979). More commonly, however, particle size distributions are compared. The proportion of total suspended sediment which originates at the stream bed has been estimated in some streams by comparison of the particle size distribution of suspended sediment and bed material (Einstein et al 1940, Johnson 1943, Hubbell & Matejka 1959). Fines transported in suspension which are poorly represented in bed material are
attributed by this method to sources other than the stream bed and are deducted from total suspended sediment to obtain the contribution from bed material. Similarly Vice et al (1968) estimate the rate of sheet erosion in the catchment of the Scott Run Basin, Virginia, U.S.A. from a comparison of the particle size distribution of stream sediments with catchment soils. They assumed that all eroded soil of clay size and finer is delivered entirely to the stream, and the coarse fraction of eroding soil not present in stream sediments is redeposited on its way to the stream channel. Using the same general approach, Lewin et al (1974) compare the particle size distribution of bed material and bank material to estimate the supply of suspended sediment from bank erosion. They assumed that the sole source of bed material is bank erosion, and that the fine fraction of bank material not present in the stream bed has been discharged as suspended sediment.

A major criticism of this second method of source analysis is the large degree of variability in particle size distribution which is typical of the soil cover of most catchments and the bed and bank material of the majority of streams. Vice et al (1968), for example, rely for their analysis upon "the surprisingly consistent" particle size distribution of soils over the 11.8km² of the Scott Run Basin; a situation which is unlikely to be duplicated in many other catchments of equivalent size.

4.1.3 Methods employed in the Narrator catchment

Elements of both methods of source analysis described above were employed in the Narrator catchment. Visible evidence of recent bank erosion along the main channel of in the forest section of the Narrator Brook suggest that this is likely to be a major source of stream sediment. Estimates of the supply of sediment from this source were obtained by measuring rates of bank erosion. Contemporary rate of bank erosion is measured by use of erosion pins and long term rate of bank erosion by analysis of downstream variations in channel width.
Comparison of the estimated supply of sediment from bank erosion with sediment yield indicates the relative importance of this source in relation to other sources. Contemporary yield of sediment from the Narrator catchment is obtained on the basis of sampling during the period of research. Long term sediment yield is obtained from depth of sediment in the Burrator Reservoir. Comparison of the particle size distributions of bank material and suspended sediment can provide some indication of the proportion of of bank material which contributes directly to suspended sediment transport. The remainder is stored on the stream bed. Assessing the likely importance of catchment slopes as a source of sediment is approached indirectly by assessing the effectiveness of rain splash and overland flow, which are the two agents responsible for supplying sediment from catchment slopes.

Some indication of the relative importance of channel and slope sources can also be gained from multivariate analysis of the factors influencing stream sediment dynamics. If catchment slopes were the major source of sediment, precipitation characteristics would be expected to emerge from multivariate analysis as the dominant factors. Alternatively, if stream channels were the major source of sediment, streamflow characteristics would be expected to assume greater importance than precipitation characteristics. The results of multivariate analysis of sediment dynamics in the Narrator Brook are discussed in chapter 5.

4.2 Sediment yield

4.2.1 Based upon period of observation

Ultimately, estimated supply of sediment from any source has to be compared with sediment yield to determine its contribution to sediment transport. Total yield of suspended sediment from the Narrator catchment during the period of observation, 25/5/75 to 13/12/76, amounted to 18.82t. Transport of sediment as bedload for this period was in the region of 0.43t. The actual amount of bedload transported may be somewhat greater than this value since on five occasions during the period of observation the capacity of the bedload trap appears to have been exceeded.

To what extent these yields are representative of the long
term is uncertain. The 19 month period of sediment observation in the Narrator Brook was unusually dry. Nevertheless, since total precipitation over this period exceeds annual precipitation (1907 mm and 1568 mm respectively) and since the period included some unusually intense rainstorms, it is probably safe to conclude that sediment yield for the period exceeds mean annual yield for the Narrator catchment.

4.2.2 Based upon reservoir sedimentation

Sedimentation in a reservoir can provide a valuable means of obtaining an estimate of mean annual sediment yield. The total amount of sediment in the reservoir, which is obtained from volumetric survey of some kind, is simply divided by the age of the reservoir to give mean annual inflow of sediment. This method is very often employed in the United States where rapid rates of sedimentation absorb any measurement error, but has also been used effectively in Britain (Young 1958, Cummins & Potter 1972, Ledger et al 1974).

Suspended sediment from the Burrator catchment of which the Narrator catchment forms a part, has been accumulating continuously in the Burrator Reservoir since the completion of the Burrator Dam in 1899 (plate 4.1). Bedload is prevented from entering the reservoir by a small sediment trap at the head of the reservoir which is periodically evacuated. In 1950 the depth of sediment in the reservoir was surveyed by the South-West Water Authority for the first time since the creation of the reservoir. In Britain, where rates of sedimentation are slow, sediment surveys are generally undertaken after the reservoirs have been drained (e.g. Young 1958, Cummins & Potter 1967). The Burrator Reservoir has never been completely drained. Instead, the method of survey involved the lowering of a sounding shaft from the surface of the reservoir into the soft sediment beneath, the depth of the deposits being indicated by the adhesion of mud to the shaft. In all, 49 observations of depth were made by this method spread over the whole reservoir basin. Depth of sediment appears to be exceedingly variable (fig 4.1). Variations in depth from 60cm to
Plate 4.1 Burrator Reservoir looking south-west. Burrator Dam is on the right and Longstone Peninsula in the centre.

Plate 4.2 Recovering a core of sediment from the Burrator Reservoir.
less than 5cms were encountered in the space of only a few metres. This is probably a reflection of down slope movement of sediment after deposition filling small topographic depressions so that over time the sediment surface becomes smoother than the original surface of deposition (Cummins & Potter 1972). There is no recognisable spatial pattern in sediment depths to warrant any areal weighting method of obtaining mean depth. This is calculated instead as a simple mean of all 49 observations, giving a value of 17.8cm. From an area of 0.67km² total volume of sediment in the Burrator reservoir is estimated at 120 000m³. To convert to gravimetric data requires some estimate of the dry weight of sediment per unit volume of reservoir deposits. Reservoir sediments incorporate varying amounts
of water depending upon the particle size distribution of the sediment and degree of compression from overlying sediment. To determine the weight of dry sediment per unit volume necessitates the procurement of undisturbed samples of the reservoir deposits. This was undertaken in connection with the present study in the summer of 1976.

Conventional lake sediment corers proved ineffective for this task due to the soft nature of the deposits coupled with a resilient, often rocky, substratum. Instead, the samples were collected manually by sub-aqua divers whose services were hired for this purpose. The samples were recovered by means of an open ended plastic tube which was pushed vertically into mud surface by the divers. After insertion, a rubber bung was fitted in the top end of the tube and the tube withdrawn, the sediment being retained in the tube by suction. After withdrawal a similar bung was placed in the bottom of the tube before it was brought to the surface (plate 4.2).

Choice of sampling site is critical in view of the post-depositional redistribution of sediment which probably occurs in the reservoir. A site was selected on a particularly flat region of the reservoir basin, possibly representing a former river terrace, where the sediment is unlikely to have experienced disturbance resulting from post-depositional movements (fig 4.2). The average depth of sediment recorded at this site was 7.4cm. This is considerably less than the mean value for the reservoir of 17.8cm obtained some 26 years previously. The site is situated in the lee of the Longstone Peninsula and is distant from major stream inlets (fig 4.2). It is likely that rates of sedimentation in this locality are lower than in other regions of the reservoir and sediment depths are therefore unrepresentative. In this situation the most profitable approach is to combine the information relating to sediment characteristics gained from the sediment samples with the volumetric data from the 1950 survey.
One of the sediment cores was sub-sampled at depth intervals of 1cm from the sediment surface. The seven sub-samples thus obtained were weighed then dried at 105°C for 24 hours, and then reweighed. The dry weight of sediment per cubic metre of reservoir deposits \((S_m)\) is then calculated from eq. 4.1 assuming a specific gravity for sediment particles of 2.65, and assuming that the sediment sample is completely saturated.

\[
S_m = \frac{S_d}{2.65} + \frac{(S_w - S_d)}{2.65} \quad \text{(4.1)}
\]

- \(S_m\) = weight of dry sediment in tonnes per cubic metre of reservoir deposits
- \(S_w\) = wet weight of sample of reservoir sediment
- \(S_d\) = dry weight of sample of reservoir sediment
Values are lowest (0.12 t/m$^3$) at the sediment water interface where sedimentation is most recent and increases steadily with depth due to compression from overlying sediments (fig 4.3). Rate of increase diminishes with depth until about mid-depth beyond which the proportion of dry sediment becomes relatively constant at around 0.26 t/m$^3$. Using a mean value of 0.21 t/m$^3$ the total dry weight of sediment which had accumulated in the Burrator catchment by 1950 is calculated to be 25200 t.

This is an underestimate of total inflow of sediment into the reservoir since a proportion of suspended sediment passes through the reservoir and is discharged at its outlet. This proportion depends upon the velocity of flow through the reservoir which in turn depends upon the capacity of the reservoir in relation to the rate of inflow.

Fig. 4.3 Variation in moisture content with depth for a core of Burrator reservoir deposits
From an empirical relation developed by Brune (1953), based upon capacity/inflow ratios, the proportion of sediment passing through the Burrator Reservoir is estimated at 5%. After correction for trap efficiency the mean annual inflow of sediment from the Burrator catchment for the period 1899 to 1950 becomes 520 t/yr. If this is spread evenly over the Burrator catchment then the mean annual contribution from the Narrator catchment is 114 t/yr. This value greatly outweighs the 18.8 t of suspended sediment discharged from the Narrator catchment during May 1975 to December 1976, a period exceeding 19 months. This disparity between reservoir sedimentation rates and contemporary sediment yield may be explained either by spatial inbalances of sediment production within the reservoir catchment, or alternatively by temporal inbalances. In view of the representative nature of the Narrator catchment in terms of slopes, soil and vegetation cover, marked spatial inbalances seem improbable. A more likely explanation is that sediment yields from the reservoir catchment as a whole have declined since the creation of the reservoir. This is probably related to the gradual improvement in the condition of the catchment, particularly with respect to vegetation cover, since the termination of private farming after purchase of the catchment area by the Plymouth Corporation in 1916. Holeman and Geiger (1965) record a similar decline in sediment inflow to the Pretty Boy reservoir, Maryland, U.S.A. which they attribute to cessation of farming activity and reversion of the catchment to its natural state.

Reservoir deposition is a very valuable tool for estimating long term catchment sediment yields, but generally only mean period values are obtained by this method; no information is provided regarding variations in rates of sediment inflow between resurveys. Stratification, however, may be present within reservoir deposits resulting from periodic influx of coarse sediment during high magnitude flood events. Murray-Rust (1972) related horizons of coarse sediment in reservoir deposits in Tanzania to
specific flood events in the hydrological record and this, together with desiccation horizons caused by periodic drying up of the reservoirs, enabled him to investigate temporal variations in rates of sedimentation. Analysis of this kind is necessarily limited to undisturbed sediments. The Burrator sediment cores were frozen and X-ray negatives prepared in order to determine whether any recognisable stratification is present. Discontinuities in particle size result in differential density between micro-strata; coarse sediments are more dense than finer sediments since they incorporate less water. The absorption of X-rays is proportional to the density of the material through which they are passed, thus providing a useful technique for analysing sediment stratigraphy. From the negatives a poorly defined stratification in the Burrator Reservoir deposits was revealed. By passing the negative through a densitometer, a trace of density variation with depth is obtained (fig 4.4). Density increases with depth to approximately half way down the core and thereafter remains relatively constant. This corresponds to the variation with depth of the proportional weight of dry sediment in the reservoir deposits (fig 4.3). The sandy texture of the former soil profile contrasts with the fine grained sediments above and its surface is marked by a sharp discontinuity in density. Superimposed on these general trends are small scale fluctuations in density which may be due to contrasts in particle size between micro-strata. It is not possible, however, to establish a reliable chronology for the micro-stratification in the sediment by reference to flood records for the Burrator catchment.

4.3 Sediment sources

4.3.1 Stream channels

A survey of the main channel of the Narrator Brook reveals that the lower section of the channel within the
4.4 Densitometer trace for an X-Ray negative of a core of Burrator Reservoir deposits (Depth of sediment is approx. 8 cm)
Coniferous forest plantation is experiencing accelerated bank erosion. This lower channel section, which is 990 metres long, contains a total of 425 metres of channel bank which appears by visual inspection to be undergoing rapid erosion (fig 2.11). The total length of eroding bank along the remaining 2480 metres of the Narrator Brook outside the coniferous forest plantation is only 100 m. Outside the forest, rapid bank erosion is restricted to the outside of tight bends in the stream. In this situation rapid bank erosion is not unnatural. Rapid bank erosion within the forest, on the other hand, is widespread. Accelerated bank erosion within the forest can be attributed directly to afforestation. Exposure of tree roots by bank erosion provides unequivocal evidence that this erosion has occurred since the forest plantation was established (plate 4.3). In extreme cases bank erosion has caused felling of trees close to the stream bank (plate 4.4). Accelerated bank erosion is probably related to the reduction in the thickness and strength of grass turf within the forest. Turf affords stream banks a degree of protection from erosion as grass roots act as a powerful binding agent. In the forest section of the Narrator Brook where turf along channel margins is thin or absent, signs of contemporary bank erosion are common (plates 4.5, 4.6).

Another possible explanation for variations in bank erosion relates to the composition of bank material. Schumm (1960, 1963b) from observations of channel form and process in the Great Plains, U.S.A., demonstrated that the proportion of silt and clay in stream bank material is very closely related to channel geometry and channel pattern. He concluded that the presence of fines enhanced the cohesive properties of bank material thereby reducing bank erodibility and limiting channel width. In order to determine if differences in bank material composition contribute to greater rates of bank erosion in the forested section of the Narrator Brook, twenty samples of bank material were collected, ten at random locations within the
Plate 4.3  Exposure of tree roots by bank erosion near St 5.

Plate 4.4  Felling of tree by bank erosion near St 4.
Plate 4.5  Bank erosion near St 6.

Plate 4.6  Bank erosion near St 7.
forest and ten at random locations between Sts 11 and 13 outside the forest. These samples were subjected to particle size analysis by the dry sieve method. The percentage silt plus clay for the twenty samples varies over a wide range from 9.7% to 82.5% (table 4.1). The mean percent silt plus clay for the ten forest samples is slightly larger than for the ten samples collected outside the forest (50.9% and 41.9% respectively) but this difference is not significant at the 0.05 level. Channel bank composition thus appears to play a subordinate role to riparian vegetation in controlling bank erodibility in the Narrator Brook. Richards (1977) from research on the upper reaches of the River Fowey in Cornwall questions the

Table 4.1 Percentages of silt plus clay in 20 samples of bank material from the Narrator Brook.

<table>
<thead>
<tr>
<th>Samples From Stream Section Within Forest Plantation(Sts 3-11)</th>
<th>Samples From Stream Section Outside Forest Plantation(Sts 11-13)</th>
</tr>
</thead>
<tbody>
<tr>
<td>60.3</td>
<td>9.7</td>
</tr>
<tr>
<td>49.7</td>
<td>59.2</td>
</tr>
<tr>
<td>28.6</td>
<td>43.6</td>
</tr>
<tr>
<td>82.5</td>
<td>29.8</td>
</tr>
<tr>
<td>46.5</td>
<td>68.9</td>
</tr>
<tr>
<td>39.8</td>
<td>54.3</td>
</tr>
<tr>
<td>42.1</td>
<td>78.2</td>
</tr>
<tr>
<td>39.7</td>
<td>16.5</td>
</tr>
<tr>
<td>64.4</td>
<td>18.9</td>
</tr>
<tr>
<td>55.4</td>
<td>39.7</td>
</tr>
<tr>
<td><strong>Mean</strong></td>
<td><strong>50.9</strong></td>
</tr>
<tr>
<td></td>
<td><strong>41.9</strong></td>
</tr>
</tbody>
</table>

$t = 1.02$ (not significant)
relevance of Schumm's (1960, 1963b) findings to small streams. The impact of riparian vegetation in small catchments on the other hand has been clearly demonstrated by previous research. Orme and Bailey (1971), for example, describe how destruction of riparian vegetation by fire in the Monroe Canyon, Southern California, resulted in accelerated bank erosion and increased channel width-depth ratios. Zimmerman et al (1967) discovered from research on small streams in Maryland that for a given drainage area channel widths under forest are up to ten times greater than in the open due to the lack of protective turf. They find, however, that for catchments above 15km² in size vegetation control of channel form falls away. Presumably as catchments and stream channels become larger, channel bank composition begins to exert a more dominant control.

Since it seemed likely from observations that channel banks in the lower Narrator Brook would form a major source of sediment attempts were made to measure rate of erosion. The first of 2 methods employed in the Narrator catchment to measure bank erosion involved the use of erosion pins.

At the start of the period of sediment observations in the Narrator Brook, fifty pairs of zinc plated six inch (150 mm) nails were inserted into stream banks on opposite sides of the channel at randomly selected locations covering the entire main channel. The heads of the erosion pins were left protruding by 20 mm in order to record any bank accretion should it occur. On installation accurate measurements were also taken from the head of each pin down to the stream bed to obtain information on aggradation and scour in the channel. At the end of the period of sediment observations, distances from pin head to bank and pin head to stream bed were remeasured.

Of the original 100 pins, 72 were recovered which yielded evidence of both bank erosion and accretion in the Narrator Brook (table 4.2). The fate of the 28 which could not be found is in many cases uncertain. Some pins appear, from signs of fresh erosion at the site, to have
Table 4.2 Results of bank erosion pin experiment, Narrator Brook, 1975/76.

**Individual Recordings**

Stream Section Within Forest Plantation - total number of pins recovered, 23.

<table>
<thead>
<tr>
<th>Stream Bank Erosion</th>
<th>Stream Bank Accretion</th>
<th>Stream Bed Aggradation</th>
<th>Stream Bed Scour</th>
</tr>
</thead>
<tbody>
<tr>
<td>5,5,5,10,10,30,55</td>
<td>5,10,10,15,15</td>
<td>1,2,3,5,6,9,15,17,22,30</td>
<td>2,2,4,4,5,6,12,20</td>
</tr>
</tbody>
</table>

Stream Section Outside Forest Plantation - total number of pins recovered, 49.

<table>
<thead>
<tr>
<th>Stream Bank Erosion</th>
<th>Stream Bank Accretion</th>
<th>Stream Bed Aggradation</th>
<th>Stream Bed Scour</th>
</tr>
</thead>
<tbody>
<tr>
<td>5,5,5,20</td>
<td>5,5,10</td>
<td>1,1,1,1,2,2,3,3,3,4,7,8,11,15</td>
<td>1,1,1,2,2,2,3,3,3,4,4,4,5,7,10</td>
</tr>
</tbody>
</table>

**Data Summary**

<table>
<thead>
<tr>
<th></th>
<th>Forest</th>
<th>Open</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of pins recording bank erosion</td>
<td>7</td>
<td>4</td>
</tr>
<tr>
<td>Mean gross erosion</td>
<td>5.2 mm</td>
<td>0.7 mm</td>
</tr>
<tr>
<td>Number of pins recording bank accretion</td>
<td>5</td>
<td>3</td>
</tr>
<tr>
<td>Mean gross bank accretion</td>
<td>2.4 mm</td>
<td>0.4 mm</td>
</tr>
<tr>
<td>Mean net bank erosion</td>
<td>2.8 mm</td>
<td>0.3 mm</td>
</tr>
<tr>
<td>Number of pins recording aggradation</td>
<td>10</td>
<td>14</td>
</tr>
<tr>
<td>Mean gross aggradation</td>
<td>4.8 cm</td>
<td>1.3 cm</td>
</tr>
<tr>
<td>Number of pins recording scour</td>
<td>8</td>
<td>16</td>
</tr>
<tr>
<td>Mean gross scour</td>
<td>2.4 cm</td>
<td>1.1 cm</td>
</tr>
<tr>
<td>Mean net aggradation</td>
<td>2.4 cm</td>
<td>0.2 cm</td>
</tr>
</tbody>
</table>

been removed by erosion. This would probably entail at least 70 mms of erosion to dislodge the pin from the bank. This is not excessive since rates of erosion recorded by
pins still in place ranged up to 55 mm. Some of the pins which could not be relocated may have been buried by bank accretion. In such cases accretion would have to exceed 20 mm. This again is not unlikely since 8 of the 72 pins which were recovered recorded accretion ranging up to 15 mm.

Data from recovered pins reveals a large degree of variability in recorded changes to both stream banks and stream bed between sites (table 4.2). While some pins recorded no measurable change over 19 months, others recorded changes in the stream banks ranging from +15 mm to -55 mm and changes in stream bed from +30 cm to -20 cm. These variations reflect variability along the channel of stream velocity, channel geometry, bed and bank material, riparian vegetation and the position of the thalweg relative to channel banks, among other factors. A similar large degree of variability among individual observations from stream bank erosion pins was obtained by Lewin & Brindle (1977) in a small Welsh catchment.

Despite the wide range of variation in the erosion pin data, a clear contrast emerges between the section of the Narrator Brook passing through forest plantation and the remainder of the stream. Outside the forest, only 8% of the erosion pins (4 out of 49) recorded bank erosion compared with 30% (7 out of 23) in the forest. Mean gross erosion for the 23 pins located in the forest is 5.2 mm in comparison to only 0.7 mm outside the forest. This difference is significant at the 0.05 level. Although bank accretion is also greater in the forest than outside the forest (2.4 mm and 0.4 mm respectively) mean net bank erosion in the forest still greatly exceeds the value outside the forest (2.8 mm and 0.3 mm respectively). These results confirm visual impressions of rapid bank erosion in the forest.

Less reliance can be placed upon data relating to stream bed changes than to stream bank changes. Variation in bed material from soft sand to cobbles limits the reproducibility of measurements from erosion pin to stream
bed. Stream bed changes were recorded more often than stream bank changes which indicates, notwithstanding measurement errors, that the stream bed of the Narrator Brook is less stable than stream banks (table 4.2). Mean gross aggradation recorded by pins in the forest is significantly greater (at the 0.05 level) than mean gross aggradation outside the forest (4.8 cm and 1.3 cm respectively). Despite the fact that mean gross scour is also greater in the forest than outside the forest (2.4 cm and 1.1 cm respectively) mean net aggradation in the forest is still appreciably greater than outside the forest (2.4 cm and 0.2 cm respectively). The larger rate of net aggradation in the forest may in part be a response to higher rates of bank erosion. As channel banks erode a proportion of the eroded material, depending upon its particle size distribution, accumulates on the stream bed. The significantly greater rates of stream bank erosion and stream bed aggradation in the forest suggest that this section of the channel is undergoing a period of readjustment.

From a mean net rate of bank erosion of 2.4 mm obtained from erosion pins, and a mean measured bank height of 0.64 m, the total volume of material eroded from the 1980 m of channel banks in the forest during the period of observation is estimated at 6.59 m³. Assuming a mean density of 1.8 for bank material this volume of erosion can be converted to an equivalent weight of 11.86 t. In view of the large degree of variability in bank erosion and the relatively small number of erosion pins used this can only be regarded an approximate value. This estimated supply of sediment from bank erosion in the forest amounts to 62% of total sediment discharged from the Narrator catchment during the period of observation. Sediment supplied from the main channel outside the forest, estimated at 2.24 t, accounts for a further 12%. However these percentages are likely to be large overestimates of the contribution of bank erosion to stream sediment transport because no account is made of storage of sediment in the stream channel. Ob-
served net aggradation in the main channel suggests that much of the coarser fraction of eroded bank material was not transported from the catchment during the period of observation.

Due to probable short term fluctuations in channel storage, particularly with regard to fine sediment (Megehan & Nowlin 1976), relating long term rates of bank erosion to long term sediment yields is likely to be more meaningful than relating contemporary bank erosion to contemporary sediment yield. A long term rate of bank erosion for the forest section of the Narrator Brook can be obtained by analysis of the changes in channel form that have arisen from bank erosion. It is apparent that accelerated bank erosion within the forest has resulted in a substantial increase in the width of the main channel. The channel immediately upstream of the forest is lined by thick turf and is in the region of 1.5 m wide (plate 4.7). The channel 600 m downstream, in the heart of the forest plantation, is over 4 m wide (plate 4.8). Surveyed cross-sections at several locations along the Narrator Brook illustrate the contrast (fig 2.12). Mean bankfull width for the six cross-sections for stream section 5A immediately above the forest is 1.75 m. Mean bankfull width for the fifteen cross-sections surveyed within the forest (stream section 5B) is 4.53 m. This difference is significant at better than the 0.001 level. Bankfull depth is more difficult to gauge than bankfull width, particularly for the forest stream section (stream section 5B). This is because bank recession in this section has resulted in opposing banks of unequal height (eg. cross-sections 33,34,37 and 40). Estimated mean bankfull depth for the six cross-sections in stream section 5A is 0.53 m, compared with a mean of 0.55 m for stream section 5B. This difference is not significant.

Although there has been a marked expansion in channel width in the forest as a result of bank erosion, mean width above the forest cannot be compared directly with mean
Plate 4.7 Channel of the Narrator Brook near St 12 just above forest plantation

Plate 4.8 Channel of the Narrator Brook near St 8 within the forest plantation.
width within the forest to determine the extent of this expansion. This is because in most streams channel width, along with channel depth and stream velocity, increase downstream as exponential functions of bankfull discharge. Early work demonstrating these relationships was undertaken by Leopold & Maddock (1953) and Wolman (1955); more recent research is reviewed by Richards (1977). In order to define downstream variations in channel width along the Narrator Brook, the entire stream was divided into 30 stream sections between 30 randomly selected stations (fig 2.9). Mean bankfull width for each section was determined from several individual measurements of bankfull width in the field. This provides a convenient method of handling the data yielding 30 observations, 10 for the channel within the forest and 20 for the rest of the stream. The 20 observations outside the forest were regressed against mean drainage area for each of the 20 stream sections (fig 4.5).

![Graph showing relation between channel width and drainage area](image)

Fig. 4.5 Relation between channel width and drainage area for the Narrator Brook
Drainage area is used as a convenient surrogate for bankfull discharge. Drainage area has previously been used as a surrogate in analysis of downstream variations in channel geometry by Miller (1958), Park (1975) and Petts (1977).

When mean width values for the 10 forest stream sections are plotted on fig 4.5 all but one lie above the regression line derived from the 20 observations outside the forest. Mean width values for five of the forest stream sections lie above the two standard error line signifying that width is significantly greater for these stream sections (at the 0.05 level) than it should be, having regard to the size of their drainage areas. The regression established on the basis of the 20 stream sections outside the forest can be extrapolated to determine what channel widths in the forest should be and hence the extent to which channel widths have expanded. This technique has previously been used to investigate channel changes resulting from urbanisation (Hammer 1972) and from creation of reservoirs (Gregory & Park 1974, Petts 1976).

The percentage explanation of downstream variations in bankfull width provided by drainage area in the Narrator catchment is 79%. In order to increase this percentage explanation and thereby improve the prediction of channel widths in the forest, a second independent variable, channel gradient, was added to the regression. Channel widths in the Narrator Brook are significantly greater, for a given drainage area, in steeper stream sections (partial correlation coefficient = 0.63, n=20). Inclusion of channel gradient in the regression boosts the percentage explanation of variations in bankfull width to 87% (equation 4.3).

Equation 4.3 is capable of predicting, within very close limits, the probable width of the channel of the Narrator Brook between Sts 1 and 11 prior to afforestation. From comparison of these predicted values with channel width at present it appears that bank recession since afforestation has ranged from zero for the two stream sections between Sts 7 and 8 and between Sts 10 and 11 to...

130
2.0 m for the stream section between Sts 3 and 4 (table 4.3).

\[ \log_e W = 0.878 \log_e D.A + 0.238 \log_e S - 0.979 \] ...... (4.3)

\[ r = 0.93 \quad n = 20 \quad S.E. = 0.152 \text{ log units} \]

\( W = \text{channel width (m)} \)
\( D.A = \text{drainage area (km}^2) \)
\( S = \text{channel gradient (m/km)} \)

<table>
<thead>
<tr>
<th>Total Correlation Coefficients</th>
<th>Partial Correlation Coefficients</th>
</tr>
</thead>
<tbody>
<tr>
<td>( DA )</td>
<td>( S )</td>
</tr>
<tr>
<td>( S )</td>
<td>-0.47</td>
</tr>
<tr>
<td>( W )</td>
<td>0.89 -0.16</td>
</tr>
</tbody>
</table>

Increased bank erosion and aggradation in the forested section of the Narrator Brook has had repercussions upon the channel pattern as well as channel cross-sectional form. Controls of channel sinuosity are very complex but research has revealed that the dominant control is valley gradient (Leopold et al 1964, Lee & Henson 1977). The planform of the Narrator Brook was surveyed in the field. In calculating sinuosity, the channel was divided into 100 metre sections commencing from the main gauging site at the mouth of the stream. Values of sinuosity for these 100 m stream sections varies from 1.003 to 1.216. Sinuosity in the non-forested part of the Narrator Brook decreases with gradient as theory suggests \((r = -0.42, n = 24 - \text{fig 4.6})\). Inclusion in the graph of the ten values from the forested section of the stream indicates that for a given gradient sinuosities have been significantly reduced. All of these points lie below the regression line and three fall outside the two standard error envelope. The change in planform of the Narrator Brook within the forest must mean that rate of bank erosion since afforestation has not been uniform along the channel and this is substantiated by the variability in bank erosion data derived from both erosion pin data.
Table 4.3 Estimation of rates of bank erosion within the forested region of the Narrator Brook.

<table>
<thead>
<tr>
<th>Stream Section Between:</th>
<th>Mean Section Distance From Catchment Exit (Metres)</th>
<th>Mean Section Width (Metres)</th>
<th>Estimated Mean Section Width Prior to Lateral Erosion (Metres)</th>
<th>Lateral Erosion (Metres)</th>
<th>Stream Section Length (Metres)</th>
<th>Land Removed By Bank Erosion (Hectares)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sts 1-2</td>
<td>24</td>
<td>3.0</td>
<td>1.6</td>
<td>1.4</td>
<td>48</td>
<td>0.0067</td>
</tr>
<tr>
<td>2-3</td>
<td>56</td>
<td>3.9</td>
<td>3.1</td>
<td>0.8</td>
<td>17</td>
<td>0.0014</td>
</tr>
<tr>
<td>3-4</td>
<td>170</td>
<td>4.5</td>
<td>2.5</td>
<td>2.0</td>
<td>210</td>
<td>0.0420</td>
</tr>
<tr>
<td>4-5</td>
<td>346</td>
<td>3.9</td>
<td>2.3</td>
<td>1.6</td>
<td>142</td>
<td>0.0272</td>
</tr>
<tr>
<td>5-6</td>
<td>429</td>
<td>3.4</td>
<td>2.6</td>
<td>0.8</td>
<td>24</td>
<td>0.0019</td>
</tr>
<tr>
<td>6-7</td>
<td>532</td>
<td>4.2</td>
<td>2.5</td>
<td>1.7</td>
<td>183</td>
<td>0.0311</td>
</tr>
<tr>
<td>7-8</td>
<td>657</td>
<td>2.6</td>
<td>2.6</td>
<td>0</td>
<td>68</td>
<td>0</td>
</tr>
<tr>
<td>8-9</td>
<td>820</td>
<td>3.1</td>
<td>2.4</td>
<td>0.7</td>
<td>247</td>
<td>0.0173</td>
</tr>
<tr>
<td>9-10</td>
<td>953</td>
<td>3.2</td>
<td>2.7</td>
<td>0.5</td>
<td>17</td>
<td>0.0008</td>
</tr>
<tr>
<td>10-11</td>
<td>979</td>
<td>2.2</td>
<td>2.3</td>
<td>0</td>
<td>35</td>
<td>0</td>
</tr>
</tbody>
</table>

* Obtained from equation 4.3

TOTAL 0.123
Reduction in sinuosity has been matched by an increase in anastomosity evidenced by the appearance of sand or gravel bars in this section of the stream (fig 2.11). There are a total of 13 bars exposed during baseflow in the forest section of the Narrator Brook. Four are mid-channel bars and the remaining nine are point bars. The only gravel or sand bars outside the forest are two small point bars, one between Sts 29 and 30, and one just below St 17.

From the estimates of bank recession in table 4.3 the total volume of material removed from the 2 km of channel banks within the forest plantation, since afforestation, is calculated to be 800 m$^3$. Assuming an average density of bank material of 1.8, total weight of eroded material becomes 1440 t. The greater part of the forest plantation in the Narrator catchment matured around 1935 and if this
date is taken as the commencement of accelerated bank erosion in the lower Narrator Brook, mean annual supply of sediment from this source since afforestation has been in the order of 35 t/yr. This long term mean annual rate of bank erosion is substantially greater than the contemporary rate of erosion in the forest stream section of 11.9t over a period of 19 months estimated from erosion pins. This suggests that rate of bank erosion is slowing down. This accords with the assertion of Brunsden & Thornes (1979) that when a channel system is disturbed change of form is very rapid initially but subsequently tails off as re-equilibrium is approached.

Long term mean annual supply of sediment from erosion of the main channel of the Narrator Brook can be usefully compared to long term mean annual yield of sediment from the Narrator catchment estimated from reservoir sedimentation providing some allowance is made for the coarser fraction of bank material not represented in reservoir deposits. Coarse sediment is prevented from entering the reservoir by means of a large sediment trap at the head of the reservoir which is periodically dredged by the South West Water Authority. Although particles up to 1 mm in size were present in the samples of sediment recovered from the bottom of the reservoir, 96% of the sediment is finer than 75μ. For bank material in forest section of the Narrator Brook the percentage finer than 75μ is in the region of 50%. Even if it is assumed that all the sediment less than 75μ supplied from eroding banks enters the reservoir, bank erosion would appear to contribute little more than 20% of the total fine sediment which the Narrator Brook discharges into the Burrator Reservoir. Although this can only be regarded as a rough approximation of the relative importance of bank erosion in the forest as a source of sediment, it does indicate that other major sources of fine sediment exist in the Narrator catchment.

Included under stream channel sources are drainage ditches and ephemeral channels which are particularly
numerous in the coniferous forest plantation (fig 2.9). Rain splash and weathering processes on exposed parts of these channels creates a pool of available sediment which is flushed into the main stream during flood periods. This is likely to form an important contribution to the fine sediment transported by the Narrator Brook, although it is a contribution which is difficult to assess. Another possible significant source of fines in the Narrator catchment is catchment slopes.

4.3.2 Catchment slopes

Supply of sediment from slopes in the Narrator catchment was not measured directly. However, the likely significance of catchment slopes as a source of sediment can be assessed indirectly by evaluation of the two processes responsible for supplying sediment from catchment slopes to the stream channel, namely rain splash and overland flow.

The effectiveness of rain splash as an agent of soil erosion increases with increasing precipitation intensity and decreases with increasing density of vegetation cover. Several workers cite threshold rainfall intensities which have to be exceeded before rain splash can be considered effective. Suggested threshold values vary depending upon climate. Hudson (1971) gives a figure of 25 mm/hr for Africa, while for Germany 6 mm/hr appears more appropriate (Richter & Negendank 1977). Morgan (1979) suggests an intensity of 10 mm/hr as being applicable to the British situation. Of the 37 events which occurred during the period of observation, 6 recorded precipitation exceeding 10 mms in the space of an hour. Several other events also probably sustained rainfall intensities exceeding 10 mm/hr over periods shorter than an hour, but this cannot be determined from weekly autographic rain charts. Over much of the Narrator catchment, vegetation is probably too dense to permit rain splash erosion even when rainfall intensities
exceed the threshold value. However, areas in the grassland region of the catchment not invaded by bracken (Pteridium aquilinum) are preferentially grazed by sheep and cattle and the grass is close cropped. In these areas the soil surface is probably not offered the same protection from rain splash as in bracken infested areas. In the moorland region of the catchment the protection offered by Molinia is significantly reduced during winter months, and bare patches of soil are exposed in some areas. Localised areas of bare soil also occur as a result of concentrated trampling in the vicinity of Deancombe Farm (fig 2.9) and at gaps in dry stone walls. There are 10 locations along the Narrator Brook and its tributaries which are favoured stream crossing points resulting in bare soil close to the channel.

Although the effectiveness of rain splash can be gauged from precipitation intensity, overland flow is more elusive in this respect. Overland flow has been observed on a number of occasions in the moorland region of the catchment during rain storms. That this overland flow is instrumental in transporting eroded material is evidenced by patches of bleached whitish grey sand commonly observed between grass tussocks following intense rainstorms. Exactly the same phenomenon is described by Tallis (1964) in the Southern Pennines which he ascribes to sheet erosion of peaty soils.

Overland flow can occur when rainfall intensity exceeds soil infiltration capacity while the soil is unsaturated, or alternatively when the top soil becomes saturated (Kirkby 1969b, Chorley 1978). Horton (1945) proposed that since the surface infiltration capacity of most soils decreased during a storm event due to increasing wetness, a point may be reached during the storm when infiltration capacity is exceeded by rainfall intensity. This would depend upon the nature of the soil together with duration and intensity of the storm. Once this point has been reached, the excess rain which cannot be accommodated by
infiltration drains off the surface as overland flow. "Hortonian" or unsaturated overland flow, although perhaps of some significance in semi-arid climates, has been found to be less applicable to catchments in humid climates. In humid climates rainfall intensity is characteristically low while denser vegetation protects the soil and prevents sealing of the soil surface by rain drop impact. Pierce (1967), for example, concluded from measurements in a New England catchment that surface soil infiltration is never likely to be exceeded by rainfall intensity. Infiltration capacity was measured periodically at two sites within the Narrator catchment by single cylinder infiltrometers fixed permanently into the ground. These two sites are located next to raingauges No. 2 and No. 4 both on flat ground, one on iron pan stagnopodsol of the moorland region and the other on brown earth (fig 3.1). Recorded infiltration capacities ranged from 1650 mm/hr to 180 mm/hr at the site on brown earth and from 940 mm/hr to 80 mm/hr at the site on iron pan stagnopodsol. A plot of infiltration capacity against antecedent precipitation in the manner of Papadakis and Preul (1973) reveals, as theory predicts, that the infiltration capacity of both soil types decreases as the soils become wet (fig 4.7). It is apparent, however, that even in the wettest conditions, when the level of saturation in the soil is close to the surface, surface infiltration at these two sites still exceeds the maximum rain intensity of 25 mm/hr recorded on the catchment during the period of research. However, there are likely to be large spatial contrasts in infiltration capacity over the Narrator catchment in response to variations in the degree of trampling by cattle and sheep. Bracken infested areas, for example, are less subject to trampling than open grassland areas. Infiltration in some parts of the catchment subject to heavy trampling may on occasions fall below rainfall intensity while the soil is unsaturated. Small localised areas where "Hortonian" overland flow is undoubtedly a common occurrence include tracks and paths, to-
Fig. 4.7 Relation between infiltration rate and antecedent precipitation for two soil types in the Narrator catchment
gether with localities of particularly intense trampling in the vicinity of Deancombe Farm, at gaps in stone walls and at stream crossing points. Observations by Ternan & Williams (1979) in the Narrator catchment indicate that unsaturated overland flow is also generated upon vegetation litter in forest, bracken and grassland areas.

Although unsaturated overland flow in the Narrator catchment may be of only localised significance, saturated overland flow in the catchment is both frequent and widespread. Soil saturation begins in the sub-soil and then rises towards the soil surface (Weyman 1974). When the level of saturation or water table in the soil intersects the soil surface overland flow is generated (Kirkby & Chorley 1967, Dunne & Black 1970). This process is very closely related to rates of throughflow. Near the surface of the soil are cracks, root channels and other macro-pores not found at depth. Water after infiltration into the
surface passes down through the soil but as permeability decreases with depth water becomes ponded in the sub-soil, particularly at levels in the soil profile where there is any marked discontinuity of permeability with depth. Such a discontinuity is often found at the base of the A horizon due to the presence here of an iron pan in podsolized soils. Water which has accumulated at depth is drained by throughflow at a rate determined by the saturated hydraulic conductivity of the soil. In some soils this may be quite low, often lower than commonly occurring rainfall intensities. While rainfall intensity exceeds saturated hydraulic conductivity water will continue to accumulate within the soil. If this situation persists for a sufficiently long period then the soil water table may reach the surface; thereafter the excess of rainfall which cannot be drained by throughflow is transmitted as overland flow.

One technique that has commonly been employed to investigate the frequency and distribution of saturated overland flow in small catchments is the soil observation well (Betson & Marius 1969, Lewin et al 1974, Weyman 1974). The level of saturation or water table within the soil is indicated by the level of standing water in the well. In the Narrator catchment twenty soil wells were installed at randomly selected locations (fig 3.1). The wells are 30 cm deep and lined with plastic drainpipe. Each is equipped with a crest-stage recording device consisting of a removable dexion rod to which is affixed thimbles at 5 cm intervals (fig 4.8; plates 4.9 & 4.10). The highest thimble to be filled with water indicates to within 5 cm the maximum level attained by the soil water table. The thimbles are fitted with lids which float open with rising water in the well and close when the water level recedes again in order to retard evaporation of water in the thimbles and ensure reliable readings. The top most thimble is positioned to coincide with the ground surface and when this has been filled it indicates that on at least
one occasion during the period since the well was last checked, saturated overland flow has occurred at the site. The wells were inspected on eighteen occasions during the period of research at approximately monthly intervals; all were visited on the same day during dry weather to facilitate spatial comparisons.

Approximately 2% of the Narrator catchment is permanently saturated during normal years and transmits virtually all precipitation received as overland flow (fig 2.7). From this extreme there is a wide ranging continuum to well drained situations where saturation to surface is likely to be an extremely rare event. All twenty soils wells became dry after a prolonged period without rain. At one site the soil well remained dry for the entire period of observation. The remaining 19 wells recorded periodic saturation to at least 25 cm from the ground surface. Out of a total of 18 visits to the soil wells the number of occasions saturation to the surface was recorded ranged from 11 to zero.
Plate 4.9  Crest stage soil well with cover removed.

Plate 4.10  Crest stage soil well showing dexion rod with thimbles attached.
To investigate these spatial variations, an index was devised to represent saturation potential. This is simply the total number of thimbles filled over eighteen visits to the site. The maximum possible is 108; values for the soil wells ranged between 78 and zero (fig 4.9). The principle control of these variations is the nature of the soil itself and in particular its organic content. It is apparent that in this respect there is a sharp distinction between the two soil types in the catchment (fig 4.10).

All of the nine wells at which saturated overland flow was recorded are located on stagnopodsol; it was never once recorded at any of the nine sites on brown earth. A similar contrast in the hydrological properties of stagnopodsol and brown earth has been reported from a small catchment in Somerset (Weyman 1974). Due to their high organic content peaty soils swell when wet sealing off macro-pores and thus greatly reducing hydraulic conductivity. Low specific yields combined with low hydraulic conductivity mean that relatively little rain can raise the level of saturation a long way (Childs 1972). The lower organic content of the brown earth results in rather higher hydraulic conductivities and hence a lower saturation potential.

In addition to soil organic content, the spatial variation in saturation potential in the Narrator catchment was also tested against soil texture and topographic variables in multiple regression (table 4.4). Neither of the two textural variables tested, % silt and clay and % gravel, contribute significantly to soil saturation potential. The range in both saturation potential and texture in the brown earth region of the catchment may be too small for the effect of texture to become manifest. In the stagnopodsol any possible effect of texture is probably overshadowed by the high organic content of the soil which can exceed 90% dry weight in some localities.

According to theory (Kirkby & Chorley 1967, Chorley 1978, Kirby 1978a), the distribution of saturated overland
Soil saturation potential at 20 sites in the Narrator catchment. Soil saturation potential is defined as the total number of thimble filled over 18 visits to each site (total possible - 6×18 = 108)
flow in a catchment is determined by topography as well as soil characteristics. Saturation potential should increase with increasing slope length and decrease with increasing slope angle. Saturation should also be favoured on concave slopes and where slopes converge, since in these situations input by throughflow into a particular area of soil will exceed output. The four topographic variables tested against soil saturation in the Narrator catchment are slope angle, slope length, a concave/convex slope index, and a converging/diverging slope index (table 4.4). In contradiction to established theory, the last three of these topographic indices are not independently related to soil saturation potential. The small but significant independent affect of slope angle is difficult to explain,
Table 4.4 Results of multiple regression analysis of spatial variations in saturation potential over the Narrator catchment based upon observations at 20 soil well sites (data untransformed).

### DEPENDENT VARIABLE

Saturation potential, measured as the total number of thimbles filled in a soil well over 18 visits to the site.

<table>
<thead>
<tr>
<th>Independent Variables</th>
<th>Total Correlation Coefficients</th>
<th>6th Order Partial Correlation Coefficients</th>
<th>Partial F Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Soil organic content</td>
<td>0.89</td>
<td>0.85</td>
<td>72.24</td>
</tr>
<tr>
<td>2 Slope angle</td>
<td>-0.11</td>
<td>0.48</td>
<td>8.71</td>
</tr>
<tr>
<td>3 Soil silt and clay</td>
<td></td>
<td>0.67</td>
<td>3.89</td>
</tr>
<tr>
<td>4 Slope plan shape index</td>
<td>0.06</td>
<td>0.22</td>
<td>0.13</td>
</tr>
<tr>
<td>5 Slope length</td>
<td>0.18</td>
<td>-0.18</td>
<td>0.50</td>
</tr>
<tr>
<td>6 Slope profile shape index</td>
<td>-0.18</td>
<td>0.09</td>
<td>0.04</td>
</tr>
<tr>
<td>7 Soil gravel content</td>
<td>-0.54</td>
<td>0.15</td>
<td>0.26</td>
</tr>
</tbody>
</table>

**LEVEL OF SIGNIFICANCE**: 0.01 0.001

<table>
<thead>
<tr>
<th>r</th>
<th>0.56</th>
<th>0.68</th>
</tr>
</thead>
<tbody>
<tr>
<td>F</td>
<td>8.29 for 1 to 9.33 for 7</td>
<td>15.38 to 18.64</td>
</tr>
<tr>
<td>n = 20</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Percent Explanation (all variables)</td>
<td>90.1%</td>
<td></td>
</tr>
</tbody>
</table>

* See appendix II.5 for basic data and derivation of independent variables.

since rather than the expected negative correlation of slope angle with saturation potential, the partial correlation coefficient is positive. A similar disparity between field observations and theory with respect to the affect of topography upon the distribution of soil saturation was also encountered by Arnett (1974) and Knapp (1974).
The independent effect of vegetation cover upon the hydrological response of soils in the catchment is more difficult to gauge since vegetation and soil distributions largely coincide. The distribution of bracken (*Pteridium aquilinum*) however, transcends soil boundaries, and a Mann-Whitney U-test indicates that saturation potential beneath bracken is significantly (0.05 level, n = 3 and 8) reduced on peaty soils. This supports the results of previous research in this respect (Weyman 1974, Arnett 1974). Since bracken will only invade the better drained areas, separating cause from effect is difficult, but it may be that the presence of bracken significantly reduces saturation potential by interception of precipitation or by the creation of root channels which improve drainage. Since only one of the nine soil wells on brown earth is not in an area of bracken infestation, the impact of bracken upon the saturation potential of brown earth could not be tested.

From these observations there is reason to believe that overland flow and rain splash in the Narrator catchment are effective in supplying sediment from catchment slopes to the stream channel. Some idea of the extent to which sediment from catchment slopes contributes to total sediment transported by the Narrator Brook can be gained from analysis of sediment dynamics.
5.1 Variations in soil saturation

Evidence presented in chapter 4 suggests that slopes in the Narrator catchment may contribute a significant proportion of the fines transported by the Narrator Brook. Soil well observations indicate that at certain times saturation overland flow is widespread over the catchment. At these times a large supply of fines from slopes can be expected. Analysis of temporal variations in the level of saturation within the soil may thus help to explain temporal variations in stream sediment transport.

During precipitation water becomes ponded in the subsoil and the level of saturation in the soil rises towards the surface. The maximum level reached is recorded by the crest stage recording device fitted into each of the 20 soil wells in the Narrator catchment. At nine sites and on several occasions during the period of observation, saturation level reached the surface and overland flow was generated. Analysis of spatial variations in recorded maximum levels of saturation at the 20 sites, discussed in the previous chapter, reveals a marked contrast in the two major soil types within the Narrator catchment. Stagnopodsols are more susceptible to saturation than brown earths. Temporal variations in the maximum level of saturation recorded over 18 visits to the soil wells depend upon variations in the amount and intensity of precipitation and upon antecedent precipitation. However, it is apparent from analysis of temporal variations that stagnopodsols and brown earths respond very differently to variations in these three factors. In order to examine temporal variations in soil saturation for these two soil types, the total number of thimbles filled in the nine soil wells on brown earth, for each of the 18 occasions on which soil wells are visited, was expressed as a percentage of the total number possible.
(total number possible on each occasion = 9 x 6 = 54). The same was also done for the 11 soil wells on stagnopodsol, but in this case the maximum number of thimbles that can be filled at any one visit is 11 x 6 = 66. This gives a total of 18 observations for each of the two soil types. Values for brown earth vary between 0% and 27.8% while values for stagnopodsol vary from 0% to 95.5%.

When these percentage values for the two soil types are correlated separately against total precipitation over the periods between visits, maximum two hour precipitation for these periods, and antecedent precipitation preceding maximum two hour precipitation, contrasting trends emerge (table 5.1). Saturation in brown earth is closely related to maximum two hour precipitation ($r = 0.88$, $n = 18$) but relatively insensitive to variations in total precipitation and antecedent precipitation ($r = 0.33$ and $-0.06$ respectively, $n = 18$). Saturation in stagnopodsol on the other hand is more closely related to total precipitation and antecedent precipitation ($r = 0.59$ and 0.57 respectively, $n = 18$). Sub-surface drainage is probably relatively slow.

Table 5.1 Product moment correlation coefficients relating saturation in two soil types in the Narrator catchment to hydrometeorological variables (data untransformed).

<table>
<thead>
<tr>
<th></th>
<th>Maximum Two Hour Precipitation</th>
<th>Total Period Precipitation</th>
<th>Precipitation Preceding Maximum Two Hour Event (API$_{20}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stagnopodsol</td>
<td>0.13</td>
<td>0.59**</td>
<td>0.57*</td>
</tr>
<tr>
<td>Brown earth</td>
<td>0.88***</td>
<td>0.33</td>
<td>- 0.06</td>
</tr>
</tbody>
</table>

$n = 18$

Significance level  
* 0.05  
** 0.01  
*** 0.001
in stagnopodsols in comparison to brown earths. Stagnopodsol in the Narrator catchment thus conforms to the simple storage model envisaged by Kirkby (1978b). The two important factors determining the level of saturation in this situation are the initial amount of water in storage (represented by antecedent precipitation) and the amount added (represented by total precipitation); precipitation intensity is inconsequential. For brown earth, on the other hand, the simple storage model is less applicable because sub-surface drainage is relatively rapid. Saturation level in this soil rises only when rate of input of water (represented by precipitation intensity) exceeds rate of output by drainage. As a result, precipitation intensity becomes the dominant control of saturation levels in this soil and the factors relating to storage (total precipitation and antecedent precipitation) are less important.

The contrast in response between stagnopodsol and brown earth is illustrated by comparing the depths of saturation at the 20 soil well sites for two periods with contrasting hydrometeorological conditions (fig 5.1). The first of these two periods, 7-27/10/76, has a high total precipitation (215 mm) but precipitation intensity is low (maximum 2 hr precipitation - 9.3 mm). Maximum saturation levels in stagnopodsol for this period are much higher than in the brown earth (fig 5.1a). While 3 of the 11 soil wells located on stagnopodsol recorded saturation to surface, 7 of the 9 wells on brown earth remained dry. The second period, 22/7-2/9/76, is drier than the first (total precipitation - 40 mm) but included a high intensity event (maximum 2 hr precipitation - 21.7 mm). Maximum saturation levels in the brown earth are equivalent to or higher than stagnopodsol for this period (fig. 5.1b). The highest level recorded by the 11 wells on stagnopodsol is 20 cm from the surface; 3 of the wells remained dry. By comparison the highest level recorded by the 9 wells on brown earth is 15 cm from the surface and only one of the wells remained dry.
Fig. 5.1 Maximum levels of saturation recorded at 20 soil well sites in the Narrator catchment for two periods with contrasting hydrometeorological conditions
(a) 7 - 27/10/76 (b) 22/7 - 2/9/76
Tributary channels in the Narrator catchment, including the North and South Forks of the Narrator Brook, the Yellowmead Brook and the Sheepstor Beck (fig 2.9), penetrate the moorland regions around the higher margins of the catchment and enable saturation overland flow in this region to contribute to quickflow runoff. Jones (1979) stresses the importance of saturated areas on catchment margins as a source of quickflow, even though these areas may be separated from the main dynamic contributing area. Newson (1976) describes pipes in a Mid-Wales catchment linking ridge top peats to flood plain flushes. Such pipes may also exist in the Narrator catchment although none have been observed.

The important contribution of moorland regions of the Narrator catchment to quickflow is clearly reflected in streamflow dynamics. Above the gauging site at St 21 the catchment area is 99% stagnopodsol while further downstream at St 11 brown earth comprises 18% of the catchment area. As a direct result of the differing proportions of soil types in the two catchment areas streamflow dynamics at the two gauging sites differ appreciably despite their close proximity on the same river. Flood magnitude (calculated as the difference between peak discharge and antecedent baseflow discharge) recorded at St 21, varies independently to some degree from that recorded at St 11. The ratio of flood magnitude at these two stations ranged from 0.09 to 0.67 over the period of observation (the ratio of drainage areas for the two stations is 0.43). This can be directly attributed to variable supply of saturation overland flow from moorland areas. Analysis of the soil well data indicates that storm events with large precipitation totals but low precipitation intensity favour saturation in moorland regions with stagnopodsols. During such events moorland regions contribute more to storm runoff than during events with high precipitation intensity but low precipitation totals. As a result, the ratio of flood magnitude at St 21 to that at St 11 is high for events with high total
precipitation but low maximum two hour precipitation, and
the ratio of flood magnitudes declines as the ratio of
maximum two hour precipitation to total precipitation in-
creases ($r = -0.57$, $n = 26$ - fig 5.2). For example a
small but intense storm event which occurred on 4-5/8/75,
with a maximum two hour precipitation of 15.7 mm in com-
parison to total precipitation of only 19.0 mm produced a
flood magnitude of only 8 l/s at St 21 in comparison to
55 l/s at St 11, giving a ratio of 0.15. By contrast, an
event which occurred on 30/9-1/10/76, with a total precipi-
tation of 57.3 mm and maximum two hour precipitation of
only 8.6 mm, produced a flood magnitude of 70 l/s at St 21
in comparison to 140 l/s at St 11 (ratio of 0.50). This

![Graph showing the relationship between the ratio of flood magnitudes at Sts. 11 and 21, and the ratio of maximum two hour precipitation to total precipitation.](image-url)

**Fig. 5.2** Relation between the ratio of flood magnitudes at Sts. 11 and 21, and the ratio of maximum two hour precipitation to total precipitation. Flood magnitude is defined as the difference between peak discharge and antecedent baseflow discharge.

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indicates that there was an appreciably greater contribution from moorland areas to storm runoff on 30/9-1/10/76 than on 4-5/8/75.

It is apparent from these observations that saturation overland flow contributes significantly to storm runoff in the Narrator catchment. It seems likely, therefore, that saturation overland flow contributes to flood period sediment transport. Variations in soil saturation can thus be expected to have some influence upon stream sediment transport during flood periods.

5.2 Variations in flood period suspended sediment concentration

5.2.1 Sediment Rating Curves

In most streams suspended sediment concentrations vary considerably over storm events rising by as much as several orders of magnitude over baseflow values. These variations are often defined by means of a sediment rating curve which most commonly takes the form of a log/log plot of measured sediment concentration against stream discharge at the time of sampling. When combined with a flow duration curve, sediment rating curves can provide a convenient method of estimating long term sediment yields and is particularly useful where sediment data are sparse and other methods are unfeasible (Miller 1951, Piest 1964, Loughran 1976). They can also be usefully employed as a tool for comparing erosion rates between catchments; the slope of the regression has been used as a dimensionless index of catchment erodibility (Parsons et al 1964, Bauer & Tille 1967).

In some streams discharge offers only poor explanation of variations in sediment concentration. This can lead to large errors when rating curves are employed to calculate yields as amply demonstrated by Walling (1977). The efficiency of the rating curve is very largely a reflection
of sediment sources in the stream catchment. For catchments in which stream channels provide the major source of suspended sediment, a strong correlation between stream sediment concentration and stream discharge can be expected. The supply of suspended sediment from bed material depends upon the competence of the stream to lift particles from the stream bed and this in turn is a function of stream discharge. Stream discharge also reflects the proportion of the channel network occupied by stream flow and hence contributing to sediment transport. For catchments which have a major supply of sediment from outside the channel network, sediment rating curves are likely to be less efficient. This is because supply of sediment from catchment slopes is determined by precipitation characteristics and the condition of the catchment surface. Because there is no causal link with discharge the correlation is poor.

In the Narrator catchment there is little relation between suspended sediment concentration and stream discharge. During a flood event which took place on the 29th August 1976, for example, suspended sediment concentration reached 330 mg/ℓ at a stream discharge of only 165 ℓ/s. By contrast, during winter months baseflow discharge in the Narrator Brook exceeds 200 ℓ/s while sediment concentration at these times is generally less than 1 mg/ℓ. The poor correspondence of sediment concentration with stream discharge in the Narrator Brook becomes particularly apparent from examination of variations in sediment concentrations over individual flood events. For all flood events in the Narrator catchment during the period of observation, peak sediment concentration preceded peak discharge giving rise to higher concentrations on the rising limb for a given discharge than on the falling limb and resulting in clockwise hysteresis (fig 5.3). This effect in other catchments in Britain has been related to the availability of sediment on catchment slopes (Walling 1974b, Wood 1977). Availability is thought to be limited, depending upon the size of the storm event and the interval since the pre-
Fig. 5.3 Hydrographs, sediment graphs and hysteresis loops for nine flood events recorded at St. 1, Narrator Brook
ceeding storm. As a result, during the initial period of the storm sheet erosion and concomitant stream sediment concentrations are relatively high, but as the available supply of sediment becomes exhausted concentrations may decrease before peak discharge is reached. Clockwise hysteresis is thus typical of catchments where the major supply of sediment is from catchment slopes rather than from the stream channel.

Included in fig 5.3 are hydrographs, sediment graphs and hysteresis loops for nine flood events which occurred during the period of observation. Enough samples were collected over these events to define variations in sediment concentration in some detail. Degree of hysteresis for these nine events varies considerably. For the flood event which took place on the 29th to 30th of August 1976, peak sediment concentration and peak discharge virtually coincide and as a result, hysteresis is barely apparent. At the other extreme, for the event which took place on the 12th to 13th of March 1976, peak sediment concentration was attained 10 hours before peak discharge and hysteresis is particularly pronounced. This variation in the degree of hysteresis can be explained to some extent on the basis of sediment availability. Hysteresis is most pronounced for the larger floods which follow wet periods such as 12-13/3/76, 21-22/3/76 and 14-15/10/76. Quickflow runoffs for these three events are 57, 28 and 58 $m^3.10^3$ respectively and antecedent precipitation ($API_{30}$) 18, 11 and 30 mm respectively. Sediment concentrations for these events are considerably greater during the rising stage than during the falling stage. For example, the event which took place on the 21st to 22nd of March 1976 recorded a sediment concentration of 18 mg/l at a discharge of 500 l/s on the rising stage of the flood. By the time discharge reached 500 l/s on the falling stage of the flood sediment concentration had dropped to only 1.5 mg/l. For small flood events following dry periods, such as 4-5/8/75 and 29-30/8/76 (quickflow runoff 0.4 and 1.4 $m^3.10^3$ respectively and $API_{30}$ 7 and 0 mm respectively) available supply of sediment...
is not exhausted to the same degree and sediment concentrations on rising and falling stages are more comparable. At a discharge of 150 l/s on the rising stage of the event of 29-30/8/76 sediment concentration is 55 mg/l in comparison to 50 mg/l at the same discharge on the falling stage. The situation is not quite as simple as this, however, since hysteresis for the flood event of 13-14/9/75 displays more pronounced hysteresis than the flood event of 3-4/10/76 even though the former event is smaller (quickflow runoff 8 and 13 m$^3$.10$^3$ respectively) and has a lower antecedent precipitation (API$^{30}$ 14 and 86 mm respectively). The reason for this discrepancy is not clear.

In catchments where sheet erosion is a prominent source, as well as contrasts in sediment concentration between rising and falling stage of the hydrograph, seasonal contrasts in concentration also commonly arise. Several studies in Britain have reported higher sediment concentrations in summer for a given discharge than in winter (Walling 1971a, Oxley 1974, Lewin et al 1974, Wood 1977). In the Narrator Brook during the period of observation mean discharge weighted sediment concentration of quickflow for summer months (April to September) is 36.3 mg/l in comparison to 20.6 mg/l for winter months (October to March). Higher summer concentrations have been variously attributed to greater rainfall intensity and erosivity in summer months, greater erodibility of catchment soils which are drier in summer thus influencing the availability of sediment, or a decrease in vegetation cover related to agricultural practices. In some British streams higher winter concentrations have also been reported (Jackson 1964, Imeson 1971a). Clearly, season has a profound influence upon flood period sediment concentrations which is independent of seasonal variations in stream runoff, but the mechanisms involved are poorly understood.

The poor correspondence of sediment concentration to stream discharge in the Narrator Brook can be seen from the sediment rating plot which was compiled from 210 samples collected during storm events over the period of observa-
tion (fig 5.4). The degree of scatter obviously precludes any reliable prediction of sediment concentration from stream discharge; the standard error in the regression of sediment concentration and discharge for total observations is 0.55 log units (table 5.2). This means that it is only possible to be 95% confident that the actual sediment concentration is within an order of magnitude both above and below the predicted value. Attempts have previously been made to improve poor rating curves by constructing separate curves for rising and falling stages of flood events (Temple & Sundborg 1972, Oxley 1974, Loughran 1976), or for different seasons (Hall 1967, Vice et al 1968, Brown 1972). Although inspection of the sediment rating plot for the Narrator Brook indicates that classifying the sediment data in this way would undoubtedly improve the situation, the result would be clearly still far from satisfactory in terms of successful modelling of sediment dynamics. Separation of the sediment concentration data according to season boosts explanation of variance by stream discharge for both winter and summer seasons to 14.4% compared to 6.3% for total observations (table 5.2). Further separation according to stage of the hydrograph increases explanation of variance in the case of both winter falling and rising.

Table 5.2 Correlation coefficients relating suspended sediment concentration to stream discharge according to season and stage of the hydrograph, Narrator Brook, main gauging site, 1975/76.
(Data log transformed).

<table>
<thead>
<tr>
<th>Number of observations</th>
<th>Total</th>
<th>S</th>
<th>W</th>
<th>R</th>
<th>F</th>
<th>WR</th>
<th>WF</th>
<th>SR</th>
<th>SF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Correlation coefficient</td>
<td>0.25</td>
<td>0.38</td>
<td>0.38</td>
<td>0.21</td>
<td>0.20</td>
<td>0.33</td>
<td>0.48</td>
<td>0.30</td>
<td>0.47</td>
</tr>
<tr>
<td>Percentage explanation</td>
<td>6.3</td>
<td>14.4</td>
<td>14.4</td>
<td>4.4</td>
<td>4.0</td>
<td>10.9</td>
<td>23.0</td>
<td>9.0</td>
<td>22.1</td>
</tr>
<tr>
<td>Standard error (log units)</td>
<td>0.55</td>
<td>0.56</td>
<td>0.50</td>
<td>0.49</td>
<td>0.50</td>
<td>0.44</td>
<td>0.37</td>
<td>0.56</td>
<td>0.49</td>
</tr>
</tbody>
</table>

S-summer, W-winter, R-rising stage, F-falling stage
Fig. 5.4 Suspended sediment rating plot, St. 1, Narrator Brook, 1975/76
summer falling to over 22% while for winter rising and
summer rising explanation of variance falls to 10.9% and
9.0% respectively. This disparity between falling and
rising stages can be traced to the clockwise hysteresis
which characterizes sediment concentration variations over
flood events in the Narrator Brook. Peak sediment con­
centration always preceeds peak discharge so that during
rising stages sediment concentration undergoes a rising
trend followed by a falling trend. For falling stages the
correlation with discharge is stronger because sediment
concentrations decline throughout the flood recession from
peak discharge to baseflow; there is no reversal of trend.
Paradoxically, clockwise hysteresis also means that
generally the greater part of flood period suspended sedi­
ment is discharged during the rising stage so that for this
stage of the hydrograph estimation of sediment concentra­
tions becomes more critical than for the falling stage. The
four separate sediment rating plots, winter falling stages,
summer falling stages, winter rising stages and summer
rising stages are all better defined than a single combined
plot (fig 5.5). However, only in the case of the winter
falling rating plot is the standard error small enough
(0.37 log units) to permit meaningful prediction of sedi­
ment concentration from stream discharge (table 5.2).

For catchments in which slopes contribute significantly
to suspended sediment, hydrometeorological variables are
likely to be much more valuable than stream discharge for
defining variations in suspended sediment concentration.
A multivariate approach is also likely to be more success­
ful than a bivariate one.

5.2.2 Multivariate Analysis

Correlating instantaneous sediment concentrations with
hydrometeorological factors is not possible because of a
variable lag between production of sediment by sheet erosion
on the catchment surface and stream sediment concentra­

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Fig. 3.5 Separate suspended sediment rating plots, according to season and stage of the hydrograph, St. 1, Narrator Brook, 1975/76 (flood period samples only)
observed at the catchment outlet. Mean discharge weighted suspended sediment concentration of quickflow for individual flood events, computed from equations 3.2 and 3.3, eliminates the problem of lag and also removes the effect of variable dilution of storm runoff concentrations by baseflow. Since sediment is supplied to the stream channel largely by storm runoff, the higher the baseflow component of stream discharge, the lower observed stream sediment concentrations are likely to be. This impairs correlation with the hydrometeorological controls which govern the supply of sediment in storm runoff.

Mean discharge weighted sediment concentration of quickflow was tested by multiple regression analysis against several hydrological and hydrometeorological variables. A large measure of interrelation is apparent among these variables (table 5.3). The independent affect of each variable was assessed from the results of partial F-tests for addition of variables to a multiple regression. Five of the ten variables tested are significantly correlated, at the 0.01 level or better, with mean quickflow sediment concentration. Only two, however, contribute significantly at the 0.01 level, to explanation of variance in mean quickflow sediment concentration. These are maximum two hour precipitation and baseflow discharge preceeding the flood (table 5.4). These two variables together account for 70% of observed variance in mean discharge weighted sediment concentration of quickflow in the Narrator Brook at the main gauging site over the period of observation (equation 5.1)

$$\log_{e} Y = 2.81 + 1.11 \log_{e} X_1 - 0.48 \log_{e} X_2 \quad \ldots \ldots \ldots \ldots (5.1)$$

- \( n = 37 \)
- \( r = 0.83 \)
- \( S.E = 0.493 \) log units

- \( Y = \) mean discharge weighted sediment concentration of quickflow (mg/L)
- \( X_1 = \) maximum 2-hour precipitation (mm)
- \( X_2 = \) baseflow discharge preceeding flood event (ℓ/s)

It is unlikely that there are any other major controls which
Table 5.3 Correlation matrix showing the degree of interrelation between hydrological and hydrometeorological variables for 37 flood events in the Narrator catchment (data log transformed).

<table>
<thead>
<tr>
<th></th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>2</td>
<td></td>
<td>-0.41</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td></td>
<td></td>
<td>-0.66</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>-0.10</td>
<td></td>
<td></td>
<td>0.52</td>
<td>0.37</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>-0.53</td>
<td>0.54</td>
<td></td>
<td>0.47</td>
<td>0.32</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>-0.13</td>
<td>0.41</td>
<td>0.33</td>
<td>0.89</td>
<td>0.33</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>0.46</td>
<td>0.19</td>
<td>-0.28</td>
<td>0.45</td>
<td>-0.14</td>
<td>0.42</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>0.41</td>
<td>0.10</td>
<td>-0.01</td>
<td>0.80</td>
<td>-0.27</td>
<td>0.58</td>
<td>0.29</td>
<td></td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>0.71</td>
<td>-0.20</td>
<td>-0.46</td>
<td>-0.08</td>
<td>-0.60</td>
<td>-0.07</td>
<td>0.20</td>
<td>0.36</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>-0.24</td>
<td>0.73</td>
<td>0.50</td>
<td>0.95</td>
<td>0.45</td>
<td>0.84</td>
<td>0.25</td>
<td>0.49</td>
<td>-0.13</td>
</tr>
</tbody>
</table>

Figures in italics indicate significant correlations at the 0.01 level or better.

1 Maximum two hour precipitation
2 Baseflow discharge preceding flood event
3 Seasonal index
4 Peak discharge
5 Antecedent precipitation (API30)
6 Quickflow runoff
7 Total precipitation
8 Intensity of flood rise
9 Mean precipitation intensity
10 Mean discharge

Significance 0.01 0.001
r 0.42 0.53
n = 37
Table 5.4 Results of multiple regression analysis of variations in mean discharge weighted suspended sediment concentration of quickflow at St 1, Narrator Brook.

**DEPENDENT VARIABLE**

Mean discharge weighted suspended sediment concentration of quickflow.

<table>
<thead>
<tr>
<th>Independent Variables</th>
<th>Total Correlation Coefficients</th>
<th>9th Order Partial Correlation Coefficients</th>
<th>Partial F Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Maximum two hour precipitation</td>
<td>0.77</td>
<td>0.58</td>
<td>49.08</td>
</tr>
<tr>
<td>2 Baseflow discharge preceding flood event</td>
<td>-0.61</td>
<td>-0.41</td>
<td>12.00</td>
</tr>
<tr>
<td>3 Seasonal index</td>
<td>-0.46</td>
<td>0.39</td>
<td>7.34</td>
</tr>
<tr>
<td>4 Peak discharge</td>
<td>-0.07</td>
<td>0.31</td>
<td>3.36</td>
</tr>
<tr>
<td>5 Antecedent precipitation (API&lt;sub&gt;30&lt;/sub&gt;)</td>
<td>-0.58</td>
<td>-0.12</td>
<td>1.30</td>
</tr>
<tr>
<td>6 Quickflow runoff</td>
<td>-0.13</td>
<td>-0.25</td>
<td>2.73</td>
</tr>
<tr>
<td>7 Total precipitation</td>
<td>0.40</td>
<td>-0.20</td>
<td>0.45</td>
</tr>
<tr>
<td>8 Intensity of flood rise</td>
<td>0.35</td>
<td>-0.17</td>
<td>0.89</td>
</tr>
<tr>
<td>9 Mean precipitation intensity</td>
<td>0.54</td>
<td>0.14</td>
<td>0.30</td>
</tr>
<tr>
<td>10 Mean discharge</td>
<td>-0.28</td>
<td>-0.13</td>
<td>0.42</td>
</tr>
</tbody>
</table>

**LEVEL OF SIGNIFICANCE**

<table>
<thead>
<tr>
<th>r</th>
<th>0.42</th>
<th>0.53</th>
</tr>
</thead>
<tbody>
<tr>
<td>F</td>
<td>7.44 for 1 to 7.72 for 10</td>
<td>12.95 to 13.74</td>
</tr>
</tbody>
</table>

n = 37 Percent Explanation (all variables) 81.4%
have been unaccounted for; much of the remaining unexplained variance is probably due to experimental error, particularly associated with sampling techniques.

Both independent variables in equation 5.1 are readily obtained from rain and water level charts, and this equation can provide a convenient estimate of sediment concentration for individual flood events where sediment data is not available. Predicted values can be multiplied by quickflow runoff to obtain sediment yield for the flood event. Individual events can then be summed to obtain long term yields. With respect to the Narrator catchment this method is clearly vastly superior to the sediment rating curve/flow duration curve method. Equation 5.1 can be extended beyond the period of record with some confidence since this period covered a wide range of hydrometeorological conditions. It is advisable, however, to renew the equation periodically on the basis of fresh observations since the relative contribution from the sediment sources in the catchment may change over time.

The significance of precipitation intensity can be related to supply of sediment from catchment slopes. Rain splash breaks down soil aggregates and thereby makes sediment available for transport by overland flow. Rain splash is determined by the kinetic energy of precipitation which in turn is a function of precipitation intensity (Hudson 1971, Morgan 1979). Sediment concentrations in the Narrator Brook are more sensitive to maximum two hour precipitation \( r = 0.77, n = 37 \) than to mean precipitation intensity \( r = 0.54, n = 37 \). This is due to the distribution of kinetic energy over a storm event. Kinetic energy increases exponentially with precipitation intensity and for a given rainfall amount of a given duration, more energy will be expended when the rain is partially concentrated into a short period than if it is evenly distributed. It is likely that shorter intensities than the two hour periods used in this analysis would be still more successful; half-hour intensities are employed, for example, in the Universal Soil Loss Equation (Wischmeier & Smith 1958).
Two hour intensity, however, is the minimum period intensity that can be reliably abstracted from weekly autographic rain charts.

Saturation overland flow is widespread in the Narrator catchment, particularly in the moorland region of the catchment. Analysis of soil well data reveals that precipitation intensity has little influence upon soil saturation; the chief control in this regard is total storm period precipitation. This factor, however, has no significant independent effect upon sediment concentration (9th order partial correlation coefficient = -0.20, n = 37). This suggests that overland flow may be essentially a transporting agent removing the sediment made available by rain splash; it is largely ineffective as an erosion agent in its own right. This conflicts with the results of laboratory experimental investigations of Bryan (1976,77) but is in accord with the view of most authorities on this matter (Hudson 1971, Stocking & Elwell 1976, Wischmeier 1977, Morgan 1979).

As well as making sediment available for transport by overland flow on catchment slopes, rain splash on exposed channel banks may be responsible for supplying sediment directly to the stream without the assistance of overland flow. Direct contribution of sediment by rain splash may also occur at cattle crossing points where trampling has created localized areas of bare earth immediately adjacent to the stream.

Explanation for the emergence of antecedent baseflow discharge as a significant independent control of mean flood period sediment concentrations in the Narrator Brook is not as straightforward as appears at first sight. Guy (1964) and Walling & Teed (1971) are among the few studies which have previously employed antecedent baseflow discharge in multivariate analysis of stream sediment dynamics. In both cases it was used as a surrogate for catchment wetness and in both cases it proved to be an important control of suspended sediment dynamics. The significance of catchment wetness is usually interpreted in terms of erodibility of
the soil surface and the consequent availability of sedi-
ment for sheet erosion. Moisture improves the cohesion of
soil thus reducing its susceptibility to erosion. Antece-
dent precipitation is more commonly used as an index of
catchment wetness. In a multiple regression analysis of
sediment dynamics in an East Devon catchment, antecedent
precipitation and season emerged as significant independent
controls (Walling 1974b). Similarly in a multivariate
analysis of suspended sediment variations in an East York-
shire catchment, antecedent precipitation and season combined
to form the principle component (Imeson 1971a). Season is
important with respect to catchment wetness because it de-
termines rates of evapotranspiration; catchments will be
drier in summer for a given antecedent precipitation than in
winter. Although antecedent precipitation is significantly
correlated with quickflow sediment concentration \( r = -0.58, \)
\( n = 37 \) its independent affect in the presence of antecedent
baseflow discharge is minor (9th order partial correlation =
\(-0.12, n = 37\)). Antecedent precipitation is probably a
more sensitive measure of catchment wetness than antecedent
baseflow discharge. Precipitation falling on a dry catch-
ment may be largely absorbed by the soil with negligible
contribution to groundwater storage, so that a rain storm
event may fundamentally alter catchment wetness without this
being reflected in baseflow discharge. Similarly, although
there is a strong seasonal trend in the sediment dynamics of
the Narrator Brook, with higher concentrations during summer
months \( r = -0.46, n = 37 \) this is entirely a reflection of
seasonal variations in precipitation intensity \( r = -0.66, \)
\( n = 37 \). The 9th order partial correlation coefficient re-
lating seasonal index to mean quickflow sediment concen-
tration \( 0.39 n = 37 \) is positive rather than negative.

The lack of any significant independent correlation of
antecedent precipitation and season with sediment concen-
tration in the Narrator Brook suggests that the significance of
antecedent baseflow discharge does not relate to catchment
wetness and supply of sediment from sheet erosion. It
probably relates instead to supply of sediment from bank erosion which has been shown to be an important source for suspended sediment in the Narrator catchment. Stage in all rivers rises more rapidly, for a given increment of discharge, at lower initial discharges. Consequently, the lower the discharge before a flood event the greater the area of bank that will be inundated for a given quickflow runoff and the greater the supply of sediment that can be expected from this source. Investigations concerned with processes of bank erosion have revealed that on exposed bank surfaces sediment is made potentially available for fluvial transport by sub-aerial weathering (Wolman 1959, Hill 1973, McGreal & Gardiner 1977). This sediment enters fluvial transport when next the bank is submerged. Baseflow discharge is also an indication of the relative extension of the drainage net in the catchment. A large proportion of the channel network in the Narrator catchment is ephemeral (2.68 km out of a total of 9.88 km - table 2.4, fig 2.9). Large amounts of fine sediment may be flushed out of these channels when they become occupied by streamflow during flood events. In view of its relation to the supply of fines from within the channel system, antecedent baseflow discharge is potentially a very valuable parameter for modelling suspended sediment dynamics; one that has been overlooked in many previous studies.

Although the significance of antecedent baseflow discharge is unrelated to catchment wetness this does not necessarily imply that catchment wetness has no effect upon soil erodibility and availability of sediment on catchment slopes. Soil saturation and rate of overland flow in the moorland region of the Narrator catchment increases significantly with catchment wetness. Both antecedent precipitation and season are significantly related to maximum soil well levels in this soil type. It may be that this largely cancels out the effect of wetness upon soil erodibility explaining the poor performance of antecedent precipitation and season in multivariate analysis of suspended
sediment dynamics. Although more sediment may become available on the catchment surface during dry periods this is offset by reduction in the rate of overland flow which transports available sediment to the stream channel. This may also explain the inconsistent performance of antecedent precipitation in attempts to model soil loss which is referred to by Morgan (1979).

The relatively poor performance of the streamflow variables included in the regression analysis, peak discharge, mean discharge, intensity of flood rise and quickflow runoff, suggests that bed material does not contribute greatly to total suspended sediment transport. Streamflow determines the stream power available to entrain sediment particles from the stream bed. If bed material were a significant source of suspended sediment, streamflow parameters would be expected to play a more prominent role in influencing variations in mean quickflow sediment concentration.

In addition to the analysis at the main gauging site, mean discharge weighted quickflow sediment concentrations at Sts 11 and 21 were also tested against hydrological and hydrometeorological variables in order to compare the results with those at St 1. Since the number of flood events included in the analysis is the same at all three stations (n = 37), correlation coefficients can be directly compared (table 5.5). Mean quickflow sediment concentrations at St 11 are similar to those at St 1, 1000 m downstream, although there is some degree of independent variation. The ratio of mean quickflow concentration at St 11 to mean quickflow concentration at St 1 varies from 0.33 to 4.11 over 37 events. The differences in mean quickflow concentrations between St 21 and St 11, 1220 m downstream are also appreciable. The ratio of mean quickflow concentration at St 21 to mean quickflow concentration at St 11 varies from 0.21 to 1.34. As these ratios indicate, mean quickflow concentration at St 21 are generally lower than those at Sts 11 and 1, in some instances very much
Table 5.5  Product moment correlation coefficients relating mean discharge weighted suspended sediment concentration of quickflow to hydrological and hydrometeorological variables for the three gauging stations on the Narrator Brook (data log transformed).

<table>
<thead>
<tr>
<th>INDEPENDENT VARIABLES</th>
<th>St 1</th>
<th>St 11</th>
<th>St 21</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum two hour precipitation</td>
<td>0.77**</td>
<td>0.69**</td>
<td>0.60**</td>
</tr>
<tr>
<td>Baseflow discharge preceding flood event</td>
<td>-0.61**</td>
<td>-0.51*</td>
<td>-0.52*</td>
</tr>
<tr>
<td>Antecedent precipitation (API$_{30}$)</td>
<td>-0.58**</td>
<td>-0.47*</td>
<td>-0.52*</td>
</tr>
<tr>
<td>Mean precipitation intensity</td>
<td>0.54**</td>
<td>0.52*</td>
<td>0.49*</td>
</tr>
<tr>
<td>Seasonal index</td>
<td>-0.48*</td>
<td>-0.48*</td>
<td>-0.38*</td>
</tr>
<tr>
<td>Total precipitation</td>
<td>0.40</td>
<td>0.33</td>
<td>0.16</td>
</tr>
<tr>
<td>Mean flood period discharge</td>
<td>-0.28</td>
<td>-0.25</td>
<td>0.29</td>
</tr>
<tr>
<td>Intensity of flood rise</td>
<td>0.35</td>
<td>0.31</td>
<td>0.18</td>
</tr>
<tr>
<td>Quickflow runoff</td>
<td>-0.13</td>
<td>-0.12</td>
<td>-0.20</td>
</tr>
<tr>
<td>Peak discharge</td>
<td>-0.07</td>
<td>-0.07</td>
<td>-0.17</td>
</tr>
<tr>
<td>Percent explanation (all variables)</td>
<td>81.4</td>
<td>73.2</td>
<td>64.8</td>
</tr>
</tbody>
</table>

Significance levels  * 0.01  ** 0.001  n = 37 throughout

lower. For example, a flood event which took place on the 14th to 16th of October 1976 resulted in a mean discharge weighted quickflow sediment concentration of 4.0 mg/l at St 21 compared with 19.2 mg/l and 15.9 mg/l at Sts 11 and 1 respectively. Lower concentrations at St 21 have resulted in a lower sediment yield in comparison to the other two gauging sites and the reasons for this are discussed in chapter 7.

The ten independent variables included in analysis together provided a better explanation of variance in mean quickflow sediment concentrations at St 1 (81.4%) than at Sts 11 and 21 (73.2% and 64.8% respectively). The reason for this probably lies in the greater number of flood
samples collected at St 1 permitting more accurate estimates of mean discharge weighted quickflow sediment concentrations. At St 1, in addition to the standard automatic vacuum operated stream sampler and rising stage samplers in use at all three gauging sites, there is also an automatic vacuum operated stream sampler designed to collect samples at half-hour intervals during flood events. At St 21, the percentage explanation is lowest for the three gauging stations. Lack of streamflow record for some flood events at this station, necessitating estimation of discharge and runoff from flow records at St 11, has probably impaired the accuracy of estimated mean quickflow concentrations to some degree and this is reflected in the relatively high proportion of unexplained variance.

Correlation coefficients for the three gauging sites are similar, although values are generally lower at Sts 11 and 21 than at St 1 for reasons discussed above (table 5.5). At all three gauging sites, maximum two-hour precipitation is the most important independent variable ($r = 0.77, 0.69$ and $0.60$ for Sts 1, 11 and 21 respectively). The major contrast between the stations relates to the performance of antecedent baseflow discharge. At St 1 correlation of this variable with mean quickflow sediment concentration is appreciably greater than for the other two stations ($r = 0.61, -0.51$ and $-0.52$ for Sts 1, 11 and 21 respectively). While antecedent baseflow discharge adds significantly to explanation of variance in mean quickflow sediment concentration provided by maximum two-hour precipitation at St 1 (partial F value = 12.0) it fails to do so at Sts 11 and 21 (partial F values = 3.6 and 3.5 respectively). Maximum two-hour precipitation is the only significant independent control at Sts 11 and 21. Since the significance of antecedent baseflow discharge probably relates to supply of sediment from stream banks, these results suggest that this supply is concentrated in the forest region of the Narrator catchment between Sts 1 and 11. This is entirely consistent with measurements of bank erosion that have been
made along the Narrator Brook, and which are discussed in chapter 4.

Correlation of total precipitation with mean quickflow sediment concentration also varies greatly in strength for the three gauging stations. The correlation at St 21 is only 0.16 compared with 0.40 at St 1. The drainage area above St 21 is 99% moorland which appears from soil well observations to be subject to saturation overland flow. Level of saturation in this region is determined more by total precipitation of storm events than by precipitation intensity. The relatively low correlation of total precipitation to mean quickflow sediment concentration at St 21 indicates, as suggested earlier, that in the absence of rain splash overland flow supplies little sediment from catchment slopes to the stream channel. Overland flow is not effective as an agent of erosion on peaty soils; its main role is to transport sediment particles that have been detached from the soil surface by rain splash.

Having examined the pattern of variation in sediment transport for flood events generated by rainfall, it is possible to assess the extent to which the two small events generated by snowmelt (6-7/2/76 and 7-8/2/76) deviate from this pattern. Since both events were caused by rainfall upon melting snow, the contribution of snowmelt to total quickflow runoff cannot be established with any precision. Some idea of the contribution of snowmelt can be obtained by comparing observed quickflow runoff for the two events with predicted quickflow runoff from a multiple regression equation based upon observed runoff for all 71 rainfall generated flood events which occurred during the period of observation (equation 5.2).

\[ \log_{e} Y = 2.391 \log_{e} X_1 + 0.052 \log_{e} X_2 + 1.109 \log_{e} X_3 - 6.605 \]  

\text{Y} = \text{Quickflow runoff as a percentage of precipitation} \\
X_1 = \text{Total precipitation of storm event} \\
X_2 = \text{Antecedent precipitation (API)} \\
X_3 = \text{Seasonal index} \\
r = 0.80, n = 71, S.E. = 0.158 \log_{e} \text{units}
For both snowmelt events, observed quickflow runoff exceeds the range of values between two standard errors above and below predicted quickflow runoff (table 5.6).

Table 5.6 Runoff and sediment yield for two snowmelt generated flood events in comparison to expected values.

<table>
<thead>
<tr>
<th>Flood Event</th>
<th>Observed Value</th>
<th>+2 Standard Errors</th>
<th>Predicted Value</th>
<th>-2 Standard Errors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quickflow runoff (m³)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6-7/2/76</td>
<td>659</td>
<td>209</td>
<td>9</td>
<td>0.4</td>
</tr>
<tr>
<td>7-8/2/76</td>
<td>6765</td>
<td>667</td>
<td>29</td>
<td>1.2</td>
</tr>
<tr>
<td>Mean discharge weighted sediment concentration of quickflow (mg/l)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6-7/2/76</td>
<td>6.4</td>
<td>8.9</td>
<td>2.9</td>
<td>0.9</td>
</tr>
<tr>
<td>7-8/2/76</td>
<td>12.4</td>
<td>22.9</td>
<td>7.5</td>
<td>2.4</td>
</tr>
<tr>
<td>Transport of sediment by quickflow (Kg)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6-7/2/76</td>
<td>4.2</td>
<td>1.9</td>
<td>0.02</td>
<td>0.0004</td>
</tr>
<tr>
<td>7-8/2/76</td>
<td>30.4</td>
<td>15.3</td>
<td>0.2</td>
<td>0.003</td>
</tr>
</tbody>
</table>

* Predicted values obtained from equations 5.1 and 5.2

These results indicate that for the first event, at least 75% (450m³) of quickflow is contributed by snowmelt and for the second event this contribution is at least 90% (6100m³). Mean discharge weighted sediment concentration of quickflow for the two events (6.4 and 12.4 mg/l for 6-7/2/76 and 7-8/2/76 respectively) both fall within the expected range of values obtained from equation 5.1. However, as a result of the greater than expected runoff, quickflow transport of sediment by the two events exceeds the range of expected values (table 5.6). The second of the two events
not only has a greater quickflow runoff than the first, but also has a greater sediment concentration. This may perhaps be explained by the greater area of catchment cleared of snow and exposed to erosion during the course of the second event. The two snowmelt events together contributed 0.13% of total runoff over the period of observation and 0.18% of total sediment yield.

5.2.3 Variations in Particle Size Composition

The low concentrations of suspended sediment in the Narrator Brook preclude conventional methods of particle size analysis. Minimum concentrations required for the pipette and hydrometer methods are 2 000 and 25 000 mg/l respectively (A.S.C.E. 1969b). The maximum concentration recorded in the Narrator during the period of observation was 330 mg/l; generally flood period concentrations are below 50 mg/l.

To overcome the problem of low concentrations in the Narrator Brook suspended sediment was collected for particle size analysis in a submerged container clamped to a metal support erected on the stream bed at the main gauging site (plate 3.9). The container is a 350ml cylindrical cannister with a removable lid into which is cut an orifice 25 mm in diameter to permit the entry of sediment particles. The cannister is fixed in an upright position in relatively slack water in the lee of the supporting structure. The orifice was set at a height of 18 cm above the stream bed and remained below water throughout the period of observation. Due to the small size of orifice in relation to the volume of the container, once sediment has collected in the container it cannot subsequently be washed out unless the container is allowed to become almost full. Over a period of time suspended sediment collects in the open container at a rate determined by the rate of stream sediment discharge and the size of the container orifice. Both the period of collection and the size of the orifice can be ad-
justed to obtain a sufficient quantity of sediment for particle size analysis by conventional methods. By experiment an orifice diameter of 25 mm combined with a weekly collection period proved to be the most suitable scheme. During dry periods in which sediment concentrations remained constantly below 1 mg/l, the period of collection was extended to up to three weeks to ensure the requisite amount of sediment. The sediment collected was dried at 105°C and weighed. Particle size distribution was determined by gently brushing the dried sediment through a series of test sieves with mesh sizes ranging from 2 mm to 75 microns. The particle size distribution of suspended sediment for individual collection periods varies considerably. For 2 of the total of 22 periods of collection, sediment retained in the submerged container is 100% finer than 300µ, while for 4 periods of collection sediment includes particles exceeding 1 mm in size. The percentage of particles finer than 75µ varies from 37.4% to 97.1%. This variation in particle size composition arises because transport of coarse particles and fine particles in suspension are subject to differing controls. The weight of particles larger than 300µ recovered from the submerged container for 22 periods of collection is closely related to mean discharge for each period \( r = 0.61, n = 22 \). The correlation with mean discharge becomes progressively weaker with decreasing particle size (table 5.7).

Table 5.7 Product moment correlation coefficients relating individual size fractions of suspended sediment to stream discharge and precipitation intensity (data untransformed).

<table>
<thead>
<tr>
<th>Period mean stream discharge</th>
<th>&lt; 75µ</th>
<th>75µ-150µ</th>
<th>150µ-300µ</th>
<th>&gt; 300µ</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.40</td>
<td>0.48*</td>
<td>0.54**</td>
<td>0.61**</td>
<td></td>
</tr>
<tr>
<td>Period maximum two hour precipitation</td>
<td>0.64**</td>
<td>0.53*</td>
<td>0.48*</td>
<td>0.39</td>
</tr>
<tr>
<td>n = 22</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Significance level</td>
<td>* 0.05</td>
<td>** 0.01</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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finer than 75μ collected in the submerged container, correlation with mean discharge is not significant at the 0.05 level (r = 0.40, n = 22). The relation of the weight of sediment retained in the submerged container with precipitation intensity displays a reverse trend. Correlation is highest for sediment finer than 75μ (r = 0.64, n = 22) and declines with increasing particle size to only r = 0.39 (n = 22) for sediment coarser than 300μ. For flood events with low peak discharge but generated by high intensity precipitation sediment transported in suspension is predominantly fine. The collection period 16/8/76 to 6/9/76, for example, included a single flood event with a peak discharge of 169 l/s and a maximum two-hour precipitation of 21.7 mm. Weight of sediment collected in the submerged container for this period is 231 mg and 96.8% is finer than 75μ. The particle size composition of sediment transported in suspension during flood events with a high discharge generated by low intensity precipitation is coarser. The collection period 6/12/76 to 13/12/76 included a single flood event with peak discharge 693 l/s and a maximum two-hour precipitation of 6.0 mm. Weight of sediment collected in the submerged container during this period is 660 mg and only 46.6% is finer than 75μ.

The differing controls for coarse and fine sediment in suspension suggest that they have different sources. However, it is apparent from table 5.7 that there is no clear division in terms of particle size but rather there is a gradation. Fine sediment, transport of which is only poorly related to discharge, is probably derived largely from beyond the channel network. Coarser sediment is probably derived largely from within the channel. A likely source for coarse suspended particles is bed material. Bed material along the Narrator Brook contains an abundant supply of medium to coarse sand derived from the sandy growan which underlies the Narrator catchment. Suspended transport of particles originating from bed material depends upon the power of the stream to entrain particles from the
stream bed and hence, unlike fine sediment, there is a direct functional relation with discharge. Transport of bed material in suspension is selective in terms of particle size. While fine particles smaller than 300μ were transported in suspension throughout the range of flows during the period of observation down to lowest baseflow discharges, particles larger than 300μ are only transported above certain critical discharges (fig 5.6). Suspended particles larger than 600μ, for example, are restricted to discharges greater than 500 ℓ/s. The duration of discharges at which these larger sediment particles are transported is short (fig 5.7). Discharges greater than 500 ℓ/s, for example, occurred during only 2% of the period of observation. As

![Fig. 5.6 Relation between maximum size of sediment particles in suspension and peak stream power](image)

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a result, although the proportion of large particles relative to fine particles in suspended sediment varies according to stream flow and precipitation intensity, overall it is minor. Particles larger than 300μ comprise only 7.7% of total sediment collected in the submerged container over the period of observation as a whole, and particles larger than 600μ only 1%. Variations in the concentration of particles larger than 300μ thus have little effect upon variations in total suspended sediment concentration. In multivariate analysis of variations in total suspended sediment concentration, discussed in the previous section, stream discharge, which controls concentration of large particles, is overshadowed by precipitation intensity, which controls the concentration of fine particles.
5.3 Variations in base flow suspended sediment

Suspended sediment transported during baseflow periods in the Narrator Brook accounts for 14.2% of total suspended sediment yield from the Narrator catchment over the period of observation. Although concentrations are low, generally below 1mg/l compared with a mean concentration in quickflow of 20.5mg/l, baseflow runoff exceeds that of quickflow by 7 times (1150 and 162mm respectively). Any reliable estimate of total sediment yield must also account for transport of sediment during baseflow and consequently it is desirable to know something of its dynamics.

During the period of research, 28 samples of baseflow were collected at each of 30 sites along the Narrator Brook at approximately fortnightly intervals. Sediment concentrations in these samples are very low in comparison to flood samples. At the main gauging site (St 1) sediment concentration in the 28 samples collected ranges between 2.2mg/l on the 8th of July 1975 to 0.1mg/l on the 30th of September 1975, and for 24 of the 28 samples concentration is below 0.3mg/l. Although sediment transported during baseflow is derived from the stream channel there is no significant correlation between baseflow concentration at St 1 and stream discharge at the time of sampling ($r = -0.32$, $n = 28$). The low concentrations of suspended sediment during baseflow presents a major difficulty in attempts to analyse variations in concentration. The reproducibility of the filtration method of determining sediment concentration from stream samples is probably at best $\pm 0.3mg/l$. This accounts for a large proportion of the range in observed values at St 1 and may be responsible for obscuring any trends that might exist.

An alternative method of investigating suspended sediment during baseflow is from sediment trapped in a submerged container. The weight of sediment retained in the submerged container provides an accurate indication of the discharge of suspended sediment through the channel cross-
section during the period of collection ($r = 0.98, n = 9$) (fig 5.8). Only those periods of sediment collection where quickflow runoff formed at least 5% of total runoff for the period are included in fig 5.8. Calculation of suspended sediment discharge for these periods is based upon stream sampling during flood events combined with an assumed baseflow sediment concentration of 0.6mg/ℓ. Since baseflow concentration may be subject to temporal fluctuations this probably accounts for a large part of the scatter in fig 5.8. Since the weight of sediment collected in the submerged container corresponds closely to measured sediment discharge, variations in the weight of sediment collected in the submerged container during baseflow can be considered to represent variations in baseflow sediment

![Graph](image)

**Fig. 5.8** Relation between weight of sediment retained in a submerged container and discharge of suspended sediment, St. 1, Narrator Brook

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transport. Weight of sediment retained in the submerged container for those periods of collection where baseflow runoff accounts for at least 99% of total runoff varies from 26.1mg/day to 1.3mg/day. These variations are very closely related to variations in maximum discharge for the periods of collection (r = 0.97, n = 9 - fig 5.9). This means that as discharge rises more sediment becomes available for transport. The relation with discharge, however, is curvilinear; the rate of increase in baseflow sediment transport tails off at higher baseflow discharges. The more likely source for sediment transported during baseflow is from channel banks rather than from bed material. Oldfield et al (1979), by analysis of the remnant magnetism of baseflow suspended sediment in a small Devon stream, were able to trace this sediment to channel banks. In the

![Graph](image-url)

Relation between weight of sediment retained in a submerged container during periods of baseflow and period maximum stream discharge, St. 1, Narrator Brook
Narrator catchment, increased availability of sediment from channel banks as discharge rises can easily be explained in terms of progressive submergence of the banks. This would also account for the slowing down in the rate of increase in baseflow suspended sediment transport at higher baseflow discharges since the area of channel bank inundated for a given increment of discharge decreases with discharge. Although transport of suspended sediment increases with increasing discharge during baseflow, concentration of suspended sediment decreases with discharge. From fig 5.9, at a discharge of 500 l/s, the weight of sediment collected in the submerged container is in the region of 20 mg/day. If this is referred to fig 5.8 it represents a sediment discharge of 18 Kg/day which at a discharge of 500 l/s means a sediment concentration of 0.42 mg/l. At a discharge of 100 l/s estimated sediment concentration rises to 0.63 mg/l. This corresponds to the trend which emerges from correlation of sediment concentration in stream samples against stream discharge at the time of sampling (r = -0.32, n = 28). The correlation is negative though insignificant.

5.4 Variations in bedload transport

Since the Second World War, equations to predict bedload transport for streams where empirical data is lacking have proliferated (eg. Meyer Peter & Muller 1948, Einstein 1950, Yalin 1963, Bagnold 1966, Yang 1973). Most of these equations have been developed either from theoretical considerations based upon the physical principles of work and energy or else from observations in laboratory flumes. The majority also originated within the United States and were designed for use on wide sand bed streams. Application of these formulas, particularly the modified Einstein technique, to rivers of this type has met with a measure of success (Colby & Hembree 1955, Hubbell & Matejka 1959). For streams such as the Narrator Brook in which bed material is
composed of a substantial proportion of particles larger than 2 mms it appears that conventional bedload equations are rather less useful. They are regarded by many sedimentologists as being of little practical value (Herbertson 1969, Allen 1970, Blenh 1973). Where bedload equations have been compared to field measurements on gravel floored streams, it has been found that predicted values from the different equations vary considerably and that none come close to actual values (eg. Fleming 1969, Hollingshead 1971). One reason for the inadequacy of existing equations is that they do not account for the variation of packing or arrangement of particles on the stream bed which becomes an important factor with larger particles. A fundamental assumption underlying all attempts to predict bedload transport is that movement of particles takes place when shear stress equals the submerged weight of the particle. Laronne and Carson (1976), however, discovered that the ratio between critical shear stress and submerged particle weight varied from 1.8 to 6.1 on a gravel bed stream depending upon the type of packing. Serr (1951) remarks that until major advances are made in predictive techniques, heavy reliance should be placed on field measurements. It is apparent that these advances have not yet been forthcoming.

Sediment for bedload transport is derived entirely within the channel from the available pool of bed material. Rate of transport thus depends upon the power of the stream to entrain particles on the stream bed. Stream power as defined by Bagnold (1966) is a product of four factors, water density, water surface slope, stream velocity and stream depth. In practice, however, for calculation of stream power water density and water surface slope are considered constant (eg. Leopold & Emmett 1976, Gomez 1979). Of the four factors which comprise stream power, therefore, only velocity and depth vary to any large degree at a site (Skibinski 1968). Stream discharge in rectangular cross-sections is also a function of depth and velocity and hence discharge is proportional to stream
power and can be conveniently used as a surrogate. The bedload rating curve, which relates bedload transport to stream discharge, is thus a logical starting point for modelling bedload dynamics (Hollingshead 1971). Bedload collected in a stream bed trap at the main gauging site on the Narrator Brook for 30 periods, ranging in duration from 7 to 28 days, is closely related to peak discharge for each collection period \( r = 0.91, n = 30 - \text{fig 5.10} \). This contrasts with the situation for suspended sediment in the Narrator Brook for which the rating curve approach is clearly inappropriate. The regression equation relating bedload transport to peak discharge was obtained by the least squares method, but the function of the independent variable was determined by trial and error. Values corresponding to periods when it was suspected, from inspection of the bedload trap, that its capacity may have been exceeded are also plotted in fig 5.10 for comparative purposes. These values, however, were omitted in curve fitting and generation of the regression equation.

Recorded rates of bedload transport for the Narrator Brook are exceedingly variable. At one extreme, for the period 1-8/12/76, during which stream discharge rose to 1 303 l/s, the capacity of bedload trap was exceeded. This represents a bedload discharge for the 7 day period of at least 75.6kg through the channel cross section at the main gauging site which is 2.4m wide. The greater part of this was probably discharged in the space of a few hours. At the other extreme, for the 14 day period 13/4/76 to 11/5/76, during which stream discharge never rose above 94 l/s, total recorded transport of bedload at the main gauging site was only 0.07kg. The bedload trap was never found to be completely empty after a period of collection, even though nine of these periods included no major flood events and stream discharges remained continuously below 100 l/s. It is not possible on the basis of the limited observations available to be certain about the significance of these low recorded rates of bedload transport.
\[ \log_y = 0.00026 (\log_x)^2 - 2.01 \]
\[
\begin{align*}
    r &= 0.91 \\
    S.E. &= 0.68 \text{ log units}
\end{align*}
\]

O Trap capacity may have been exceeded

Fig. 5.10  Bedload rating curve, St. 1, Narrator Brook, 1975/76
at low stream discharges. It may be, for example, that disturbances created by trout in the stream could cause small quantities of gravel to enter the bedload trap. In any event, because of the rapid rate of increase in recorded bedload discharge with increasing stream discharge, recorded bedload discharge during low flow periods contributes very little to total recorded discharge during the period of observation as a whole. Stream discharges less than 100 l/s occurred during 70% of the period of observation, but less than 1% of total recorded bedload transport occurred at these times.

The bedload rating curve for the Narrator Brook displays a certain amount of scatter representing unexplained variance and suggesting possibly that the inclusion of additional independent variables in the form of a multiple regression would materially improve the prediction. The multiple regression approach to modelling bedload dynamics has previously been used with some success by the Institute of Hydrology in catchments in Mid-Wales (N.E.R.C. 1977). One problem of investigating bedload dynamics using sediment traps is that only total yield over a period of time is obtained; nothing is known regarding variations in transport over this period. Runoff over a period is a product of two dimensions, duration and discharge. At higher discharges particularly, bedload transport is very sensitive to small changes in discharge and this becomes the dominant controlling dimension. Mean discharge and total runoff, which incorporate the duration dimension, fail to add significantly to the explanation of variance achieved by peak discharge which is totally free of the duration dimension (table 5.8).

The significance of water temperature in relation to bedload transport has been stressed by Colby & Scott (1965) and Franco (1968). Within the range of temperatures commonly occurring in streams, there is little material effect upon water density and hence tractive force or stream power. Small variations in stream water temperature, can
Table 5.8 Results of multiple regression analysis of variation in bedload transport by the Narrator Brook (data log transformed).

DEPENDENT VARIABLE

Total bedload transported past St.1 for 30 periods of observation, each about two weeks in duration. The 5 periods during which the capacity of the bedload trap may have been exceeded are excluded from the analysis.

<table>
<thead>
<tr>
<th>Independent Variables</th>
<th>Total Correlation Coefficients</th>
<th>5th Order Partial Correlation Coefficients</th>
<th>Partial F Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Peak discharge</td>
<td>0.87</td>
<td>0.76</td>
<td>89.51</td>
</tr>
<tr>
<td>2 Total runoff</td>
<td>0.71</td>
<td>0.45</td>
<td>7.38</td>
</tr>
<tr>
<td>3 Mean water temperature</td>
<td>-0.11</td>
<td>0.40</td>
<td>4.46</td>
</tr>
<tr>
<td>4 Intensity of flood rise</td>
<td>0.48</td>
<td>-0.27</td>
<td>1.11</td>
</tr>
<tr>
<td>5 Mean particle size of bedload</td>
<td>-0.01</td>
<td>0.07</td>
<td>0.86</td>
</tr>
<tr>
<td>6 Mean discharge</td>
<td>0.71</td>
<td>-0.27</td>
<td>1.31</td>
</tr>
</tbody>
</table>

LEVEL OF SIGNIFICANCE

- \( r = 0.01 \)
- \( r = 0.46 \)
- \( F = 7.64 \) for 1 to 7.88 for 6

\( n = 30 \) Percent Explanation (all variables) 86.3%

However, substantially influence viscosity and hence the stream's ability to entrain particles. Intensity of flood rise has been demonstrated by Skibinski (1968) to be another important factor affecting rates of bedload transport. He found that during sharply rising floods, water
surface slope and stream power are higher on the rising stage of the flood for a given discharge than would normally be expected, thus promoting higher rates of bedload transport.

Neither of these two factors, stream water temperature and flood intensity, contribute significantly to the explanation of variance in bedload transport in the Narrator Brook and this may be due to the hydrological make-up of the catchment. Baseflow, which is supplied at least partially from groundwater, comprises almost 90% of the total runoff from the Narrator catchment. Groundwater is remote from atmospheric temperature fluctuations experienced at the catchment surface and itself varies little in temperature. Consequently stream water temperature during the period of observation varied within a relatively restricted range between 5.6°C and 13.8°C, a range which may not have been sufficiently great to significantly influence bedload transport. High baseflow discharges coupled with low rates of quickflow generation mean that flood rises are rarely very intense; probably not intense enough for this factor to have any effect either.

A final factor considered important with respect to bedload transport, which is included in all bedload equations, is particle size of bed material. Mean particle size of bedload collected in the Narrator Brook over the period of research varied over a wide range from 0.1 mm to 3.6 mm. In contrast to rate of bedload transport, the particle size of bedload transported is unrelated to peak discharge ($r = 0.13, n = 31$). This suggests that observed variations in the particle size composition of bedload are not a result of variations in stream competence but instead are largely a reflection of variations in the particle size composition of bed material. This supports the belief expressed earlier that bedload transport in the Narrator Brook does not discriminate in terms of particle size, but rather involves movement of bed material more or less en masse. This accords with observations made by Bogardi (1951) of
bedload movement in gravel-bed streams in Hungary and by Lewin & Brindle (1977) in a small Welsh stream. Mean particle size of bedload collected in the stream bed trap does not contribute significantly to explanation of variance in rates of bedload transport by the Narrator Brook indicating that bedload transport is insensitive to changes in the particle size composition of bed material. This is in direct contrast to the observations of Leopold & Emmett (1976) in the East Fort River, Wyoming, where rate of bedload transport decreases with increasing particle size of bed material. Bed material in the East Fork River is predominantly sand. In the Narrator Brook, where bed material contains a large proportion of gravel, it may be that packing of particles in the stream bed has more influence upon rate of bedload transport than mean particle size of bed material.

Multiple regression analysis thus failed to improve upon the predictive power of the bedload rating curve. Nevertheless the relation of bedload to discharge is sufficiently strong to be used for estimation of long term bedload yields by reference to water level records.
CHAPTER 6
SOLUTE SOURCES AND TEMPORAL VARIATIONS
IN SOLUTE CONCENTRATION

6.1 Solute source categories and characteristics

6.1.1 Atmosphere

The two sources for stream solutes in unpolluted catchments are dissolution of soluble particles and gases in the atmosphere and weathering of catchment rocks. The stream itself lies between these two sources systems and temporal variations in stream solute concentration reflect the operation of both systems.

There are several possible sources for atmospheric particles, including sea spray, wind blown soil particles and pollutants. In coastal locations sea spray is likely to be the most important source. Evaporation of sea spray produces tiny salt crystals which become suspended in the atmosphere. These particles can be transported long distances overland by wind, although atmospheric concentrations decrease away from the coast due to progressive fallout. Stevenson (1968), examined spatial variations in the composition of atmospheric particles over the British Isles. She found that in coastal regions sea salt crystals dominate and that there is decline in atmospheric concentration of sea salt crystals away from the windward west coast of Britain. Fallout of salt particles from the atmosphere occurs by three mechanisms: wet fallout, gravitational dry fallout, and impaction.

Wet fallout, the first of these three mechanisms, involves the incorporation of soluble particles in the atmosphere as solutes in precipitation. A distinction can be made between rain out and wash out (Burt & Day 1979). Rain out occurs when salt crystal act as rain drop nuclei and subsequently become dissolved by the rain drops which form around them. Wash out refers to the sweeping of salt crys-
Measurement of the supply of solutes to the catchment by wet fallout is a relatively simple procedure requiring only a bottle and funnel assembly for the collection of rainfall samples (Gregory & Walling 1973).

Fallout of salt particles from the atmosphere occurs during dry periods as a result of gravitational settling and in some catchments this type of fallout may contribute substantially to total atmospheric supply. Swank & Henderson (1976), for example, report that this type of atmospheric fallout is equivalent to around 25% of wet fallout in the Coweeta watershed (N. Carolina) and closer to 50% in the Walker Branch watershed (Tennessee). Gravitational dry fallout is retained in a bottle and funnel along with wet fallout, although the collection efficiency of these slow falling particles in the presence of air turbulence is probably severely limited. Solutes retained in a precipitation sampler thus represent a composite of both wet fallout and dry fallout in indeterminate proportions and together this has been termed bulk fallout (Whitehead & Feth 1964). If bulk fallout is composed predominately of wet fallout then the product of precipitation amount and precipitation solute concentration yields total mass of dissolved solids reaching the catchment as bulk fallout during the period of collection. As dry fallout becomes a larger proportion of bulk fallout, however, estimating the atmospheric supply of solutes by this method becomes progressively more unreliable.

A third process of atmospheric fallout is impaction of wind blown salt particles upon vegetation during dry periods. Sea salt particles are hygroscopic which renders them sticky and they tend to adhere to foliage upon contact (Gorham 1961). Subsequent rainfall removes in solution the salts accumulated on the surface of the vegetation during the intervening dry period and eventually by various pathways it reaches the stream to augment stream solutes. Since
this type of fallout is not gravitational it is not collected by a precipitation sampler, or at least representative samples cannot be obtained in this way. Unlike gravitational dry fallout it varies considerably over space depending upon surface conditions, particularly the nature of vegetation cover. Because of these difficulties, direct measurement of the supply of solutes by this type of fallout has never been attempted. The results of recent research in which indirect estimates of the solutes trapped by vegetation have been made from analysis of stream solutes show that this type of fallout is often of considerable significance in terms of overall supply (Juang & Johnson 1967, White et al 1971, Zeman 1975). Juang and Johnson (1967), for example, found that annual input of chloride to the Hubbard Brook catchment New England in bulk fallout is only 270 kg/km² in comparison to output of 410 kg/km². Since the rocks underlying the catchment contain no chloride they attribute the difference between input and output to impaction of atmospheric salts (i.e. 52% of bulk fallout). The presence of impaction fallout in the Narrator catchment can be readily demonstrated; its relative importance is not so easy to determine. In the present study the funnel of the bulk fallout collector at rain gauge site 1 was fitted with a nylon mesh with the initial intention of excluding leaves and insects. From comparison of the concentration of precipitation samples in this collector with those from a standard collector at the same site it appears that the nylon mesh is responsible for trapping air-borne salt particles by impaction resulting in appreciably increased concentrations, particularly when rainfall amounts and antecedent precipitation are low (fig 6.1). A similar effect was noted by Juang & Johnson (1967) in the Hubbard Brook catchment. In catchments where dry fallout of atmospheric salt particles, either by gravity or impaction, is important, accurate assessment of total atmospheric input of solutes by direct measurement becomes very difficult.
The principle ions contributed by fallout of solids from the atmosphere are sodium and chloride together with smaller proportions of magnesium, sulphate, and other ions present in sea-water (table 6.1). In addition to fallout of particles in the atmosphere certain ions in stream water originate from dissolution of atmospheric gases, including bicarbonate and nitrate. Atmospheric pollution in the form of sulphur dioxide can contribute sulphate to the stream supplementing the supply of sulphate from sea-spray (Johnson et al 1972).
Table 6.1 Chemical composition of Narrator stream water, bulk fallout, sea water, and Dartmoor Granite.

<table>
<thead>
<tr>
<th></th>
<th>Sea Water</th>
<th>Bulk Atmospheric Fallout Over Narrator Catchment (Precipitation weighted values)</th>
<th>Stream Water Narrator Brook (Discharge weighted values)</th>
<th>Dartmoor Granite</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cl</td>
<td>55.3</td>
<td>52.2</td>
<td>28.0</td>
<td>*</td>
</tr>
<tr>
<td>Na</td>
<td>30.8</td>
<td>25.5</td>
<td>19.6</td>
<td>2.5</td>
</tr>
<tr>
<td>SO₄</td>
<td>7.5</td>
<td>10.8</td>
<td>13.4</td>
<td>*</td>
</tr>
<tr>
<td>Mg</td>
<td>3.7</td>
<td>3.2</td>
<td>2.4</td>
<td>0.5</td>
</tr>
<tr>
<td>Ca</td>
<td>1.2</td>
<td>5.1</td>
<td>8.3</td>
<td>1.3</td>
</tr>
<tr>
<td>K</td>
<td>1.1</td>
<td>1.9</td>
<td>3.0</td>
<td>4.8</td>
</tr>
<tr>
<td>HCO₃</td>
<td>0.4</td>
<td>*</td>
<td>8.8</td>
<td>*</td>
</tr>
<tr>
<td>SiO₂</td>
<td>*</td>
<td>*</td>
<td>15.1</td>
<td>79.7</td>
</tr>
<tr>
<td>NO₃</td>
<td>*</td>
<td>1.3</td>
<td>0.8</td>
<td>*</td>
</tr>
<tr>
<td>Fe</td>
<td>*</td>
<td>*</td>
<td>0.6</td>
<td>2.6</td>
</tr>
<tr>
<td>Al</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>8.6</td>
</tr>
<tr>
<td>Total</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
</tr>
</tbody>
</table>

* Proportion minimal
1 Determined from a mean of 19 Burrator Reservoir samples
2 Data from Brammall & Harwood (1923)

6.1.2 Catchment Rocks

In all natural catchments some stream solutes are supplied from rock weathering. Supply from this source depends upon rock composition and the prevailing climatic conditions. Under the moist temperate climate of Britain carbonate rocks weather rapidly and supply of solutes from rock weathering to streams draining these rocks is large in comparison to atmospheric supply. Smith & Newson (1974), for example, report solute yields by streams draining the limestone area of the Mendips exceeding 200 t/km²/yr. By con-
trast, yield of solutes from a small catchment on Old Red Sandstone, also in the Mendips, is only 3.9 t/km²/yr (Waylen 1979). In the Old Red Sandstone catchment 3.1 t/km²/yr is supplied from the atmosphere and this forms 80% of solutes exported from the catchment. If this atmospheric supply also applies to the limestone regions of the Mendips its contribution relative to supply from rock weathering is negligible. In the humid temperate climate of Britain weathering of granite supplies a relatively small amount of solutes for stream transport. Gorham (1957) attributes the greater part of solutes in streams draining the Cairngorms to atmospheric supply.

Granite weathers through the process of hydrolysis whereby hydrogen ions in precipitation replace the metal cations (magnesium, sodium, potassium and calcium) in silicate minerals. Soluble silica is also released from silicate minerals by this reaction. Most of the dissolved silica transported by streams originates through hydrolysis of silicate minerals; quartz is virtually insoluble (Bricker 1968). Not all the magnesium, sodium, potassium, calcium and silicon contained in catchment rocks is released to the stream as solutes. Secondary minerals which form from decomposition of granite contain varying proportions of these elements. The proportion of any constituent in stream solutes relative to its proportion in catchment rocks is known as its mobility and varies from element to element and from region to region. In New Hampshire, for example, magnesium is the most mobile element released by granite weathering (Anderson & Hawkes 1958) while in New Mexico magnesium comes second to calcium (Miller 1961) and in the Sierra Nevada it comes third behind calcium and sodium (Feth et al 1964). The composition of solutes supplied from granite weathering thus depends upon the composition of the granite and the relative mobility of the elements. Silica has a low mobility in relation to magnesium, calcium, sodium and potassium, but because it forms such a large proportion in granite (70.5% in Dartmoor Granite) it still forms
a major constituent of stream solutes draining granite areas. Iron and aluminium have lower mobilities than silica and only relatively minor amounts of these elements are supplied to the stream from granite weathering. Chloride, sulphate, bicarbonate and nitrate are very rare in granite and these constituents in stream draining granite areas are supplied almost exclusively from the atmosphere.

6.1.3 Catchment Vegetation

Another possible supply of stream solutes is from vegetation decay. Properly, this should be regarded as a secondary source since all the solutes stored in catchment vegetation are originally derived from the atmosphere and from rock weathering. There is a constant flux of nutrients through vegetation (Bormann & Likens 1967, Deevey 1970). In stable ecosystems inputs and outputs balance over the long term; there is no change in vegetation storage and the solute output of stream catchments is a true reflection of atmospheric supply and rates of rock weathering (Zeman & Slaymaker 1978). There may, however, be short term fluctuations in vegetation storage, particularly on a seasonal level, leading to temporary inbalances in inputs and outputs. Variations in stream concentrations may therefore reflect ecosystem dynamics within the catchment, although there is no net effect as long as the biomass within the catchment remains unchanged. In situations where the catchment biomass is regenerating or degenerating following disturbance, output of stream solutes cannot be equated with the supply from atmospheric sources or rock weathering. This is an important consideration when using solute yield to estimate rate of chemical denudation. By disturbing vegetation man can exert a profound influence upon stream solute transport. For this reason stream solutes are often employed in ecological studies to monitor the health and operation of catchment ecosystems (eg. Crisp 1966, Bormann et al 1968).

Individual dissolved constituents are taken up by vege-
tation in varying proportions. Some constituents which form major plant nutrients such as nitrogen, phosphorus, calcium, magnesium and potassium are stored by vegetation in large amounts. Supply of these constituents are particularly affected by changes in vegetation. De Bano & Conrad (1976), for example, report that supply of nitrogen, phosphorus, calcium, magnesium and potassium from chaparall covered slopes in California increased from 210 kg/ha/yr before burning to 7300 kg/ha in the year immediately after burning. Supply of other constituents common in stream water which are not major plant nutrients (e.g. chloride) is unlikely to be affected by vegetation dynamics to the same degree.

6.2 Solute source analysis

6.2.1 Chemical Mass Balance of Inputs and Outputs

Having identified the possible sources of stream solutes, the task remains to determine the relative contribution of each to the solute yield of the Narrator catchment. Two major approaches to stream solute source analysis may be distinguished. The first involves a chemical mass balance of atmospheric inputs and stream outputs; excess of outputs over inputs is attributed to rock weathering. A major drawback encountered in this approach, already discussed, lies in accurate measurement of total atmospheric input which is seldom possible. A second difficulty is balancing inputs and outputs over specific time periods. In stream catchments where there is appreciable storage of solutes in groundwater and soil moisture, account has to be made of any change in storage. Walling (1974a) and Cryer (1976) account for changes in groundwater storage to determine solute budgets by selecting periods for mass balance analysis which are bounded by baseflow discharge of similar magnitude. It is assumed by this method that baseflow discharge is a reflection of groundwater...
storage and therefore over such periods changes of storage are equalized so that inputs and outputs can be directly balanced. Soil moisture storage, although rather smaller than groundwater storage in most catchments, should also be accounted for if reasonably accurate results are to be achieved. In the Narrator catchment the soil mantle can absorb up to 50 mm of continuous light rain after a dry period, without any appreciable effect upon stream discharge. One possible method of allowing for changes in soil storage is to select a period which is bounded by similar antecedent precipitation; the period should also be twelve months in duration so that rates of evaporation at start and finish are approximately equal. An annual period also ensures that seasonal cycles of uptake and release of solutes by catchment vegetation are averaged out.

The only period to satisfy all these requirements in the Narrator catchment during the nineteen months of observation is the period 5 Sept. 1975 to 4 Sept. 1976 inclusive. Baseflow discharge for these dates are 60 l/s and 59 l/s respectively and antecedent precipitation (API\textsubscript{30}) 6.1 mm and 6.3 mm. Analysis of hydrologic data for this period indicates that 76.5% of precipitation was discharged as runoff at the main gauging site while at St 11 the figure is 96.7% (table 6.2). These percentage runoff figures are unacceptably high. It is clear, therefore, that even though stringent measures were observed in an attempt to

Table 6.2 Water balance for the Narrator catchment over the period 5/9/75 to 4/9/76.

<table>
<thead>
<tr>
<th>Sub-Catchment Above:</th>
<th>St 21</th>
<th>St 11</th>
<th>St 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drainage area (km\textsuperscript{2})</td>
<td>1.56</td>
<td>3.67</td>
<td>4.68</td>
</tr>
<tr>
<td>Precipitation input (mm)</td>
<td>885</td>
<td>885</td>
<td>885</td>
</tr>
<tr>
<td>Total stream output (mm)</td>
<td>811</td>
<td>856</td>
<td>677</td>
</tr>
<tr>
<td>Output/Input %</td>
<td>91.6</td>
<td>96.7</td>
<td>76.5</td>
</tr>
</tbody>
</table>
account for changes in storage, results obtained from the Narrator catchment are unreliable. One reason may lie in the very large volume of groundwater storage in the Narrator catchment in comparison to annual inputs and outputs. The ratio of quickflow runoff to total runoff from the Narrator catchment during the period of observation is only 0.12. The lowest ratio of five East Devon catchments investigated by Walling (1971b) is 0.16; this particular catchment is infilled by periglacial head deposits. The head and growan infill of the Narrator catchment provides an excellent aquifer. Sandeman (1901), at the time of the construction of the Burrator Dam, remarked upon the "extraordinary quantity of dry weather flow" from the catchment area of the Burrator Reservoir. Hewlett & Hibbert (1967) also obtain low ratios of quickflow to total flow from granite catchments in North Carolina and conclude that depth of growan is the critical factor in this respect. Because the volume of stored groundwater is large, baseflow discharge is an insensitive measure of it. Additions or subtractions to groundwater, amounting to a large percentage of average annual runoff, involves relatively little proportional change in storage and little impact upon baseflow discharge. The twelve month test period 5/9/75 to 4/9/76 was unusually dry and may have witnessed a large net drain on groundwater reserves even though baseflow discharges before and after were almost identical. The lowest discharge recorded in the very dry summer of 1976, when precipitation in the preceding twelve months was only 796 mm, still exceeds the lowest discharge recorded during the summer of 1975 even though in this case precipitation in the preceding twelve months was 1 705 mm and groundwater storage is likely to have been considerably greater. In this situation the short term mass balance approach to solute source analysis cannot be expected to yield meaningful results.

These two difficulties, both of accurate measurement of inputs and accounting for changes in storage, have led, in many previous chemical mass balance studies, to discrepancies
in the chloride budget. Since rock weathering supplies very little chloride in most catchments, inputs and outputs of chloride should match. In many studies such a match has not been achieved (e.g. Zeman 1975, Spraggs 1976, Zeman & Slaymaker 1978). Zeman (1975), for example, estimated the input of chloride to a British Colombian catchment to be 23.1 kg/ha/yr compared with an estimated output of 38.1 kg/ha/yr. The discrepancy between input and output cannot be attributed to rock weathering since the catchment is underlain by diorite which contains no chloride. In situations such as these, serious doubt must be cast upon the reliability of results from solute budget calculations. Unless a balance can be achieved in the chloride budget, calculated budgets for the other constituents must be in error.

6.2.2 Analysis of the Chemical Composition of Stream Water

The chemical composition of stream water to a large extent reflects the contribution of solutes from the major sources. Since sodium and chloride are, at least in coastal regions, the major ions in bulk fallout, and since chloride in particular is rare in the majority of rocks, sodium chloride in stream water is generally considered to represent atmospheric influence. Walling & Webb (1978) in a study of chemical denudation within the Exe River Basin, merely subtract sodium and chloride from total stream solutes in order to remove the non-denudational component. This method ignores the fact that other cations besides sodium are also supplied by bulk fallout. Furthermore, as Waylen (1979) points out, the anions bicarbonate, nitrate and sulphate in stream water also originate, at least in part, from the atmosphere. In the present study, solute source analysis is approached by comparing the mean discharge weighted chemical composition of the Narrator Brook with both the mean precipitation weighted composition of bulk fallout over the Narrator catchment and the geochemistry
The mean discharge weighted chemical composition of the Narrator Brook was conveniently obtained from analysis of samples drawn from the Burrator Reservoir. The composition of stream solutes varies temporally, particularly over flood events, when water arriving at the stream by different pathways and with dissimilar chemical composition is mixed together in continually varying proportions. The reservoir has a large capacity in relation to inflow and consequently the turnover of water in storage is slow. The chemistry of the reservoir water thus represents a short term discharge weighted mean of inflow. Reservoir water is also an integrated mean of inflow from all parts of its catchment, of which the Narrator catchment is just a part, but since the physical characteristics of the reservoir catchment as a whole are relatively uniform, this is not believed to be a significant problem.

The reservoir outlet is situated at the bottom of the dam, which ensures good circulation of reservoir water and inhibits thermal stratification. Tests by the South-West Water Authority in 1976 during the hottest, driest summer on record, revealed that water surface temperature was less than two degrees centigrade greater than temperature at the bottom of the reservoir. Water samples taken at the surface can thus be regarded as representative of the reservoir as a whole. Evaporation of reservoir water may increase total solute concentration above that in inflowing water to a small degree but this will not affect the proportional representation of individual dissolved constituents upon which this method of source analysis relies. One problem of using the chemical composition of reservoir water for source analysis arises from certain constituents in stored water being drawn into the aquatic ecosystem. The only two constituents which display any seasonal variations in concentration in the reservoir indicating ecosystem incorporation are nitrate and silica. Nitrate and silica are taken up by algae and diatoms respectively during early summer.
and released during winter months (fig 6.2). The relative proportions of these two to total dissolved solids are determined instead from analysis of selected Narrator stream samples. Although this invariably introduces a certain amount of error, this is not believed to greatly affect the overall results of source analysis. The concentration of the remaining major ions is unlikely to be significantly affected by storage in the reservoir. Crisp (1977) could detect no difference in the concentrations of sodium, magnesium, calcium, potassium, chloride, and sulphate between stream water entering and leaving the Cow Green Impoundment, Upper Teesdale.

Burrator Reservoir water is subjected to a full chemical analysis by the South-West Authority on a regular basis at approximately monthly intervals. Results of the nineteen such analyses completed during the period of the present research vary very little indicating the effect of

![Graph showing seasonal variations in silica and nitrate in the Burrator reservoir, 1975/76](image-url)

**Fig. 6.2** Seasonal variations in silica and nitrate in the Burrator reservoir, 1975/76
the reservoir in dampening temporal fluctuations in the chemical composition of inflow. Excepting silica and nitrate, a mean of these results was employed to represent the mean discharge weighted composition of the Narrator Brook during this period (table 6.1). The mean specific electrical conductance of the 19 samples of reservoir water analysed is 58.1 micromhos/cm at 25°C which compares favourably with the mean discharge weighted value of 56.2 micromhos for the Narrator Brook determined from more than one thousand stream samples.

Chemical analyses were carried out on eleven of the 36 weekly samples of bulk fallout collected over the period of observation. Although specific conductance of the 11 samples varies considerably over a range from 15 to 144 umhos, chemical composition is more stable. The ratios of sodium and chloride, which are the two predominant ions in bulk fallout, to specific conductance for the 11 samples tested varied from 0.10 to 0.15 and 0.14 to 0.25 respectively. The composition of bulk fallout over the Narrator catchment is very similar to the composition of sea-water, confirming that sea-spray is the major source for solutes in bulk fallout (table 6.1). The percentage of sodium and chloride to total dissolved solids in bulk fallout over the Narrator catchment is 77.7% which is a little lower than this percentage in sea-water at 86.1%, indicating that a small part of the solutes in bulk fallout is also supplied from non-marine sources. Calcium and potassium, which both have appreciably higher proportions in bulk fallout (5.1% and 1.9% respectively) than in sea-water (1.2% and 1.1% respectively), appear to be the major ions supplied from these non-marine sources. Chemical analyses of bulk fallout at two other sites in South-West England presented in Stevenson (1968) support results from the Narrator catchment (table 6.3). Bulk fallout at Camborne which is closer to the windward (west) coast than the Narrator catchment is dominated by chloride and sodium from sea-spray which together form 82.6% of total dissolved solids compared
Table 6.3 Chemical composition of bulk atmospheric fall-out at three locations in South West England.

<table>
<thead>
<tr>
<th></th>
<th>Cambourne</th>
<th>Narrator Catchment</th>
<th>Newton Abbot</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>mg/l</td>
<td>%</td>
<td>mg/l</td>
</tr>
<tr>
<td>Ca</td>
<td>0.8</td>
<td>3.5</td>
<td>0.8</td>
</tr>
<tr>
<td>Na</td>
<td>7.7</td>
<td>33.5</td>
<td>4.0</td>
</tr>
<tr>
<td>K</td>
<td>0.4</td>
<td>1.7</td>
<td>0.3</td>
</tr>
<tr>
<td>Mg</td>
<td>0.6</td>
<td>2.6</td>
<td>0.5</td>
</tr>
<tr>
<td>NO\textsubscript{3}</td>
<td>0.3</td>
<td>1.3</td>
<td>0.2</td>
</tr>
<tr>
<td>SO\textsubscript{4}</td>
<td>1.9</td>
<td>8.3</td>
<td>1.7</td>
</tr>
<tr>
<td>Cl</td>
<td>11.3</td>
<td>49.1</td>
<td>8.2</td>
</tr>
<tr>
<td>T.D.S.</td>
<td>23.0</td>
<td>100</td>
<td>15.7</td>
</tr>
</tbody>
</table>

1 Period May 1975 to Dec. 1976, mean precipitation weighted values

with 86.1% in sea-water. At Newton Abbot sodium and chloride are relatively less important comprising only 64.8% of total dissolved solids, while those constituents which are derived largely from non-marine sources, including potassium and calcium, make up a relatively greater proportion. Bulk fallout over the Narrator catchment lying between these two sites is intermediate in composition.

Comparison of the chemical composition of stream water with bulk fallout and granite bedrock enables the relative importance of the major sources for stream solutes to be established. The anions in stream water, chloride, sulphate, bicarbonate and nitrate, are not present in granite in significant proportions (table 6.1) and are thus supplied almost exclusively from the atmosphere. Conversely, since silica and iron were not detected in bulk fallout they may be regarded as being derived entirely from rock weathering. The four cations, sodium, magnesium, calcium and potassium
are supplied from both the atmosphere and rock weathering in unknown proportions. Since chloride is entirely atmospheric in origin, the ratios of chloride to each of the four cations can be used to calculate the relative proportion of each contributed by the atmosphere and rock weathering. If it is assumed that there is no net uptake or release of solutes by catchment vegetation, any decrease in the chloride/cation ratio from bulk fallout to stream water indicates contribution from rock weathering. Ratios of chloride to sodium, magnesium, calcium and potassium in bulk fallout are 2.0, 16.3, 10.2 and 27.5 respectively; these same ratios in stream water fall to 1.4, 11.5, 3.3, and 9.3 respectively. The concentration of a cation in stream water originating from atmospheric fallout can be obtained from equation 6.1

\[ X_A = \frac{X_{BF}C_{1SW}}{C_{1BF}} \] .......................... (6.1)

and the concentration attributable to rock weathering from equation 6.2

\[ X_C = X_{SW} - X_A \] .......................... (6.2)

where \( X_A \) is the concentration of a cation in stream water supplied from the atmosphere

\( X_C \) is the concentration of a cation in stream water supplied from rock weathering in the catchment

\( C_{1BF} \) is the concentration of chloride in bulk fallout

\( X_{BF} \) is the concentration of a cation in bulk fallout

\( C_{1SW} \) is the concentration of chloride in stream water

\( X_{SW} \) is the concentration of a cation in stream water.

Results of the calculations for the Narrator Brook reveal that sodium and magnesium are supplied largely from the atmosphere (71% and 70% respectively - table 6.4). Calcium and potassium on the other hand, are supplied mainly from
rock weathering; only 32% and 33% of these two elements respectively are supplied from the atmosphere. According to Douglas (1972), this situation is to be expected in coastal regions where sea spray is a major source of stream solutes since sodium and magnesium form larger proportions in sea water (30.8% and 3.7% respectively) than calcium and potassium (1.2% and 1.1% respectively). Combining the silica and iron in Narrator stream water with the proportions of the four cations derived from rock weathering, the denudational component of the solute load transported by the Narrator Brook is estimated at only 29.9%. Subtracting sodium and chloride from total solutes in the Narrator Brook, in the manner of Walling & Webb 1978, gives a denudational component of 52.4% which is a considerable overestimate.

Table 6.4 Relative importance of the atmosphere and rock weathering as sources for solutes transported by the Narrator Brook (figures in percent of total dissolved solids).

<table>
<thead>
<tr>
<th></th>
<th>Atmosphere</th>
<th>Rock Weathering</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ca</td>
<td>2.7</td>
<td>5.6</td>
<td>8.3</td>
</tr>
<tr>
<td>Na</td>
<td>13.7</td>
<td>5.9</td>
<td>19.6</td>
</tr>
<tr>
<td>K</td>
<td>1.0</td>
<td>2.0</td>
<td>3.0</td>
</tr>
<tr>
<td>Mg</td>
<td>1.7</td>
<td>0.7</td>
<td>2.4</td>
</tr>
<tr>
<td>Fe</td>
<td>0</td>
<td>0.6</td>
<td>0.6</td>
</tr>
<tr>
<td>HCO₃</td>
<td>8.8</td>
<td>0</td>
<td>8.8</td>
</tr>
<tr>
<td>NO₃</td>
<td>0.8</td>
<td>0</td>
<td>0.8</td>
</tr>
<tr>
<td>SO₄</td>
<td>13.4</td>
<td>0</td>
<td>13.4</td>
</tr>
<tr>
<td>Cl</td>
<td>28.0</td>
<td>0</td>
<td>28.0</td>
</tr>
<tr>
<td>SiO₂</td>
<td>0</td>
<td>15.1</td>
<td>15.1</td>
</tr>
<tr>
<td>Total</td>
<td>70.1</td>
<td>29.9</td>
<td>100.0</td>
</tr>
</tbody>
</table>
The solute yield of the Narrator Brook fits squarely into the category of precipitation dominance in a scheme of classification proposed by Gibbs (1970). The Narrator conforms to the stipulated requirements of this class by having a total dissolved solids concentration of less than 50mg/l with sodium and chloride being among the dominant ions. Catchments where this situation arises in Britain are typically located in highland regions close to the west coast where atmospheric inputs are high. Precipitation dominance in stream solutes has previously been reported from catchments in Mid-Wales (Lewin et al. 1974, Cryer 1976), the Lake District (Gorham 1958, White et al. 1971) the Cairngorms (Gorham 1957), and the Mendips (Waylen 1979).

The relative proportion of the dissolved constituents which are supplied by rock weathering reflect both their proportion in the bedrock and their relative mobility. Varying amounts of these constituents instead of being released to stream solutes upon weathering of primary minerals form clay minerals. Relative mobility is calculated as the ratio of the proportion of a constituent in total solutes supplied from rock weathering to its proportion in catchment rocks (Feth et al. 1964). Calcium has the highest mobility in the Narrator catchment. Calcium comprises 18.7% of total solutes supplied from rock weathering in comparison to its proportion in granite of 1.3% giving a ratio of 14.4. Sodium has the next highest mobility with a ratio of 7.9 followed by magnesium (4.7), potassium (1.4), iron (0.8) and silica (0.6). Relative mobilities for the Narrator catchment conform in general with those from other studies (table 6.5).

Iron in the Narrator catchment, however, appears to have an anomalously high mobility. The mobility of iron in most catchments is low even though it does not take part to any large extent in the formation of clay mineral residues. Iron in its oxidised form is insoluble and dissolved ferrous iron in groundwater becomes oxidised and precipitates upon reaching the stream channel. This process is evidenced in
Table 6.5 Relative ion mobilities in the Narrator catchment in comparison with other granite regions.

Granite, Dartmoor  Ca > Na > Mg > K > Fe > SiO₂ > Al Present Study
Granite, Sierra Nevada  Ca > Na > Mg > SiO₂, > K > Fe > Al  Feth et al, 1964
Granite, New Mexico  Ca > Mg > Na > SiO₂ > K > Fe > Al  Miller, 1961
Granite, New Hampshire  Mg > Ca > Na > K > SiO₂ > Fe = Al  Anderson & Hawkes, 1958
Average World  Ca = Na > Mg > K > SiO₂ > Fe = Al  Polynov, 1937

= equal to  > equal to or greater than  > greater than  >> very much greater than

the Narrator Brook by a reddish gel on the underside of the larger boulders on the stream bed which have remained stationary for a sufficiently long period. The mobility of iron in the Narrator catchment where streams commonly rise in marshes is rather greater than would otherwise be the case due to the formation of iron-organic complexes which are transported in colloidal suspension by the stream. This phenomenon has previously been described by Lee et al (1975) in a Wisconsin catchment.

Sulphate forms a larger proportion of chemicals in Narrator stream water than in sea-water suggesting that sea-spray is not the only source for this sulphate (table 6.1). The ratio of sulphate to chloride in sea-water is 0.14 but this ratio in bulk fallout rises to 0.21. Muller (1975) ascribes over 75% of sulphate in leachate from the soil of a New Zealand catchment to sulphur dioxide pollution. Studies in Finland (Haapala et al 1975) and British Colombia (Zeman & Slaymaker 1978) reveal that in some catchments the greater part of sulphate in stream water can also be attributed to atmospheric pollution. Any sulphate from this source has to be matched by an equivalent weight of cations. This reasoning led Johnson et al (1972) to the conclusion that natural rates of rock weathering over large
areas of the U.S.A. have been greatly accelerated as a result of sulphur dioxide pollution. Another possible source for sulphate, however, is from the drying out of marshes and the consequent oxidation of accumulated sulphide compounds (Gorham 1961).

6.3 Variation in bulk fallout

Since bulk fallout is the major source of solutes transported from the Narrator catchment variations in the concentration of bulk fallout over the catchment, and the factors which govern these variations, might be expected to have an important bearing upon stream solute dynamics and controls. For this reason bulk fallout was collected over weekly intervals during the period of observation at a site close to raingauge No 1 (fig 3.1; Plate 3.1). The bulk fallout collector consists of a simple bottle and funnel assembly as used by Cryer (1976), Zeman & Slaymaker (1978) and others. All samples were analysed for specific electric conductance, and 11 were subjected to a full chemical analysis. Sodium and chloride together make up the bulk of total solutes in the 11 samples tested (77.7% - table 6.1) and variations in the concentration of both ions correspond closely to variations in specific conductance (fig 3.8). In this situation, use of specific conductance in place of individual ions for analysis of bulk fallout variations does not impose serious limitations.

One problem that does arise is from the use of a nylon mesh over the funnel of the bulk fallout collector in the Narrator catchment. This was found to increase the specific conductance of bulk fallout samples by as much as three times (fig 6.1). For example, for the week 10-17/5/76 the specific conductance of precipitation in the collector with a nylon mesh is 150 μmhos compared with 50.5 μmhos in a collector without a nylon mesh at the same site. To avoid any error from this source only data covering the period 10/5/76 - 13/12/76 were included in analysis of bulk
fallout variations. During this period bulk fallout collectors without a nylon mesh were in operation at two sites in the catchment (rain gauge sites 1 and 2 - fig 3.1) in addition to the collector with nylon mesh in order to provide a check on results. The bulk fallout collectors were not fitted with vapour traps and therefore evaporation may have appreciably increased the solute concentration of small samples adding a further possible source of error. Data for weeks in which precipitation was less than 10 mm were therefore excluded from analysis in order to minimise this error. This left 19 observations, values varying over a wide range from 17 μmhos to 83 μmhos. This range is somewhat smaller than the range of 7 μmhos to 130 μmhos reported by Cryer (1976) for weekly bulk fallout samples in a Mid-Wales catchment but in this case the period of bulk fallout observations exceeds 18 months, in comparison to only 7 months for the Narrator catchment.

According to Douglas (1968b), the solute concentration of precipitation commonly decreases during the course of a storm event because salt particles in the atmosphere become progressively washed out by falling rain drops. For this reason also, Douglas (1968b) maintains that precipitation solute concentrations should be greatest for small events with low precipitation totals and also following dry periods when availability of salt particles in the atmosphere is high. According to Gorham (1958), where atmospheric fallout is dominated by salts derived from sea-spray solute concentrations can be expected to be related to wind speed and direction. With higher wind speed sea-spray increases and when the wind is blowing from the direction of the nearest coastline a greater availability of atmospheric salt particles derived from sea-spray can be expected.

Records from the Mountbatten meteorological station on the coast at Plymouth 15 km from the Narrator catchment were used to obtain wind speed and direction during storm events. Testing the influence of wind direction upon the specific conductance of bulk fallout in the Narrator catchment cannot
be done satisfactorily. The penninsular location of the Narrator catchment means that the coast is in close proximity over a wide arc from north-west through south to south-east. Almost all rain bearing winds affecting the catchment come from directions within this arc (appendix II.7). The only exception during the period of bulk fallout observations is an event occurring on the 29/8/76. Wind direction during this event, which was a thunderstorm of high intensity following a long dry period, was predominantly north easterly. The specific conductance for the week 23-30/8/76, in which this was the only storm event, is a little higher than the precipitation weighted mean for the remaining 18 weekly samples (52 and 34 μmhos respectively). Because of the variability in the specific conductance of bulk fallout (σ = 17.3 μmhos) no significance can be attached to this.

Mean precipitation weighted wind speed corresponding to each of the 19 weekly bulk fallout samples covers a wide range from 3.6 knots to 29.0 knots. Both precipitation totals and antecedent precipitation (API30) also cover wide ranges (12.0 mm to 103.6 mm and 0 mm to 59.9 mm respectively). However, none of these three variables are significantly correlated with the specific conductance of bulk fallout (r = 0.31, -0.13, and 0.29 respectively, n = 19 - table 6.6). Cryer (1976), in a Mid-Wales catchment also failed to obtain any significant correlations between the specific conductance of weekly samples of bulk fallout and these three variables. These results suggest that factors affecting the availability of salt particles in the atmosphere are less important than those related to the mechanisms whereby atmospheric salt particles become incorporated into rain drops. Isolating the factors which influence bulk fallout concentrations could be useful in revealing something of these mechanisms. Rainfall intensity, for example, which is closely related to rain drop size and velocity, might be expected to affect the efficiency of falling rain to wash salt particles from the atmosphere.
Rainfall intensity, however, also failed to significantly influence the specific conductance of bulk fallout both in the Narrator catchment and in Cryer's (1976) research (table 6.6). Cryer (1976) obtained a significant correlation of bulk fallout concentration with a seasonal index in his Mid-Wales catchment, but using the same seasonal index in the Narrator catchment failed to produce a significant correlation. It may be that the period of record in the Narrator catchment is not of sufficient duration to highlight any seasonal trend.

Despite the low correlation coefficients, the five variables tested, wind speed, total precipitation, precipitation intensity, antecedent precipitation, and season, together account for 47.5% of variance in bulk fallout concentrations in the Narrator catchment, indicating that the variables exert more influence in combination than individually. Since bulk fallout is the major source of solutes transported by the Narrator Brook, future research could be usefully directed towards improving this level of explanation. Priorities in this regard are sampling over individual storm events, rather than on a fixed time basis, and separation of wet fallout from dry fallout.
6.4 Variations in stream solute concentrations

6.4.1 Total Flow

Temporal variations in the solute concentration of total stream flow is determined by the changing proportion of quickflow and baseflow. These two components of stream flow have very different solute characteristics. Baseflow is sustained by groundwater which in most catchments is associated with relatively high concentrations. Although almost all groundwater originates from precipitation it may remain within the catchment for a prolonged period possibly exceeding several years in duration. During this period in contact with catchment rocks groundwater acquires the soluble products of rock weathering, in addition to those solutes supplied by precipitation. Quickflow, on the other hand, has relatively little residence time on the catchment and consequently concentrations of quickflow in most streams are relatively low. During storm events, baseflow is diluted by an influx of quickflow so that solute concentration can be expected to decrease with rising discharge. Less commonly than is the case with studies of suspended sediment solute rating curves, plots of discharge against total solute concentration have been employed to define stream solute dynamics (Crippen 1967, Spraggs 1976, O'Connor 1976). Using the same technique devised for suspended sediment, solute rating curves have been combined with flow duration curves as a method of computing long term solute yields (Douglas 1968c, Walling & Webb 1978).

One problem facing the rating curve approach for defining variations in the concentration of total solutes in stream water is that the individual dissolved constituents which make up total solutes vary independently with discharge. Foster (1978a), for example, working on a small stream in Devon, found that while the concentration of most ions decreases in concentration with rising discharge, potassium increases and nitrate displays no consistent variation with
discharge. Despite this, Foster (1978a) still obtained 71.9% explanation of variance in specific conductance from stream discharge.

In the Narrator Brook the explanation of variance in specific conductance for 210 samples collected during flood events over the period of observation achieved by stream discharge at the time of sampling is only 6.8% (table 6.7).

Table 6.7 Correlation coefficients relating specific conductance of stream samples to stream discharge according to season and stage of the hydrograph, Narrator Brook, main gauging site, 1975/76 (data log transformed).

<table>
<thead>
<tr>
<th>Total</th>
<th>S</th>
<th>W</th>
<th>R</th>
<th>F</th>
<th>WR</th>
<th>WF</th>
<th>SR</th>
<th>SF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of observations</td>
<td>210</td>
<td>66</td>
<td>144</td>
<td>120</td>
<td>90</td>
<td>.93</td>
<td>.51</td>
<td>.27</td>
</tr>
<tr>
<td>Correlation coefficient</td>
<td>-0.27</td>
<td>0.23</td>
<td>-0.26</td>
<td>-0.32</td>
<td>-0.16</td>
<td>-0.32</td>
<td>-0.15</td>
<td>0.15</td>
</tr>
<tr>
<td>Percentage explanation</td>
<td>6.8</td>
<td>5.3</td>
<td>6.8</td>
<td>10.2</td>
<td>2.6</td>
<td>10.2</td>
<td>2.3</td>
<td>2.3</td>
</tr>
<tr>
<td>Standard error (log units)</td>
<td>0.05</td>
<td>0.07</td>
<td>0.03</td>
<td>0.04</td>
<td>0.07</td>
<td>0.03</td>
<td>0.03</td>
<td>0.07</td>
</tr>
</tbody>
</table>

S-summer, W-winter, R-rising stage, F-falling stage

Separating the data according to season and the stage of the hydrograph does not materially improve the explanation of variance as it does in the case of suspended sediment. A solute rating curve is thus entirely inadequate for defining variations in total solute concentrations in the Narrator Brook. Although standard errors are very much smaller than is the case with the suspended sediment rating curves, this is entirely a result of the lower range of variation for specific conductance. The inadequacy of the rating curve is to some extent a reflection of solute sources in the catchment. Since 70% of stream solutes are
supplied from the atmosphere, a strong and consistent dilution of stream solute concentration during storm events cannot be expected.

Besides the problem of individual dissolved constituents varying independently in concentration, a major drawback with the solute rating curve approach is that the proportion of quickflow and baseflow in all streams varies greatly for a given discharge. Concentrations of baseflow and quickflow may also vary independently of each other. A more useful approach is to define variations in baseflow and quickflow concentrations separately. Estimated values for each can then be fed into a mixing equation to compute stream concentration (equation 6.3).

\[
C_T = \frac{C_Q Q_Q + C_B Q_B}{Q_T} \quad \text{(6.3)}
\]

- \(C_T\) = specific conductance of stream water
- \(C_Q\) = specific conductance of quickflow
- \(Q_Q\) = quickflow discharge
- \(C_B\) = specific conductance of baseflow
- \(Q_B\) = baseflow discharge
- \(Q_T\) = stream discharge

From observations of the specific conductance of stream flow, mean discharge weighted values were determined for those 37 flood events for which quickflow comprises at least 20\% of total flow. By substitution in equation 6.3 mean discharge weighted concentration of quickflow was obtained for each of the 37 events. The specific conductance of baseflow during each of the events (\(C_B\) in equation 6.3) is taken to be the specific conductance of baseflow no more than 8 hours from the start of the event (obtained from the standard automatic vacuum operated stream sampler which samples at 8 hour intervals).
6.4.2 Baseflow and Quickflow

The groundwater in the Narrator catchment which sustains baseflow in the Narrator Brook, is itself recharged by percolation of the surface and near surface runoff which generates quickflow during flood events. As a result, a certain degree of correspondence between the solute concentrations of quickflow and baseflow can be expected. The specific conductance of both flow components fluctuates about a stable value of 55.5 μmhos which may represent some form of chemical buffering in the Narrator catchment (fig 6.3). The specific conductance of baseflow remained within 1 μmho of 55.5 μmhos during 78% of the period of observation. Accepting a certain amount of inaccuracy in the method, the specific conductance of baseflow can be regarded as constant over this period. No seasonal trend in baseflow specific conductance is apparent. The specific conductance of quickflow also remained constant at 55.5 μmhos over 14 of the 37 flood events which occurred during the period of observation. The major contrast between the two flow components is in the range of variation in specific conductance. Values for baseflow range from 53.5 μmhos to 65.0 μmhos; corresponding limits for quickflow are 47.2 μmhos and 152.5 μmhos. The more stable specific conductance of baseflow suggests that chemical buffering becomes more effective as the residence time of water on the catchment increases.

The mechanisms responsible for maintaining specific conductance at near constant levels in the Narrator Brook are not altogether clear. Davis (1964), Bricker (1968), and others, have suggested that clay minerals in growan may adjust their composition according to the concentration of silica and cations in aqueous solution thereby keeping these concentrations within a narrow range. When concentration of these constituents rise above a critical level, the excess if absorbed by conversion of gibbsite to kaolinite or montmorillomite and conversely any deficit is made good by
Fig. 6.3 Variations in stream discharge and specific conductance of quickflow during the period 26/5/75 - 13/12/76, St 1, Narrator Brook
a reverse transformation. Bricker (1968) evoked this mechanism to explain near constant concentrations of cations and silica in a Maryland catchment underlain by granitic rocks, and cited the presence of both gibbsite and kaolinite in the catchment as supportive evidence. Since even over flood events concentrations of cations and silica vary little in this catchment, Bricker (1968) concluded that this buffering mechanism can operate very rapidly. A similar conclusion was reached by Zeman & Slaymaker (1978) in a British Colobomian catchment. Analyses of Dartmoor grown reported by Eden & Green (1971) reveal both gibbsite and kaolinite to be present and this has been confirmed by subsequent observations in the Narrator catchment (A. Williams pers. comm.). This means that the chemical reactions described above may well be an effective buffering mechanism in the Narrator catchment. However, these reactions can only provide a partial mechanism because chloride, which comprises about 25% of total solutes in the Narrator Brook and hence contributes substantially to specific conductance, plays little part in these reactions. Johnson et al (1969) also report a very stable concentration of chloride in the Hubbard Brook, New Hampshire, for which they were unable to offer an explanation. Whatever the mechanisms involved, the fact that storm runoff during some flood events in the Narrator catchment stabilises at 55.5 μmhos before entering the stream channel means that on certain occasions buffering must be completed within the space of a few hours. On other occasions, however, it appears to take much longer. It must be stressed again at this point, however, that specific conductance represents only the ionized constituents of stream water. Silica, which does not contribute to specific conductance, experiences a drop in concentration over all flood events (Ternan & Williams 1979).

On four occasions during the period of observation baseflow specific conductance rose above or dropped below 55.5 μmhos for periods lasting up to 60 days (fig 6.3).
This appears to be in response to flood events during which specific conductance deviates markedly from 55.5 μmhos. On the first occasion a flood event on 7/7/75 recording a mean quickflow specific conductance of 86.5 μmhos caused baseflow specific conductance to rise to a peak of 64.5 μmhos. Specific conductance returned to 55.5 μmhos 20 days later. On the second occasion a series of three small floods during 25-29/11/75 all recording mean quickflow specific conductance less than 55.5 μmhos (47.2, 50.1, and 47.9 μmhos respectively) resulted in a fall of baseflow specific conductance to 54.0 μmhos, but this returned to 55.5 μmhos within 15 days. On the third occasion a large flood on 12/2/76 with a mean quickflow specific conductance of 52.1 μmhos depressed baseflow specific conductance to 53.0 μmhos and the value of 55.5 μmhos was not regained until 30 days later. Finally in September and October 1976, after a long dry period, 9 floods varying in mean quickflow specific conductance from 152.5 μmhos to 58.1 μmhos pushed baseflow specific conductance up to a peak of 66.0 μmhos and values remained above 55.5 μmhos for 60 days.

Overall, the mean discharge weighted specific conductance of baseflow during the period of observation is very similar to the corresponding value for quickflow (55.9 μmhos and 58.4 μmhos respectively. It would seem, therefore, that there is little contribution of solutes to groundwater from weathering reactions below the water table. As a result, residence time of groundwater in the catchment appears to have very little effect upon its specific conductance. During the summer drought of 1976 after several months without appreciable precipitation, the Narrator Brook must have tapped deep and hence very old reserves of groundwater to maintain flow, yet specific conductance showed no detectable deviation from 55.5 μmhos.

For 23 of the 37 flood events during the period of observation, mean quickflow specific conductance differs from 55.5 μmhos. Of these, 16 have values for mean quickflow specific conductance exceeding 55.5 μmhos and 7 have values
less than 55.5 μmhos. Those events for which mean quickflow specific conductance exceeds 55.5 μmhos may result from flushing of solutes accumulated on the catchment over the period since the preceding event. Such accumulation of solutes may arise from biochemical reactions within the soil or else by dry atmospheric fallout on the surface. Flushing of solutes from small catchments in Britain has previously been described by several workers (Edwards 1973b, Walling 1974a, Spraggs 1976, Foster 1978b). Foster (1978b) working in a small Devon catchment discovered that the degree of flushing increases with increasing soil moisture deficit. Consistent with the possible existence of flushing in the Narrator catchment mean quickflow specific conductance exceeding 55.5 μmhos is usually associated with small events following a dry period. In normal conditions, a total quickflow runoff of 25 000 m³ for the event plus the preceding 20 days appears to be a threshold above which quickflow specific conductance exceeding 55.5 μmhos is unlikely (fig 6.4). However, after the unprecedented summer drought of 1976 a prolonged period of flushing followed which involved all 9 of the flood events occurring during the period 29/8/76 to 21/10/76 (fig 6.3). The last of these events on 21/10/76 recorded a mean quickflow specific conductance of 66.8 μmhos even though quickflow runoff over the preceding 20 days reached 200 000 m³. Anderson & Burt (1978) report a similar prolonged period of abnormally high stream solute concentrations following the 1976 summer drought in some Southern Cotswold catchments which persisted into November 1976.

The flood events with mean quickflow specific conductance less than 55.5 μmhos in the Narrator Brook are restricted to the larger events following wet periods. All of the 7 such events which occurred during the period of observation exceeded the quickflow runoff threshold of 25 000 m³. Putting aside events occurring during the period 29/8/76 to 21/10/76, there is thus a clear distinction between events with mean quickflow specific conductance
Fig. 6.4 Variation in mean discharge weighted specific conductance of quickflow in relation to antecedent quickflow runoff. Open circles represent the nine flood events which occurred during 29/8/76 - 21/10/76.
less and greater than 55.5 µmhos in terms of quickflow runoff volumes (fig 6.4). However, the 14 events which recorded no deviation from 55.5 µmhos occur on both sides of the threshold. The difference between these 14 events, and the remaining 23 events cannot be explained on the basis of hydrological or hydrometeorological factors. A series of Mann-Whitney U tests incorporating peak discharge, quickflow runoff, flood intensity, total precipitation, mean precipitation intensity, maximum two hour precipitation, antecedent precipitation (API^q) and season failed to throw up any significant differences (table 6.8).

In order to investigate the effect of bulk fallout upon quickflow solute concentrations, mean weekly discharge weighted values of quickflow specific conductance were computed to correspond with the weekly values for bulk fallout. The analysis covers the period 10/5/76 to 13/12/76 during which the open funnel bulk fallout collector at rain gauge site 1 was in operation. No significant correlation between the specific conductance of bulk fallout and quickflow exists over this period (r = 0.16, n = 10; fig 6.5). This result is surprising in view of the fact that bulk fallout is the predominant source of solutes transported by the Narrator Brook. In a Mid-Wales catchment, where bulk fallout is also the predominant source of solutes, Cryer (1976) discovered a very close correspondence between the specific conductance of bulk fallout and quickflow over weekly periods. In the Narrator catchment it appears that precipitation is chemically transformed within a very short time of reaching the surface. This chemical transformation does not only involve addition of solutes from the catchment; for the week 6-13/12/76 the specific conductance of bulk fallout is appreciably greater than that of quickflow (83.0 µmhos and 55.5 µmhos respectively).

The two flood events which were generated in part by snowmelt both have mean discharge weighted specific conductance of quickflow exceeding that of baseflow (128.4 and 74.1 µmhos for 6-7/2/76 and 7-8/2/76 respectively). Since
Table 6.8 Results of Mann-Whitney U tests for differences between those flood events recording no deviation in quickflow specific conductance from baseflow specific conductance, and those events recording either a reduction or an increase in quickflow specific conductance

<table>
<thead>
<tr>
<th>Smaller U Values</th>
<th>A v B</th>
<th>C v D</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak stream discharge</td>
<td>17</td>
<td>15</td>
</tr>
<tr>
<td>Quickflow runoff</td>
<td>22</td>
<td>15</td>
</tr>
<tr>
<td>Flood intensity</td>
<td>11</td>
<td>16</td>
</tr>
<tr>
<td>Total precipitation</td>
<td>25</td>
<td>9</td>
</tr>
<tr>
<td>Mean precipitation intensity</td>
<td>23.5</td>
<td>18.5</td>
</tr>
<tr>
<td>Maximum two hour precipitation</td>
<td>22.5</td>
<td>17.5</td>
</tr>
<tr>
<td>Antecedent precipitation (API30)</td>
<td>14</td>
<td>9</td>
</tr>
<tr>
<td>Seasonal index</td>
<td>25</td>
<td>15.5</td>
</tr>
</tbody>
</table>

A Quickflow specific conductance exceeding baseflow (n = 7)
B No deviation in quickflow specific conductance from baseflow; total quickflow runoff for the event and over a preceding period of 20 days < 25,000 m$^3$ (n = 8)
C As for B but with quickflow runoff for the event and preceding period of 20 days > 25,000 m$^3$ (n = 6)
D Quickflow specific conductance falling below baseflow (n = 7)

1. Events during the period 29/8-21/10/76 excluded from the analysis.
2. To reach the 0.05 significance level U values must be smaller than 10 for A v B and 6 for C v D.

both events have a 20 day antecedent quickflow runoff below 25 000 m$^3$ (13044 and 19808 m$^3$ respectively) they conform in this respect to the pattern established from flood events generated entirely by rainfall.

For the purpose of estimating long term mean annual solute yields for calculation of chemical denudation, defining concentration variations in the Narrator Brook in terms of
The relationship between specific conductance of quickflow and bulk fallout, Narrator catchment, May - Dec. 1976 is shown in Fig. 6.5. Hydrological and/or hydrometeorological controls are not necessary. Deviations of specific conductance from 55.5 μmhos are likely to be averaged out over the long term. The mean discharge weighted specific conductance of total flow for the period of observation is 56.2 μmhos. Referring to Fig. 3.7, a specific conductance of 55.5 μmhos represents a solute concentration of 41.6 mg/l and this can be combined with mean annual runoff from the catchment to obtain long term mean annual solute yield. Walling & Webb (1978) also discovered that for streams in the Exe River Basin with total solute concentration less than 50 mg/l, baseflow concentration is virtually identical to long term mean discharge weighted concentration.
CHAPTER 7
SPATIAL VARIATIONS IN SUSPENDED SEDIMENT AND SOLUTES

7.1 Downstream variations in concentration during baseflow

7.1.1 Suspended Sediment

In order to investigate downstream variations in both suspended sediment concentration and specific conductance during baseflow, sampling stations were established at 30 sites along the main channel of the Narrator Brook from source to mouth (figs. 2.9, 2.11 and 3.1). Three of the stations, stations 1, 11 and 21, are the permanent gauging sites on the Narrator Brook. Nine additional stations between each of the three gauging sites were selected randomly. Samples at each station were collected by dipping a wide necked 600 ml polythene bottle into the stream at the location of maximum velocity. All sites were visited during the same day on 27 sampling dates spaced at approximately fortnightly intervals.

Of the total 810 observations of sediment concentration, 693 are below 1 mg/l. Laboratory analysis of such low concentrations is subject to a wide range of error in relative terms amounting to approximately 0.5-0.6 mg/l. This inaccuracy cloaks small variations in sediment concentration between sites and as a result downstream variations in measured sediment concentration for individual sampling dates reveal no consistent trends. This is illustrated by correlation of downstream variations for the 27 sampling dates (table 7.1). Excluded from the correlation analyses are data from stations 26-30. These stations often have very high concentrations in comparison to other stations, for reasons discussed later, and hence distort correlation results. Correlations generally are low; none exceed 0.66 and several are negative. However, a very slight degree of association is apparent. Of the 351 correlations 11 reach 0.01 significance whereas only 3 or 4 would be expected in a
Table 7.1 Correlation matrix showing the degree of similarity in downstream baseflow sediment concentration profiles for individual dates
completely random set of data. Of the 11 correlations only one does not involve any of the last 8 sampling dates (nos. 20-27 - table 7.1). This probably reflects a slight improvement in the accuracy of laboratory determination of sediment concentration. The major inaccuracy sustained in laboratory analysis arises from weighing of filters. This inaccuracy is random and is diminished by taking a mean of several samples. An experiment involving analysis of two groups of 10 samples of baseflow collected at a single site over the space of an hour produced a range of values from 0.2mg/ℓ to 0.9mg/ℓ but mean values for the two groups (0.59 mg/ℓ and 0.55mg/ℓ) are very similar (table 3.3). For this reason, downstream variations in the mean suspended sediment concentration at each site (n = 27) were first examined to identify any major trends present before turning to individual sampling dates. These mean sediment concentration values permit meaningful inter-site comparisons of differences at least as small as 0.1mg/ℓ.

The mean baseflow sediment concentration profile covers a wide range of values from 1.83mg/ℓ to 0.31mg/ℓ (fig 7.1, table 7.2). The dominant feature of the profile is the sharp increase in mean concentration below St 30, from 0.41 mg/ℓ at St 30 to 1.23mg/ℓ at St 29, and the equally sharp fall in concentration below St 27, from 1.84mg/ℓ at St 27 to 0.56mg/ℓ at St 25. The coefficients of variation in sediment concentration for Sts 29, 28 and 27 (98.3%, 105.8% and 109.0% respectively) are significantly higher (at the 0.001 level) than the remaining 27 stations where values range from 50.3% to 77.7% (table 7.2). Mean sediment concentration at these 27 stations is below 1mg/ℓ and random weighing errors in the range ± 0.3mg/ℓ could account entirely for variation in concentration at these stations. The relatively large coefficients of variation at Sts 27-29, however, indicate that this variation is not entirely random. Both sediment concentrations and sediment dynamics in the upper reaches of the Narrator Brook during baseflow are clearly quite distinct from the remainder of the stream.

The baseflow suspended sediment in this upper reach of
the stream consists largely of colloidal material composed of iron organic complexes which is fed into the stream by marshes which border the channel between Sts 30 and 27. As the groundwater feeding the marshes become oxygenated upon reaching the surface, dissolved iron in the groundwater is oxidised to the ferric state which being insoluble precipitates and combines with humic colloids in the bogs. This process has previously been described in streams draining marshes in Wisconsin (Lee et al 1975). The presence of this colloidal suspension imparts a distinctive reddish brown colouration to stream water in this section of the Narrator Brook during baseflow. During storm flow much greater quantities of this material is mobilised and the entire stream becomes discoloured.

The decrease in concentration beyond St 27 may possibly be attributable to the filtering effect of weed on the stream bed which is unusually thick in the section between Sts 28 and 25. Disturbance of the weeds is observed to discolour the water by the release of stored colloidal material.
stream of St 25, stream water is virtually completely cleared of colloidal humus during baseflow. The fall in concentration in the section between Sts 27 and 26 where channel weed is at its most dense, must have represented an overall loss of almost one tonne of colloidal suspension to weed storage during times of baseflow over the period of observation as a whole. It is unlikely that absolute storage is as great as this and release from storage probably occurs during storm flow as a result of turbulence disturbing the weeds. This may be at least partially responsible for observed discolouration throughout the remainder of the stream below St 25 during flood periods.

Table 7.2 Mean baseflow suspended sediment concentrations and coefficients of variation recorded at 30 sampling sites along the Narrator Brook.

<table>
<thead>
<tr>
<th>St No.</th>
<th>Mean Suspended Sediment Concentration (mg/l)</th>
<th>Coefficient of Variation (%)</th>
<th>Mean Suspended Sediment Concentration (mg/l)</th>
<th>Coefficient of Variation (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.65</td>
<td>67.1</td>
<td>16</td>
<td>0.37</td>
</tr>
<tr>
<td>2</td>
<td>0.60</td>
<td>64.9</td>
<td>17</td>
<td>0.40</td>
</tr>
<tr>
<td>3</td>
<td>0.54</td>
<td>76.5</td>
<td>18</td>
<td>0.31</td>
</tr>
<tr>
<td>4</td>
<td>0.53</td>
<td>66.5</td>
<td>19</td>
<td>0.29</td>
</tr>
<tr>
<td>5</td>
<td>0.57</td>
<td>75.0</td>
<td>20</td>
<td>0.41</td>
</tr>
<tr>
<td>6</td>
<td>0.56</td>
<td>76.0</td>
<td>21</td>
<td>0.37</td>
</tr>
<tr>
<td>7</td>
<td>0.52</td>
<td>66.5</td>
<td>22</td>
<td>0.59</td>
</tr>
<tr>
<td>8</td>
<td>0.53</td>
<td>51.1</td>
<td>23</td>
<td>0.60</td>
</tr>
<tr>
<td>9</td>
<td>0.58</td>
<td>60.7</td>
<td>24</td>
<td>0.51</td>
</tr>
<tr>
<td>10</td>
<td>0.57</td>
<td>61.9</td>
<td>25</td>
<td>0.56</td>
</tr>
<tr>
<td>11</td>
<td>0.54</td>
<td>62.7</td>
<td>26</td>
<td>0.87</td>
</tr>
<tr>
<td>12</td>
<td>0.53</td>
<td>60.5</td>
<td>27</td>
<td>1.84</td>
</tr>
<tr>
<td>13</td>
<td>0.40</td>
<td>52.4</td>
<td>28</td>
<td>1.75</td>
</tr>
<tr>
<td>14</td>
<td>0.47</td>
<td>70.4</td>
<td>29</td>
<td>1.23</td>
</tr>
<tr>
<td>15</td>
<td>0.34</td>
<td>62.8</td>
<td>30</td>
<td>0.41</td>
</tr>
</tbody>
</table>

* n = 27
The magnitude of the peak in the sediment concentration profile between Sts 30 and 25 varied considerably over the period of observation. Concentration at St 27, which generally records the highest value of all the sampling stations reached 9.9mg/l on 6/7/76 while the highest concentration for stations downstream of St 26 on this date was 1.5mg/l. By contrast, for 11 of the 27 sampling dates, concentration at St 27 was below 1mg/l and not significantly different from concentrations along the remainder of the stream (fig 7.2). Sediment concentration at St 27 varies in sympathy with stream stage at this station (r = -0.62, n = 27). It is at a maximum during low discharges while at higher discharges the concentration of colloidal material issuing from marshes is diluted and concentration declines (fig 7.2). However, there is also a certain amount of variation in the sediment concentration at St 27 which is independent of discharge. For the three consecutive sampling dates 8/6/76, 6/7/76 and 20/7/76 no change in stage could be detected at St 27, yet sediment concentrations at St 27 for these sampling dates were 1.5mg/l, 9.9mg/l and 3.5 mg/l respectively. This can only represent fluctuations in the rate of discharge of colloidal material from the marshes for reasons which are not clear. Addition of API and season to the regression failed to contribute significantly to explanation of variance in sediment concentration at St 27 (table 7.3).

Downstream of St 25, with the absence of colloidal matter in large quantity, mineral fragments larger than 1 micron form the bulk by weight of baseflow suspended sediment. From microscope examination of the filtered sediment it is apparent that larger mineral fragments above 100 microns are dominated by biotite flakes. Quartz and tourmaline mineral fragments, are more spherical in shape, and are generally below 50 microns in size during baseflow. The majority of these sediment particles probably do not travel from their point of origin in the channel to the catchment exit in a single journey. Particles travelling
in suspension are continually being lost to the stream bed. Einstein (1968), who studied this process experimentally in a flume, demonstrated that in the absence of renewed supply of sediment particles, sediment concentrations can decline by half within the space of a few metres, particularly in the presence of gravel bed material. In the natural situation sediment lost from suspension during baseflow is compensated.
Table 7.3 Results of multiple regression analysis of suspended sediment concentration at St 27 (data untransformed).

**DEPENDENT VARIABLE**

Suspended sediment concentration at St 27.

<table>
<thead>
<tr>
<th>Independent Variables</th>
<th>Total Correlation Coefficients</th>
<th>5th Order Partial Correlation Coefficients</th>
<th>Partial F Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>1  Stream stage at St 27</td>
<td>-0.62</td>
<td>-0.45</td>
<td>15.63</td>
</tr>
<tr>
<td>2  Antecedent precipitation (API\textsuperscript{30})</td>
<td>-0.03</td>
<td>-0.06</td>
<td>0.03</td>
</tr>
<tr>
<td>3  Seasonal index</td>
<td>-0.49</td>
<td>-0.17</td>
<td>0.71</td>
</tr>
</tbody>
</table>

LEVEL OF SIGNIFICANCE 0.01 0.001

\( r \)

| 0.49 | 0.60 |

\( F \)

7.77 for 1 to 7.88 for 3 13.88 to 14.19

n = 27 Percent Explanation (all variables) 40.4%

to a variable degree by a continual supply of sediment, mainly from submerged channel banks. Suspended sediment concentration at any point along the channel is thus a result of the relative rate of loss and supply and this in turn is determined by the nature of the channel.

Mean sediment concentrations for Sts 1-25 in the Narrator Brook vary from 0.29mg/L at St 19 to 0.65mg/L at St 1 (fig 7.1). The mean baseflow sediment concentration profile downstream of St 25 shows slow and progressive changes from station to station. The mean concentration at a station is closely related to the concentration at the next station upstream (\( r = 0.71, n = 24 \)), even though distance between stations ranges up to 275 m. This means that the change in concentration between adjacent stations is related
to conditions over the entire length of intervening section. If sediment concentration at a station were a response to the nature of the channel in the immediate upstream vicinity of the station, the sediment concentration profile would appear more irregular and sediment concentration at a station would bear no relation to the concentration at any appreciable distance upstream. This has some implication with respect to the distance travelled by individual particles in the Narrator Brook and suggests that for the majority of particles this distance exceeds 110 m which is the average distance between sampling stations.

In attempt to explain downstream variations in mean baseflow suspended sediment concentration, multiple regression analysis was performed with mean sediment concentration at a station as the dependent variable and concentration of the next station upstream as one of the independent variables. The other independent variables tested were the length of the intervening channel section, together with mean gradient of the section, width/depth ratio and hydraulic radius. Only channel gradient succeeds in contributing significantly to the explanation of variance in the dependent variable achieved by the concentration of the next station upstream (table 7.4). Over steep sections of the Narrator Brook concentration of sediment declines downstream indicating that there is an increase in the rate of loss of sediment particles from suspension relative to the rate of supply. In lower gradient sections, on the other hand, sediment concentrations increase downstream indicating a decrease in the rate of sedimentation relative to supply.

The greater rate of sedimentation in steep sections can perhaps be explained by the large number of plunge pools in these sections. During baseflow water in these pools can become sufficiently still to allow settling out of sediment particles from suspension. After prolonged periods of baseflow it has been observed that the rocks lying at the bottom of plunge pools acquire a thin brown coating of sediment. At higher flows, during flood periods, the turbulence
Table 7.4 Results of multiple regression analysis of downstream variations in mean baseflow suspended sediment concentration recorded at 30 sampling stations along the Narrator Brook.

<table>
<thead>
<tr>
<th>Independent Variables</th>
<th>Total Correlation Coefficients</th>
<th>4th Order Partial Correlation Coefficients</th>
<th>Partial F Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Mean sediment concentration at neighbouring upstream station</td>
<td>0.71</td>
<td>0.68</td>
<td>21.95</td>
</tr>
<tr>
<td>2 Mean gradient of intervening stream section</td>
<td>-0.40</td>
<td>-0.48</td>
<td>9.52</td>
</tr>
<tr>
<td>3 Mean hydraulic radius of intervening stream section</td>
<td>-0.45</td>
<td>-0.27</td>
<td>2.03</td>
</tr>
<tr>
<td>4 Mean width/depth ratio of intervening stream section</td>
<td>0.57</td>
<td>-0.01</td>
<td>0.01</td>
</tr>
<tr>
<td>5 Length of intervening stream section</td>
<td>-0.18</td>
<td>-0.12</td>
<td>0.24</td>
</tr>
</tbody>
</table>

LEVEL OF SIGNIFICANCE

- r: 0.46
- F: 7.64 for 1 to 7.82 for 5

n = 30 Percent Explanation (all variables) 69.2%

within the plunge pools evacuates the sediment accumulated over the preceding period of low flow. The amount of sediment involved is small. The greatest drop in mean sediment concentration occurs from St 22 (0.59mg/l) to St 21 (0.37mg/l). The intervening stream section falls at a rate of 110.3 m/km and consists almost entirely of waterfalls and plunge pools. During average baseflow conditions (about
35 l/s at St 21) net loss of sediment is 700 gm/day spread over the 110 m between Sts 22 and 21. As well as increased sedimentation in steep sections, supply of sediment is probably reduced to some degree since channel margins are typically composed of boulders and other coarse material so that source of fines for suspended transport in steep sections is limited. The largest increase in concentration between stations occurs from St 13 (0.40mg/ℓ) to St 12 (0.53mg/ℓ) involving a net gain of 1 200 gm/day over 189 m of channel during baseflow. The stream section between Sts 12 and 13 falls at a rate of 17.9 m/km.

Concentration of sediment at any point along the stream during baseflow can be predicted within close limits (± 0.13 mg/ℓ with 95% confidence) on the basis of the concentration at an upstream location and the gradient of the intervening stream section (equation 7.1).

\[
Y = 0.189 + 0.734X_1 - 0.00154X_2 \tag{7.1}
\]

\[
n = 24 \quad r = 0.81 \quad S.E. = 0.063 \text{mg/ℓ}
\]

\[
Y = \text{Mean baseflow suspended sediment concentration (mg/ℓ)}
\]

\[
X_1 = \text{Mean baseflow suspended sediment concentration of an upstream location (mg/ℓ)}
\]

\[
X_2 = \text{Channel gradient of the intervening stream section (m/km)}
\]

By use of this empirical relation, from known concentration at any one location, the downstream sediment profile can be extrapolated. Starting from a measured mean concentration of 0.41 ppm at St 30, a predicted sediment concentration profile for the Narrator Brook was projected downstream by this method (fig 7.3). Although data from the stream section above St 25 were not included in the regression analysis, predicted and observed profiles correspond quite closely over the lower part of the stream, and serves to highlight the important contribution of colloidal matter to total suspended sediment in the upper reaches.

Mean baseflow suspended sediment concentrations in the
forest section of the Narrator Brook (Sts 1-11) range from 0.52mg/l at St 7 to 0.65mg/l at St 1. These concentrations are somewhat higher than concentrations in the section between St 21 and St 11 which range from 0.29mg/l at St 19 to 0.54mg/l at St 11. However, observed and predicted profiles correspond very closely for the section between Sts 11 and 1 indicating that the relatively high concentrations in this section are due almost entirely to the relatively low gradients. Eroding banks and ephemeral channels in the forested region of the catchment appear to have more influence upon flood period sediment transport than baseflow sediment transport.

Aside from the upper reaches of the stream where colloidal material contributes substantially to suspended sediment, the greatest disparity between observed and predicted values is at St 15 (fig 7.3). Mean baseflow sediment concentration at this station is 0.34mg/l whereas from consideration of concentration at St 16 (0.37mg/l) and the low
gradient between these two stations (27.5 m/km), concentration at St 15 should be in the region of 0.50mg/l. Between Sts 15 and 16 a thick brush lines the channel and in places hangs into the stream trapping leaves and twigs to form temporary debris dams. These dams may be responsible for filtering sediment particles from the stream during baseflow and depressing sediment concentration at St 15.

Data for individual sampling dates were also regressed against the sediment concentration for the neighbouring station upstream and the gradient of the intervening channel section. Multiple correlation coefficients vary from 0.79 to 0.08; none exceed the 0.81 achieved using mean values for all sampling dates. This means that the trend which emerges from analysis of mean values is masked to some degree for individual sampling dates by inaccuracies in the data. It also means that the trend was more consistent for the 27 sampling dates than the wide variation in multiple correlation coefficients would suggest. If this were not the case, the multiple correlation coefficient obtained from mean concentration values would be closer to a mean of the multiple correlation coefficients for individual sampling dates. To what extent the variations in the multiple correlation coefficients for individual sampling dates reflect temporal changes in strength of the trend represented by equation 7.1 is not certain. The 27 multiple correlation coefficients were tested against discharge at St 1 for each sampling date, season, and a 30 day antecedent storm period sediment discharge index calculated in the same fashion as API_{30} (equation 3.4). The low correlation coefficients \( r = 0.13, -0.22 \) and 0.05 respectively, \( n = 27 \) indicate that if the form of the mean baseflow suspended sediment concentration profile (fig 7.1) is subject to temporal changes, these changes are not influenced by the three factors tested and must be related to more subtle controls.
7.1.2 Solutes

The stream samples which were collected on 27 occasions at 30 sampling sites along the Narrator Brook as described in section 7.1.1 were analysed for specific conductance as well as suspended sediment concentration. Specific conductance for baseflow samples is considerably more reproducible than suspended sediment concentration. This enables meaningful interpretation of downstream variations in specific conductance for individual sampling dates whereas this is not possible for suspended sediment. The low degree of variability in baseflow specific conductance at the main gauging site has been discussed in section 6.3.2. Specific conductance was equally constant at the other 29 sites during the period of observation. Coefficients of variation for specific conductance at the 30 sampling stations are very low in comparison to suspended sediment ranging from only 3.6% to 5.9% (table 7.5). As a result of the low variability at a station the downstream specific conductance profile changes very little. This is illustrated by correlation of downstream variations in the specific conductance for the 27 sampling dates (table 7.6). In sharp contrast to the sediment concentration matrix (table 7.1) only 62 of the 351 correlation coefficients are below 0.90 and 7 reach 0.99. The overall form of the baseflow specific conductance profile for the Narrator Brook is less variable than individual values at a site. On two of the sampling dates 8/7/75 and 31/8/76, baseflow specific conductance at St 1 was higher than normal (fig 6.5). Although for these sampling dates specific conductance values overall are respectively approximately 12% and 6% higher than normal the form of the specific conductance profile remains relatively unchanged (fig 7.4). Included in fig 7.4 for comparative purposes is the profile for 20/7/76 which is typical of normal baseflow conditions.

The main feature of the specific conductance profile of the Narrator Brook is an irregular but pronounced increase downstream of St 13 (fig 7.4). This coincides with the
Table 7.5 Mean baseflow specific conductance and coefficients of variation recorded at 30 sampling sites along the Narrator Brook.

<table>
<thead>
<tr>
<th>St No.</th>
<th>Mean Specific Conductance (μmhos/cm at 25°C)</th>
<th>Coefficient of Variation (%)</th>
<th>St No.</th>
<th>Mean Specific Conductance (μmhos/cm at 25°C)</th>
<th>Coefficient of Variation (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>55.7</td>
<td>4.0</td>
<td>16</td>
<td>48.5</td>
<td>3.6</td>
</tr>
<tr>
<td>2</td>
<td>55.5</td>
<td>4.2</td>
<td>17</td>
<td>48.0</td>
<td>3.7</td>
</tr>
<tr>
<td>3</td>
<td>54.8</td>
<td>4.1</td>
<td>18</td>
<td>48.4</td>
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</table>

* n = 27

appearance of conifers in the catchment area of the Narrator Brook below St 13. Baseflow specific conductance profiles were also obtained for the other two major feeder streams of the Burrator Reservoir, the Meavy River and the Newleycombe Lake (fig 7.5). Only the lower part of the Meavy River was sampled, below the point where the river is diverted to the Devonport Leat. Both streams, like the Narrator Brook, have catchments which are partially forested at their lower ends. The Meavy River has proportionally more of its catchment under forest (28.2%) than that of the Narrator
Table 7.6 Correlation matrix showing the degree of similarity in downstream baseflow specific conductance profiles for individual sampling dates
Comparison of downstream baseflow specific conductance profiles for the Narrator Brook for sampling dates 9/7/75, 20/7/76 and 31/8/76

Brook (11.3%), and the Newleycombe Lake catchment (2.4%) has rather less. The solute concentration profiles of these two streams display the same general form as the Narrator Brook (fig 7.6). For all three streams there is no significant downstream increase in specific conductance until each stream enters its respective forested sub-catchment from which point downstream increase is significant at the 0.01 level or better. The downstream increase in concentration is most pronounced in the Meavy River, which has the greatest proportion of its catchment under forest, and least marked in the Newleycombe Lake. Respective rates of increase downstream are 7.6, 5.9 and 4.8 µmhos per km of river length. From these observations there can be little doubt that in some manner the presence of forest cover locally increases baseflow solute concentrations. Walling and Webb (1975) in a study of the spatial variation of baseflow specific conductance within the Exe River Basin also obtain higher values in forested areas than in moorland areas on the same lithology, but offer no explanation.
Fig. 7.5 Drainage basin of the Burrator Reservoir showing the areas under coniferous forest
Fig. 7.6 Comparison of downstream baseflow specific conductance profiles for the Narrator Brook, Newleycombe Lake and Meavy River, July 1976
Increasing solute concentration downstream is a characteristic feature of many streams. Aside from pollution, this can result from an increase downstream firstly in the supply of solute from rock weathering, secondly in the supply of solutes from the atmosphere, or thirdly in the rate of evapotranspiration. With respect to supply of solutes from rock weathering, in catchments containing two or more rock types, the rocks more susceptible to chemical denudation often lie in the bottom of the catchment with more resistant rocks occupying the higher altitudes. The Hodge Beck in the North Yorkshire Moors, for example, experiences rising solute concentrations downstream after the stream passes from Lower Oolite and Upper Lias into Middle and Lower Lias (Imeson 1973). Similarly the downstream increase in specific conductance in the River Exe, Devon, is attributed by Walling & Webb (1975) to the higher rates of denudation of the Permian and Triassic rocks underlying the lower parts of the drainage basin in comparison to the more resistant Devonian rocks in stream source regions. Although the Narrator catchment is underlain by a single rock type, the possibility cannot be excluded that the coniferous forest plantation in Narrator catchment, possibly by affecting soil acidity, may be responsible for increasing the rate of chemical denudation in the underlying granite.

A second possible cause for downstream increase in solute concentration relates to spatial variations in atmospheric fallout. Marked declines in bulk fallout concentrations away from windward coasts have been observed in Sweden (Eriksen 1955), The United States (Junge & Werby 1958), Australia (Hutton 1968) and Britain (Stevenson 1968). According to Rodda et al (1976) the chemical nature of rivers with low solute concentrations is influenced by the change in composition of rainfall as the coast is approached. It is unlikely that this explanation can be applied to catchments as small as that of the Narrator Brook. For the period 26/4/76 to 13/12/76 bulk fallout was collected at site above the forest plantation close to raingauge 2 in addition to
the permanent sampling site near raingauge 1 at the catchment exit (fig 3.1). Although the two sites are separated by almost two kilometres in distance and 55 metres in altitude, and also have very differing exposures, conductivities recorded at the two sites are relatively consistent (fig 7.7). Weekly values rarely show more than 20% difference and in any case these differences are largely random so that mean precipitation weighted specific conductance values for the two sites, over the period when both were in operation, are very similar (34.0 and 33.6 µmhos at raingauge

![Graph showing specific conductance of bulk fallout](image)

**Fig. 7.7** Comparison of specific conductance of bulk fallout recorded at two sites in the Narrator catchment

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sites 1 and 2 respectively). Johnson et al (1968) report a similar spatial uniformity in concentrations of bulk fallout within a small New England catchment as does Foster (1979) in a small Devon catchment. However, where impaction of wind blown salt particles is an important component of atmospheric fallout, spatial variability is likely to be much greater since the effectiveness of this process is dependent upon the type of vegetation cover (Gorham 1961). According to Erikson (1955) the needle leaves of coniferous trees are particularly efficient in filtering salt particles from the atmosphere. Chemical mass balance studies of small catchments under coniferous forest, often reveal an excess of chloride leaving the catchment in stream water over that entering the catchment in bulk fallout, and this is generally attributed to impaction of atmospheric salts on the forest canopy (Juang & Johnson 1967, White et al 1971, Zeman 1975). Spraggs (1976), on the other hand, in a chemical mass balance study of a Hampshire catchment obtains greater inputs of chloride in the form of bulk fallout than outputs in stream water even though the catchment is densely wooded, much of it coniferous, and also lies close to the coast. Similar results from some Australian catchments are described by Douglas (1968b). The solute concentration of throughfall from a coniferous forest canopy is often appreciably higher than the solute concentration of bulk fallout, and this also has been ascribed to impaction of air-borne salt particles (Tamm 1953, White & Turner 1970, Hart & Parent 1974). However, Attiwill (1966) maintains that high throughfall concentrations can be as much a result of foliar leaching as impaction of atmospheric salts. The influence of foliar leaching upon stream solute concentration is likely to be minor. Foster (1979), in a small Devon catchment, discovered that the large increase in potassium concentration in throughfall compared to bulk fallout, which he attributes to foliar leaching, does not affect the potassium concentration of stream water and concluded that solutes released by foliar leaching are recycled.
The third possible mechanism to explain downstream increases in solute concentration in the Narrator Brook is differential evapotranspiration and/or interception. Increased rates of evapotranspiration and interception by the forest plantation in comparison to other vegetation types in the Narrator catchment would reduce the volume of water passing through the forested area. If the availability of solutes from rock weathering and atmospheric fallout remained unchanged, the solute concentration of water draining the forested area would be greater than unforested areas. This explanation is perhaps supported by the low baseflow runoff from the forested area of the Narrator catchment. Baseflow runoff for the period of observation is 1 331 mm at St 11 above the forest plantation compared with 1 151 mm at the catchment exit.

It is not possible to establish with any confidence the relative importance of the three mechanisms outlined above as far as the Narrator catchment is concerned. Some insight can be obtained by comparison of the chemical composition of springs, seeps and tributaries draining forest areas during baseflow with those draining grassland or moorland areas. Small tributaries, springs and seeps provide a more accurate indication of local groundwater chemistry than the main stream since they have smaller drainage areas. The mean specific conductance of samples drawn from springs, seeps and tributaries in the forest is 74.6 μmhos in comparison to 55.2 μmhos for non-forest areas (table 7.7). This difference is significant at better than the .001 level. The concentrations in these samples of chloride, which is supplied entirely from atmospheric fallout, and silica, which is derived entirely from rock weathering, are both significantly greater in the forested region of the catchment. Chloride, however, undergoes a greater proportional increase than silica. The ratio of silica to chloride in the forested region of the catchment is significantly less than this ratio for the non-forested region (0.61 and 0.71 respectively). This does not indicate which
Table 7.7 Specific conductance, chloride and silica concentration for tributaries, springs and seeps in forested and non-forested regions of the Narrator catchment.

<table>
<thead>
<tr>
<th>Specific Conductance (µmhos/cm at 25°C)</th>
<th>Concentration (mg/l)</th>
<th>Ratio:</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Forest</td>
<td>Open</td>
<td>Forest</td>
</tr>
<tr>
<td></td>
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<td>.001</td>
<td>.01</td>
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</table>

1 Samples collected by author 19/11/76
2 Samples collected by J.L. Ternan 14/3/77

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is the dominant process responsible for increased stream solute concentrations in the forested region of the Narrator catchment. It does suggest, however, that preferential entrapment of atmospheric salts by the forest is of some significance.

Regardless of the probable mechanism responsible, downstream variations in baseflow specific conductance penetrated by forest cover in the catchment can be modelled on the basis of a simple mixing equation:

\[
C_Y = \frac{A_A C_A + A_F C_F}{A_A + A_F}
\]

where \(C_Y\) is the specific conductance of baseflow at any point along the forested section of the stream; \(A_A\) is the area of non-forested catchment above the point on the stream to which \(C_Y\) refers; \(C_A\) is the specific conductance of baseflow supplied from non-forested regions of the catchment; \(A_F\) is the area of forested catchment above \(C_Y\); and \(C_F\) is the specific conductance of baseflow supplied from the forested regions of the catchment.

This is equally applicable to other catchments where stream solute concentrations are influenced by a partial cover of forest within the catchment. It is, however, limited to catchments underlain by a single rock type and also to small catchments over which hydrometeorological conditions can be considered relatively uniform. The model can be tested by correlation of the proportional increase in baseflow specific conductance \(C_Y\) for various sampling sites along the stream against the proportional areal representation of forest in the sub-catchment above each site sampled. The specific conductance of baseflow supplied from non-forested regions of the catchment \(C_A\) can be approxi-
mated by a mean of observed stream baseflow specific conductance for all sampling sites in this region. For the Narrator Brook, Newleycombe Lake and Meavy River $C_A$ values obtained in this way are 47.6, 47.8 and 52.2 $\mu$hmhos respectively (table 7.8). Values for the Narrator Brook and Newleycombe Lake are very similar; baseflow concentrations in non-forested regions probably do not deviate greatly from around 48 $\mu$hmhos over the larger part of Dartmoor. The $C_A$ value for the Meavy catchment is higher possibly due to the practice of salting roads on Dartmoor during winter months. The Yelverton to Princeton road runs through the Meavy catchment for a distance of four kilometres and salt washed from this stretch of road may be responsible for increasing groundwater concentrations in the catchment (fig 7.5). Since the turnover in groundwater storage is slow the resulting effect upon stream baseflow concentration is likely to be sustained throughout the year. Credence is lent to this explanation by a steadily rising baseflow solute concentration in an upstream direction in the Meavy River from 51.7 $\mu$hmhos

<table>
<thead>
<tr>
<th>Catchment area (Km$^2$)</th>
<th>Narrator Catchment</th>
<th>Newleycombe Catchment</th>
<th>Meavy Catchment</th>
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<tr>
<td>Catchment area (Km$^2$)</td>
<td>4.68</td>
<td>4.70</td>
<td>3.58*</td>
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<tr>
<td>Forest area, (Km$^2$)</td>
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<td>0.115</td>
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<td>Length of forest margin L(Km)</td>
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<tr>
<td>Observed $C_A$ ($\mu$hmhos/cm at 25°C)</td>
<td>47.6</td>
<td>47.8</td>
<td>52.2</td>
</tr>
<tr>
<td>Corrected $C_A$ ($\mu$hmhos/cm at 25°C)</td>
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<td>47.0</td>
<td>51.8</td>
</tr>
<tr>
<td>Computed $C_F$ ($\mu$hmhos/cm at 25°C)</td>
<td>110.8</td>
<td>239.1</td>
<td>97.5</td>
</tr>
<tr>
<td>$C_F/C_A$</td>
<td>2.26</td>
<td>5.09</td>
<td>1.88</td>
</tr>
<tr>
<td>L/A$_F$</td>
<td>5.28</td>
<td>10.43</td>
<td>3.37</td>
</tr>
</tbody>
</table>

* Contributing catchment area only (see fig 7.5)
just before the stream enters the forest to 58.6 \mu mhos close to its source; the road crosses the upper part of the catchment. The baseflow concentration of the Hart Tor Brook, a tributary of the Meavy River which has no roads in its catchment, is around 47 to 48 \mu mhos matching that of the Narrator Brook and Newleycombe Lake. The effect of road salt upon stream solute concentration has previously been described by Mulkowicz & Salem (1974) in a catchment near Chicago, and by Edwards (1973a) in a Norfolk catchment.

For all three catchments, the parameter $\frac{A_F}{A_A + A_F}$ explains at least 93% of variance in baseflow solute concentrations illustrating the large measure of success achieved by the proposed model (equation 5.2; fig 7.8). Both the regression coefficients and intercept values, however, differ appreciably for the three catchments.

For all three regressions, intercept values deviate from unity. According to the proposed model (equation 5.2) when forest is absent in the catchment there should be no increase in stream solute concentration, so that when $A_F$ equals zero, $C_Y$ should equal 1.0. This may be a result of some slight inaccuracy in the estimation of $C_A$ obtained from mean baseflow specific conductance for non-forested regions in each of the three catchments. When the regression constants are adjusted to unity, corrected $C_A$ values for the Narrator Brook, Newleycombe Lake and Meavy River are 49.0, 47.0, and 51.8 \mu mhos respectively which are very similar to the observed $C_A$ values of 47.6, 47.8 and 52.2 \mu mhos (table 7.8).

The differing regression coefficients for the three streams indicate that although in all three streams baseflow solute concentration increases in response to the proportion of catchment forested it does so at a different rate in each case. This can only mean that the specific conductance of baseflow supplied from the forest area $C_F$ differs for the
Fig. 7.8 Relation of baseflow specific conductance to area of catchment forested for the Narrator Brook, Newleycombe Lake and Meavy River. See equation 7.2 for notation.

three catchments. Values of $C_F$, obtained by substitution in equation 5.2 for the Narrator, Newleycombe and Meavy catchments are 110.8, 239.1 and 97.5 μmhos respectively. The ratio of baseflow specific conductance from forested and non-forested regions $C_F/C_A$ is a measure of the degree to which solutes have been concentrated by forest cover (table 7.8). In the Narrator catchment, for example, specific conductance of baseflow supplied from the forest has been increased by a
factor of 2.26, compared with 5.09 and 1.88 for the Meavy and Newleycombe catchments respectively.

These differences in $C_F$ values for the forested areas of the three catchments seems to be related to the shape and size of the plantation in each catchment (fig 7.5). Increase in specific conductance is greater for forest plantations which have a longer perimeter in relation to areal extent (table 7.8). The influence of the length of forest perimeter can be accommodated in two of the mechanisms previously discussed to explain higher solute concentrations within the forest. It might be expected that if impaction of atmospheric salts is an important process in the Narrator catchment higher rates would occur along forest margins, since here there is a greater surface area of vegetation exposed to salt bearing winds. Exposure to winds along forest margins is also likely to promote evapotranspiration. Forest interiors are more sheltered and circulation is reduced with the result that the atmosphere beneath the forest canopy remains more humid thereby inhibiting evapotranspiration. The margin effect means that the specific conductance of baseflow from forested areas is not spatially uniform and the $C_F$ values quoted in table 7.5 are mean areal values. The specific conductance of samples of groundwater drawn from several boreholes within the forest area of the Narrator catchment range from 65 to 140 μmhos (J. Alexander, pers. comm.) compared to a computed $C_F$ value of 110 μmhos.

Although the increase in specific conductance downstream in the lower half of the Narrator Brook is a permanent feature, significant temporal changes in the upper half of the stream can be detected. These changes emerge very clearly from analysis of the variability in specific conductance values at each site. If variability in specific conductance at each site were the same, it would indicate that this variability is due entirely to an upward or downward shift in the specific conductance profile without any appreciable change in form as illustrated in fig 7.4. In reality
the coefficient of variation for each of the 30 stations increases sharply from St 30 to St 29 (fig 7.9). Thereafter it decreases gradually downstream until St 19 beyond which values are relatively constant.

The rise in specific conductance from St 30 to St 29 which is illustrated by the profiles in fig 7.4 is due to discharge of water from marshes just upstream of St 29 with a higher specific conductance than the stream. A sample of the outflow from the largest of these marshes collected in 6/7/76 recorded a specific conductance of 49.5 µmhos in comparison to 47.1 µmhos at St 29 and 44.9 µmhos at St 30 on the same day. The high specific conductance at St 29 is gradually diluted with increasing discharge downstream to about St 19. The high coefficient of variation at St 29 means that the supply of solutes from marshes above St 29 is variable. The rate of decline in specific conductance from St 29 downstream is correspondingly variable and is reflected in declining values for coefficient of variation from 5.9% at St 29 to 3.6% at St 19.

This varying trend in the specific conductance profile
for the upper half of the Narrator Brook is best illustrated by the contrast between sampling dates 13/4/76 and 14/9/76 (fig 7.10). Also included in fig 7.10 as in fig 7.4 is the profile for 20/7/76 for comparative purposes. On 13/4/76 the specific conductance profile changes little downstream from St 30 while on 14/9/76 specific conductance rises from 45.5 \( \mu \text{mhos} \) at St 30 to 53.2 \( \mu \text{mhos} \) at St 29. By St 19 the specific conductance profiles for the two dates merge together once more. This aberration in the specific conductance profile, caused by variations in the solute discharge of marshes upstream of St 29, is responsible for the few low correlation coefficients in table 7.6. The correlation between sampling dates 13/4/76 and 14/9/76, for example, is only 0.79 (n = 30).

The cause of variations in the solute outflow from the marshes cannot be established from the limited observations available. The difference in specific conductance between St 29 and 30 varies from 0.6 to 8.5 \( \mu \text{mhos} \) for the 27 sampling dates. These variations are not significantly related to

![Graph of specific conductance profiles](image)

**Fig. 7.10** Comparison of downstream baseflow specific conductance profiles for the Narrator Brook for sampling dates 13/4/76, 20/7/76 and 14/9/76
variations in the concentration of sediment at St 27 which is composed largely of humic colloids also discharged from marshes in this region \( (r = 0.32, n = 27) \). The fact that highest specific conductance occurs at St 29 while highest sediment concentration is further downstream at St 27 implies that the marshes which supply the bulk of the colloidal humus are not the same as those which are responsible for increasing the specific conductance of the stream. The difference in specific conductance between Sts 29 and 30 was tested in multiple correlation against antecedent precipitation \( (\text{API}_{30}) \), stage at station 29, and season (table 7.9). Strongest correlation is with \( \text{API}_{30} \) \( (r = 0.76, n = 27) \). The significance of \( \text{API}_{30} \) is probably related to the rate of outflow from marshes. Increased outflow from marshes when the catchment is wet reinforces their influence upon stream conductivity. This trend is opposed by changing stage at St 29 which also contributes significantly to the multiple

Table 7.9 Results of multiple regression analysis of the difference in specific conductance between Sts 29 and 30 (data untransformed).

<table>
<thead>
<tr>
<th>DEPENDENT VARIABLE</th>
<th>Independent Variables</th>
<th>Total Correlation Coefficients</th>
<th>2nd Order Partial Correlation Coefficients</th>
<th>Partial F Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Difference in specific conductance between Sts 29 and 30.</td>
<td>1 Antecedent precipitation ( (\text{API}_{30}) )</td>
<td>0.76</td>
<td>0.81</td>
<td>33.42</td>
</tr>
<tr>
<td></td>
<td>2 Stream stage at St 29</td>
<td>-0.36</td>
<td>-0.45</td>
<td>9.98</td>
</tr>
<tr>
<td></td>
<td>3 Seasonal index</td>
<td>-0.32</td>
<td>0.06</td>
<td>0.08</td>
</tr>
</tbody>
</table>

LEVEL OF SIGNIFICANCE: 0.01

\( r \): 0.49

\( F \): 7.77 for 1 to 7.88 for 3

\( n = 27 \) Percent Explanation (all variables) 69.8%
regression. When stage at St 29 rises more rapidly in relative terms than outflow from bog sources their influence becomes diluted. These two variables together account for 70% of the variance in the difference in specific conductance between Sts 29 and 30. Season has no significant independent effect.

Outflow from marshes in the region of the Narrator Brook from St 27 to St 30 not only contributes substantially to streamflow during baseflow conditions but also contributes even more substantially to suspended sediment and solute transport. Unexplained fluctuations in this contribution have a marked effect upon the baseflow sediment concentration and specific conductance profiles in the upper reaches of the Narrator Brook. For these reasons this phenomenon certainly warrants more detailed research. Ideally this would involve monitoring the outflow from each of the more important marshes.

7.2 Comparison of yields between subcatchments

7.2.1 Suspended Sediment

Yield of sediment or solutes is the product of concentration and runoff. Due to the limitations of the discharge rating curves, determination of runoff at the three gauging sites along the Narrator Brook is subject to a certain amount of inaccuracy which is transferred to estimated sediment and solute yields. Recorded depth of runoff at St 1 over the period of observation is 17% less than at St 11 (1 312 and 1 582 mm respectively - table 7.10). This drop in runoff at St 1 could perhaps in part be attributed to higher rates of interception and/or evapotranspiration by forest cover in comparison to grassland or moorland. However, there is strong evidence to suggest that there is seepage of water from the channel in the forest section of the stream into the underlying growan.

On the 8th of July 1976 during low baseflow and on the
Table 7.10 Outputs from three nested sub-catchments of the Narrator Brook for the period 26/5/75-13/12/76.

<table>
<thead>
<tr>
<th>Sub-catchment above:</th>
<th>St 21</th>
<th>St 11</th>
<th>St 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drainage area (km²)</td>
<td>2.56</td>
<td>3.67</td>
<td>4.68</td>
</tr>
<tr>
<td>Mean slope (°)</td>
<td>5.8</td>
<td>7.6</td>
<td>8.0</td>
</tr>
<tr>
<td>Drainage density (km/km²)</td>
<td>0.89</td>
<td>1.50</td>
<td>2.06</td>
</tr>
<tr>
<td>Moorland/stagnopodsol (%)</td>
<td>99.0</td>
<td>81.7</td>
<td>69.8</td>
</tr>
<tr>
<td>Grassland/brown earth (%)</td>
<td>1.0</td>
<td>16.4</td>
<td>18.7</td>
</tr>
<tr>
<td>Forest/brown earth (%)</td>
<td>0</td>
<td>1.9</td>
<td>11.5</td>
</tr>
<tr>
<td>Total runoff (mm)</td>
<td>1420</td>
<td>1582</td>
<td>1312</td>
</tr>
<tr>
<td>Baseflow runoff (mm)</td>
<td>1148</td>
<td>1331</td>
<td>1150</td>
</tr>
<tr>
<td>Quickflow runoff (mm)</td>
<td>272</td>
<td>251</td>
<td>162</td>
</tr>
<tr>
<td>Suspended sediment (t)</td>
<td>5.2</td>
<td>19.0</td>
<td>18.8</td>
</tr>
<tr>
<td>discharge (t/km²)</td>
<td>3.32</td>
<td>5.17</td>
<td>4.02</td>
</tr>
<tr>
<td>Solute discharge (t)</td>
<td>81</td>
<td>215</td>
<td>257</td>
</tr>
<tr>
<td>(t/km²)</td>
<td>51.9</td>
<td>58.5</td>
<td>54.9</td>
</tr>
<tr>
<td>Bedload discharge (t)</td>
<td>-</td>
<td>-</td>
<td>0.43</td>
</tr>
<tr>
<td>(t/km²)</td>
<td>-</td>
<td>-</td>
<td>0.09</td>
</tr>
</tbody>
</table>

12th of October 1976 during high baseflow, stream discharge was measured at 8 sites along the Narrator Brook. These sites are at or near Sts 28, 24, 21, 16, 13, 11, 7 and 1 (fig 2.9). Downstream baseflow discharge profiles on 8/7/76 and 12/10/76 are broadly similar in form even though discharges on 12/10/76 were much greater than on 8/7/76 (fig 7.11). On both dates discharge displays a declining trend through the forest. On the 8th July discharge near St 7 was 48 l/s compared with only 44 l/s at St 1. On the 12th October, discharge near St 7 and St 1 were 219 l/s and 182 l/s respectively. This represents, in the case of 12/10/76, for example, a seepage loss of at least 133 m³/hr.
from the channel between Sts 7 and 1, or an average rate of 52 mm/hr over the 2560 m² of channel floor between these stations. Comparative downstream discharge profiles for flood periods could not be obtained since discharge measurements at the 8 sites takes at least 6 hours to complete and changes in stream stage during this time would prevent inter-site comparisons. Quickflow runoff recorded at Sts 11 and 1, however, can be directly compared. For 31 of the 37 major flood events which occurred during the period of observation quickflow runoff at St 11 exceeds that at St 1. For example, for an event which took place on the 5th to 7th of October 1976 116 951 m³ of quickflow runoff was recorded at St 11 in comparison to only 87 316 m³ at St 1 representing a loss of at least 29 635 m³ of quickflow by seepage. Seepage in the forest section of the Narrator Brook may have
been enhanced to some degree by accelerated bank erosion in this section. Accelerated bank erosion has increased the channel floor area between Sts 1 and 11 from a probable 1,925 m² before afforestation to 3,858 m² at present. Total measured runoff at St 11 during the period of observation is also greater than at St 21 (1,582 mm and 1,420 mm respectively). The reason for this is not immediately apparent. The difference may be largely accounted for by errors in estimation of runoff incurred by extrapolation of discharge rating curves.

Measured unit area sediment yields at Sts 21, 11 and 1 are 3.3, 5.2 and 4.0 t/km² for the period of observation. Although these differences are small they exceed differences in recorded runoff and thus probably represent a real disparity in sediment production between the three sub-catchments of the Narrator Brook. Unit area sediment yield is lowest for the catchment area above St 21 which consists of 99% moorland. At St 11 unit area sediment yield is 1.9 t/km² (58%) greater, even though the catchment area above St 11 contains 16% grassland. Soil well observations indicate that overland flow is more frequent on moorland than on grassland. However, mean slope for the catchment area above St 11 is greater than for catchment area above St 21 (7.6° and 5.8° respectively) and this may promote a higher rate of sediment production per unit area of catchment slopes. In addition there are several specific sources of sediment in the catchment area between Sts 21 and 11 which may help to account for the relatively large sediment yield at St 11. There are 100 m of eroding banks between Sts 21 and 11 but no eroding banks above St 21 (fig 2.11). There is an abundance of fine sandy bed material in the low gradient section between Sts 13 and 11 which may contribute to suspended sediment transport at St 11. Above St 21 the channel is steeper and bed material ranges from coarse gravel to boulders. Between Sts 11 and 21 there are 7 cattle crossing points which may contribute sediment during heavy rain in comparison to only 2 above St 21 (fig 2.11).
2.9). During wet periods a spring rises in the farmyard of Deancombe Farm and flushes sediment out of the farmyard via the Deancombe Brook into the Narrator Brook.

The discharge of suspended sediment passing St 1 over the period of observation (18.8 t) is marginally less than that passing St 11 (19.0 t), causing a drop in calculated unit area yield from 5.2 t/km² at St 11 to 4.0 t/km² at St 1. This is despite the widespread bank erosion along the main channel between Sts 11 and 1 and also the drainage ditches and land rover tracks in the forest which undoubtedly supply some sediment. This can perhaps be explained to some extent by deposition of sediment in the channel between Sts 11 and 1. Erosion pin observations reveal that rates of aggradation in the forest section between Sts 1 and 11 are significantly higher than along the remainder of the stream. Nevertheless the relatively low sediment yield at St 1 suggests that sediment production from the forested region of the Narrator catchment is not much greater than from other regions of the catchment. These results contrast very sharply with results of a study by Painter et al (1974) in a moorland catchment in Mid-Wales, which like the Narrator catchment has been partially afforested. They found yield from the forest area to be considerably greater than from moorland areas and this they attribute to accelerated channel erosion in the forest area. Although afforestation has also been responsible for accelerated channel erosion in the Narrator Brook, evidence indicates that this is declining as channel readjustment nears completion. Erosion pin observations and analysis of channel geometry indicate that contemporary rate of bank erosion in the forest is inferior to the mean rate over the period since afforestation. Channel readjustment in the Mid-Wales catchment studied by Painter et al (1974) may not be as far advanced as the Narrator Brook.

7.2.2 Solutes

Unit area solute yields at Sts 21, 11 and 1 for the period of observation differ less in relative terms than
suspended sediment yields (table 7.10). Values at the three sites are 51.9, 58.5 and 54.9 t/km² respectively. These differences between Sts 21, 11 and 1 correspond closely to differences in runoff for the three gauging stations. This means that disparities in solute production between the three sub-catchments in the Narrator catchment are very small. Solute yield at St 11 is 12.7% greater than solute yield at St 21, but this is almost entirely accounted for by an 11.4% increase in estimated runoff at St 11. Runoff at St 1, on the other hand, is 17.1% less than at St 11 while solute yield is only 6.2% less. This suggests that production of solutes per unit area is greater in the forested region of the catchment than in the moorland or grassland regions. This could be due to the effect of forest increasing rates of rock weathering. Alternatively the forest may be responsible for locally enhancing atmospheric fallout.

The relatively small differences in solute yield between sub-catchments in the Narrator Brook, despite the contrasts in vegetation, soil and topography between the sub-catchments, supports the conclusions reached by Miller (1961) and Walling & Webb (1975) that rock type is the predominant control governing spatial variations in solute yield.

7.3 Spatial Models

Several attempts have been made to model observed spatial variations in both sediment and solute yields with the aim of predicting yields from ungauged catchments. These models take the form of multiple regression equations which include an assortment of climatic, geological, physiographic, vegetational and pedological variables. A major obstacle encountered in such attempts is successful quantification of the controlling factors. This is less of a problem with respect to physiography and climate because the influence of these two factors upon sediment and solute yields is relatively well defined. For this reason climatic and physio-
graphic variables are the most frequently employed in regression equations, although these two factors are not necessarily the most important. Quantification of geology, vegetation and soil poses a far more acute problem. The relationships of sediment and solute yields to these factors are more subtle and less thoroughly understood. For example, the protection afforded the soil by vegetation is complex and many sided from enhancement of surface infiltration to dispersion of rainfall energy and consequently is virtually impossible to index effectively in terms of measurable vegetation characteristics (Stocking & Elwell 1976).

Another problem arises from the heterogeneity of stream catchments with respect to one or more of the environmental factors which influence sediment and solute yields. Even over very small catchments slope angles and slope lengths may vary considerably. In larger catchments spatial variations in vegetation characteristics can be expected and in still larger catchments precipitation characteristics and other climatic characteristics also vary spatially to a significant degree. Lumped mean catchment values for physiography and other factors have to be used in the regression models. Sediment and solutes transported by streams may be derived from a relatively localised regions of the catchment. Research by Kirby & Chorley (1967), Betson & Marius (1969), Dunne & Black (1970) and others indicates that, in humid climates at least, the surface runoff which is responsible for transporting sediment from catchment slopes to the stream channel is not distributed evenly over stream catchments but is restricted to certain favoured locations. Consequently mean catchment values for physiographic and other factors may be entirely unrepresentative of those regions of the catchment actually producing sediment and solutes for stream transport.

The wide range in the number and type of independent variables used in the regression equations listed in table 7.11 is symptomatic of the complexities involved in sediment and solute yield prediction, and the lack of consensus re-
Table 7.11 Regression equations for prediction of sediment and solute yields from ungauged catchments applied to the Narrator catchment. (Actual annual yields of sediment and solutes from the Narrator catchment are approximately 4 and 40 t/km$^2$ respectively).

<table>
<thead>
<tr>
<th>Sediment Yield</th>
<th>Predicted Yield for Narrator catchment (t/km$^2$/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Source</strong></td>
<td><strong>Intended Applicability</strong></td>
</tr>
<tr>
<td>log $SS = 2.65 \log P + 0.46$</td>
<td>Fournier World</td>
</tr>
<tr>
<td>$\log A = 1.56$</td>
<td>1960</td>
</tr>
<tr>
<td>$\log SS_B = 1.124 \log P + 1.733$</td>
<td>Douglas Eastern</td>
</tr>
<tr>
<td>$\log B = 1.107$</td>
<td>1973</td>
</tr>
<tr>
<td>$\log SS_C = 1.0207 \log Q + 2.0678$</td>
<td>Fleming</td>
</tr>
<tr>
<td>$\log A = 1.125 \log A + 0.585$</td>
<td>Jansen &amp;</td>
</tr>
<tr>
<td>$\log H = 1.104 \log L + 3.056$</td>
<td>Painter</td>
</tr>
<tr>
<td>$\log P = 3.053 V - 3.055$</td>
<td>1974</td>
</tr>
<tr>
<td>$\log SS_s = 0.5532 \log S - 0.5859$</td>
<td>McPherson Alberta, Can.</td>
</tr>
<tr>
<td>$\log A_d + 0.8332 \log CL + 1.3788$</td>
<td>1975</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Solute Yield</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1975</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Units</th>
<th>Explanation</th>
<th>Value for Narrator catchment</th>
</tr>
</thead>
<tbody>
<tr>
<td>$SS_a$</td>
<td>t/km$^2$/yr</td>
<td>Yield of suspended solids</td>
<td></td>
</tr>
<tr>
<td>$SS_b$</td>
<td>m$^3$/km$^3$/yr</td>
<td>Yield of suspended solids</td>
<td></td>
</tr>
<tr>
<td>$SS_c$</td>
<td>t/yr</td>
<td>Yield of suspended solids</td>
<td></td>
</tr>
<tr>
<td>$SS_d$</td>
<td>tons/mi$^2$/yr</td>
<td>Yield of suspended solids</td>
<td></td>
</tr>
<tr>
<td>DS</td>
<td>tons/mi$^2$/yr</td>
<td>Yield of dissolved solids</td>
<td></td>
</tr>
<tr>
<td>$P$</td>
<td>mm</td>
<td>Mean precipitation for wettest month</td>
<td>188</td>
</tr>
<tr>
<td>Symbol</td>
<td>Units</td>
<td>Explanation</td>
<td>Value for Narrator Catchment</td>
</tr>
<tr>
<td>--------</td>
<td>-------</td>
<td>-------------</td>
<td>-----------------------------</td>
</tr>
<tr>
<td>P</td>
<td>mm</td>
<td>Mean annual precipitation</td>
<td>1568</td>
</tr>
<tr>
<td>MR</td>
<td>m</td>
<td>Mean relief (difference between mean altitude and minimum altitude)</td>
<td>113</td>
</tr>
<tr>
<td>A_a</td>
<td>km²</td>
<td>Drainage area</td>
<td>4.68</td>
</tr>
<tr>
<td>A_b</td>
<td>mi²</td>
<td>Drainage area</td>
<td>1.81</td>
</tr>
<tr>
<td>B</td>
<td></td>
<td>Mean bifurcation ratio</td>
<td>3.55</td>
</tr>
<tr>
<td>Q</td>
<td>cusecs</td>
<td>Mean annual discharge</td>
<td>5.0</td>
</tr>
<tr>
<td>H</td>
<td>m</td>
<td>Mean altitude</td>
<td>334</td>
</tr>
<tr>
<td>R</td>
<td>m</td>
<td>Relief (difference between maximum and minimum altitude)</td>
<td>233</td>
</tr>
<tr>
<td>L</td>
<td>km</td>
<td>Drainage basin length</td>
<td>3.17</td>
</tr>
<tr>
<td>V</td>
<td></td>
<td>Vegetation index (forest-4; grassland-3)</td>
<td>3.1</td>
</tr>
<tr>
<td>S</td>
<td>°</td>
<td>Mean slope</td>
<td>7.95</td>
</tr>
<tr>
<td>CL</td>
<td>mi</td>
<td>Main channel length</td>
<td>2.16</td>
</tr>
<tr>
<td>BD</td>
<td>mi</td>
<td>Drainage basin diameter</td>
<td>2.00</td>
</tr>
</tbody>
</table>

a One of four separate equations for different vegetation categories.
b One of five separate equations for different climate and relief categories.

garding the most important controls reflects the state of the art. According to Slaymaker & McPherson (1973), as a result of these problems predictive equations are not sufficiently robust to be applied beyond the group of catchments upon which they are based. Five regression equations which appear in the literature for prediction of sediment yield were applied to the Narrator catchment in order to compare predicted yields with actual yield (table 7.11). Predicted sediment yields for the Narrator catchment vary over two orders of magnitude from 4 035 t/km²/yr with Fournier's (1960) equation to 34 t/km²/yr using Jansen & Painter's (1974)...
equation. None come close to the value of 4 t/km² discharged from the Narrator catchment over the period of observation which itself is probably an overestimate of actual contemporary mean annual sediment yield.

Predictive equations for solute yield are far less common than sediment yield. This is because rock type, which is the major factor determining spatial variations in solute yield, is difficult to quantify effectively. The only equation to predict solute yield which the present author has come across is that of McPherson (1975) which does not include rock type among the independent variables (table 7.11). Although, the predicted yield of solutes from McPherson's (1975) equation at 30 t/km²/yr is close to the probable mean annual yield from the Narrator catchment of around 40 t/km²/yr this does not inspire any real confidence in the value of predictive equations in general.

Until a deeper understanding of the spatial variations in sediment and solute yields is achieved, reliance must be placed upon results from representative catchments. Although the Narrator catchment is fairly representative of the Dartmoor environment it cannot be expected that sediment and solute yields from the Narrator catchment will precisely match those of all other catchments on Dartmoor. Nevertheless, there can be little doubt that yields from the Narrator catchment will provide a better approximation of yields from ungauged catchments on Dartmoor than any available predictive equations.
3.1 Sediment and solute sources

In order to determine supply of sediment from channel banks, an attempt was made to measure rate of bank erosion by the use of erosion pins. Results show that during the period of observation 14.1 t of sediment was supplied by bank erosion along the main channel of the Narrator Brook which is 3.46 Km in length. The greater part of the sediment supplied (11.9 t or 34.4% of the total) originated from the lower section of the Narrator Brook which passes through coniferous forest plantation. This section, which is 1 Km in length, appears to be undergoing accelerated bank erosion as a direct result of afforestation. Supply of sediment from channel banks in the forest section of the Narrator Brook is equivalent to 62% of total sediment exported from the Narrator catchment. This is likely to be an overestimate of the contribution to sediment transport from bank erosion because no allowance is made for storage of sediment in the channel. The proportion of eroded sediment stored probably increases with increasing particle size. The percentage of particles larger than 75μ in bank material along the forest section of the Narrator Brook is 51%, based upon analysis of 10 samples. This means that around 6 t of sediment larger than 75μ was supplied from eroding banks in the forest section of the Narrator Brook during the period of observation. Export of sediment larger than 1 mm in size from the Narrator catchment during this period, however, is only 5.8 t (5.4 t in suspension and 0.4 t as bedload). Storage of coarse sediment on the stream bed in the forest section is evidenced by aggradation during the period of observation averaging about 2.4 cm over the section as a whole.

In addition to comparing contemporary rate of bank erosion with contemporary sediment transport, an alternative method of assessing the contribution of sediment from eroding banks in
the forest section of the Narrator Brook is by comparing long term erosion rate with long term sediment transport. Extrapolation of the relation between bankfull width and drainage area for the channel above the forest indicates that mean channel width in the forest section prior to afforestation averaged 2.5 m in comparison to 3.4 m at present. Channel widening has therefore involved an average annual supply of sediment in the region of 35 t/yr. This is greater than supply during the period of observation suggesting that supply from this source is declining. Mean annual transport of fine sediment (< 75μ) from the Narrator catchment, estimated from reservoir sedimentation over a 50 year period, is 109 t/yr. Since this is greater than transport of fine sediment during the period of observation (13.4 t), transport of fines appears to be declining. If it is assumed (based upon analysis of 10 samples) that about 50% of eroding bank material is finer than 75μ then mean annual supply of fine sediment from bank erosion in the forest section of the Narrator Brook is only about 20% of total fine sediment transported. The overall conclusion, therefore, from measurements of both contemporary and long term rates of bank erosion in the forest section of the Narrator Brook, is that although this may form a major source of coarse sediment exported from the Narrator catchment it is only a relatively minor source of fine sediment.

Another possible source of fine sediment is sheet erosion of catchment slopes. Supply of sediment from this source was not measured directly. Soil well observations, however, indicate that saturation overland flow in moorland regions of the catchment, which account for 68% of total catchment area, is both frequent and widespread. Saturation overland flow was recorded on at least one occasion at 9 of the 11 sites located in the moorland region of the catchment. Overland flow from moorland regions enters the channel network of the Narrator Brook via the North Fork, South Fork, Yellowmead Brook and Sheepstor Beck, and thus provides a vehicle for transporting fine sediment eroded from catchment slopes to the stream channel. Saturation
overland flow was not observed at any of the 9 sites located in the grassland and forest regions of the catchment. However, saturation to within 20 cm of the surface occurred at 6 sites and saturation overland flow probably does occur in localized areas where conditions are favourable. Overland flow also occurs without saturation to the surface on Landrover tracks and also in localities where surface infiltration has been reduced by heavy trampling.

Other possible important sources of sediment include ephemeral channels, Landrover tracks which discharge storm water into stream channels, and cattle crossing points along the Narrator Brook and its tributaries.

The two sources for stream solutes in the Narrator catchment are rock weathering and atmospheric fallout. The relative contribution of these two was determined by comparison of the chemical compositions of stream water, bulk fallout and Dartmoor Granite. Chloride, sulphate, bicarbonate and nitrate, which together account for 51% of total solutes, are very rare in Dartmoor Granite and hence are supplied almost exclusively by atmospheric fallout. Conversely, silica and iron, which together account for 15.7% of total stream solutes, are very rare in bulk fallout and hence are supplied almost exclusively by weathering of Dartmoor Granite. Sodium, magnesium, calcium and potassium are supplied from both sources. While sodium and magnesium are supplied mainly from atmospheric fallout (71% and 70% respectively), calcium and potassium are supplied mainly from rock weathering (68% and 67% respectively). Overall, 70.1% of total stream solutes can be attributed to atmospheric fallout.

Stream solutes supplied from the atmosphere in the Narrator catchment originate mainly from sea spray. Sodium and chloride, the major ions in sea-water, together account for 77.7% of total solutes in bulk atmospheric fallout. However, sea spray is not the only source. Calcium and potassium comprise larger proportions in precipitation than in sea-water. The additional supply of these ions is probably from wind blown soil particles. Sulphate also comprises a larger proportion in bulk fallout than in sea-water. This
may be attributable to atmospheric pollution.

The predominance of the atmosphere as a source of solutes in the Narrator catchment is not unexpected in view of its location in a highland region close to a windward coast. For catchments in this situation accurate estimation of the atmospheric contribution to stream solutes is critical for obtaining reliable rates of chemical denudation. This can only be achieved by monitoring bulk fallout. Subtracting sodium and chloride from total stream solutes to calculate chemical denudation in the manner of Walling & Webb (1978) is inadequate for the Narrator catchment.

8.2 Temporal variations in sediment and solute transport

Rate of transport of bed material is governed by stream power which can be conveniently represented by stream discharge. Temporal variations in bedload transport by the Narrator Brook were successfully defined (83% explanation of observed variance) on the basis of a simple rating curve. The relation of bedload transport \( Y \) to peak discharge \( X \) is given by:

\[
\log e^Y = 0.00026 (\log e^X)^5 - 2.01
\]

No thresholds in bedload transport are apparent in the Narrator Brook; transport continues during baseflow although rate of transport at these times is very slow.

Particles in suspension larger than around 300\( \mu \) in size are derived largely from bed material. As in the case of bedload, transport of bed material in suspension is governed by stream power and is closely related to stream discharge. However, particles larger than 300\( \mu \) account for only 7.7% of total suspended sediment transported by the Narrator Brook. Stream discharge provides relatively little explanation of variance in total suspended sediment concentrations. Suspended sediment concentrations are higher on the rising stage of flood events at a given discharge than on the falling stage. Sediment concentrations are also higher in summer for a given discharge than in winter. Separation of
sediment concentration data according to season and stage of the hydrograph improves the relation between sediment concentration and discharge to some extent but the rating curve approach cannot be considered adequate for predicting rates of suspended sediment transport in the Narrator Brook. The heterogeneity of sources for suspended sediment in the Narrator catchment necessitates a multivariate approach to this problem.

The principle control to emerge from multivariate analysis of mean discharge weighted sediment concentration of quickflow at all three gauging sites on the Narrator Brook is maximum two hour precipitation. This factor explains 59%, 48% and 35% of variance in mean quickflow concentration at Sts 1, 11 and 21 respectively. In contrast peak discharge explains only 0.5%, 0.5% and 2.9% of variance in mean quickflow sediment concentration at Sts 1, 11 and 21 respectively. This is clear evidence that the major source of suspended sediment transported by the Narrator Brook is from above stream water level rather than below it. Precipitation intensity determines the erosivity of precipitation acting upon catchment slopes, dry channels, and channel banks exposed above stream level.

A subordinate control of mean quickflow sediment concentration at St 1 is antecedent baseflow discharge. This parameter is generally employed in studies of stream sediment dynamics as an index of catchment wetness and its significance is interpreted in terms of supply of sediment from catchment slopes. In the Narrator catchment antecedent precipitation, which is a more sensitive measure of catchment wetness, is outweighed by antecedent baseflow discharge in multiple regression analysis of flood period sediment concentrations. This suggests that the significance of antecedent baseflow discharge in the Narrator catchment is related in part, at least, to the supply of sediment from channel banks. At a lower antecedent baseflow discharge a greater area of stream bank is submerged for a given increment of discharge over the flood event. A multiple re-
gression equation including precipitation intensity \(X_1\) and antecedent baseflow discharge \(X_2\) can predict mean quickflow concentration at St 1 \(Y\) within \(\pm 0.986\) log units with 95% confidence.

\[
\log_e Y = 2.81 + 1.11 \log_e X_1 - 0.48 \log_e X_2
\]

This equation can be used to determine mean annual sediment yield from the Narrator catchment as a whole by reference to long term precipitation and flow records for the catchment.

At Sts 11 and 21 antecedent baseflow discharge fails to contribute significantly to explanation of variance in mean quickflow sediment concentration; maximum two hour precipitation is the only significant control. This may signify that supply of sediment from bank erosion is concentrated between Sts 11 and 1 in the forest section of the Narrator Brook. This supports the results of bank erosion pin observations and analysis of downstream variations in channel width.

The mean discharge weighted specific conductance of quickflow in the Narrator Brook is not as variable as mean sediment concentration of quickflow. However, variations in mean quickflow specific conductance are more difficult to account for. Although atmospheric fallout is the major source of solute transport, there is no significant correlation between the mean specific conductance of quickflow and the specific conductance of the precipitation which generates the quickflow. This is because the catchment acts as a buffer absorbing large variations in the specific conductance of precipitation and maintaining the specific conductance of stream water at near constant levels. For 14 of the 37 major flood events which occurred during the period of observation, mean quickflow specific conductance does not differ significantly from the normal baseflow value of 55.5 \(\mu\)mhos. For 7 small flood events following dry periods mean quickflow specific conductance exceeds the baseflow value of 55.5 \(\mu\)mhos. In each case quickflow runoff for the event and over the preceding 10 days is less than 25 000 \(m^3\). This is interpreted as flushing of solutes from the catchment,
which have accumulated during the dry period prior to the flood event. However, a further 8 small flood events which follow dry periods do not record a mean quickflow specific conductance exceeding baseflow for reasons which are not clear. Seven flood events record a drop in mean quickflow specific conductance below the baseflow value of 55.5 µmhos. In all cases quickflow runoff for the event plus quickflow runoff in the preceding ten days exceeds 25 000 m³. However this cannot be regarded as a simple dilution effect since for one of the events the specific conductance of precipitation exceeds that of baseflow.

Modelling temporal variations in solute concentrations to obtain an estimate of mean annual solute yield from long term precipitation and stream flow records is not necessary. Variations in specific conductance over flood events in the Narrator Brook tend to average out to a mean value which does not differ greatly from the baseflow value of 55.5 µmhos. This means that mean annual solute yield can be estimated by simply combining baseflow solute concentration with mean annual runoff.

8.3 Spatial variations in suspended sediment and solute transport

As a result of its small areal extent, inputs of precipitation and bulk fallout to the Narrator catchment can be considered to be spatially uniform. This means that downstream variations in sediment and solute concentrations and contrasts in unit area sediment and solute yields between sub-catchments can be related directly to spatial variations in catchment characteristics. Since the Narrator catchment is underlain by a single rock type, catchment characteristics which vary spatially are limited to vegetation, soil type, topography and channel characteristics.

The most prominent feature of downstream variations in mean baseflow suspended sediment concentration along the Narrator Brook are the high values for Sts 29, 28 and 27.
close to the source of the stream. High mean concentrations exceeding 1 mg/l at these stations are due to influx of colloidal material from the marshes which border the stream in this vicinity. Between Sts 27 and 25 this colloidal material is filtered from the stream by weeds on the stream bed. Below St 25 mean baseflow suspended sediment concentrations are all below 1 mg/l. Downstream variations in mean sediment concentration below St 25 are gradual and mean concentration at a station is largely a reflection of the concentration at the next station upstream. Differences in mean concentration between stations are related to the gradient of the intervening channel section. Mean concentrations tend to decline downstream along channel sections with steep gradients, possibly as a result of settling out of suspended sediment in plunge pools during baseflow periods. A multiple regression equation with mean sediment concentration at the adjacent upstream station (x₁) and the gradient of the intervening channel section (x₂) as independent variables can be used to predict mean baseflow sediment concentration at a station (y) within ± 0.13 mg/l with 95% confidence.

\[ y = 0.189 + 0.734x₁ - 0.00154x₂ \] (Data from Sts 30-26 are excluded).

Besides channel gradient, another factor of some importance with respect to baseflow suspended sediment, which helps to explain some of the discrepancy between observed and predicted baseflow sediment concentrations, is the formation of debris dams. Debris dams between Sts 16 and 15 may be responsible for depressing mean baseflow sediment concentration at St 15 from a predicted value of 0.50 mg/l to an observed value of 0.34 mg/l.

The main feature of downstream variations in mean baseflow specific conductance along the Narrator Brook is a rising trend below St 13 from 48.8 umhos at St 13 to 55.7 umhos at St 1. This is clearly linked to the presence of the forest plantation. The proportion of forest area to total catchment area explains 94% of the variations in specific conductance below St 13. The increase in baseflow specific conductance in the forest section of the Narrator Brook could
be due to one or a combination of increased evapotranspiration, rock weathering, or atmospheric fallout in the forest region of the catchment relative to moorland or grassland regions.

Above St 13, mean baseflow specific conductance varies little from 48 μmhos except in the section between Sts 29 to 27 where values range from 48.9 μmhos to 49.1 μmhos. These higher values are due to inflow from marshes bordering this section of the channel.

Yield of suspended sediment or solutes is the product of concentration and runoff. Differences in suspended sediment and solute yields for the three gauging sites on the Narrator Brook are due in part to differences in recorded runoff at the three sites (1312 mm, 1582 mm and 1420 mm for Sts 1, 11 and 21 respectively). These differences in runoff may be partly a result of inaccuracy in the estimation of runoff introduced mainly through extrapolation of discharge rating curves. However the low runoff at St 1 in comparison to St 11 can be explained by influent seepage in the channel between Sts 11 and 1.

Differences in sediment yield for the three gauging sites (4.0 t/km², 5.2 t/km² and 3.3 t/km² for Sts 1, 11 and 21 respectively) are greater than differences in runoff and thus represent contrasts in sediment production among the three sub-catchments. The increase in sediment yield at St 11 relative to St 21 is probably a result of higher grazing density in the grassland region of the catchment which forms 16% of the catchment area above St 11 in comparison to only 1% above St 1. Heavily trampled ground, particularly if close to the stream channel as in the case of cattle crossing points, may be an important source of sediment. Bank erosion between Sts 13 and 11 provides an additional supply of sediment. Sediment yield at St 1 is not as great as might be expected considering both the network of ephemeral streams between Sts 1 and 11 and the eroding banks along the main channel. This apparent inconsistency can be explained, at least to some extent, by aggradation along the main channel.
between Sts 1 and 11.

Differences in solute yields for the three gauging stations (54.9 t/km², 58.5 t/km² and 51.9 t/km² for Sts 1, 11 and 21 respectively) are less than differences in sediment yield, and correspond more closely to differences in runoff. Rock type, which is uniform over the Narrator catchment, is the predominant factor controlling yield of solutes. Vegetation, land use and channel characteristics appear to have much less influence upon solute yield than upon sediment yield. Nevertheless, solute yield is a little greater at St 1 than would be expected simply from runoff indicating that solute production in the forest region of the catchment is higher than in moorland or grassland regions. This can be traced to impaction of atmospheric salts, although rates of weathering may also be greater in the forest.

The complexity of the processes operating and the multiplicity of factors involved, many of them difficult to quantify, have defied efforts to model rates of fluvial transport successfully in terms of environmental controls. At present, probably the most realistic approach to estimating the sediment or solute yield of an ungauged catchment is by reference to measured yield from a representative catchment which can be judged broadly similar with respect to environmental setting. Measured yields from the Narrator catchment serve as useful guide to estimating approximate yields for other catchments on the granite area of Dartmoor.

8.4 Rates of denudation

In order to compute reliable rates of denudation from stream sediment and solute yields two adjustments have to be implemented. The first, which relates particularly to computation of chemical denudation from solute yields, is deduction of the non-denudational component of total solute yield contributed from the atmosphere. The greater the
proportion of total stream solutes originating from the atmosphere the more crucial its accurate estimation. In the case of suspended sediment the total yield can be regarded as denudational. Waylen (1979) reports that in a Mendips catchment particulate matter in atmospheric fallout can contribute substantially to stream sediment yield. However, following Waylen (1979) it may be assumed that dust supplied to the catchment from the atmosphere is balanced by dust released to the atmosphere from the catchment surface.

The second adjustment, which relates principally to computation of mechanical denudation from stream sediment transport, concerns approximation to long term mean annual yields. Rate of denudation is, by implication, representative of an extended period of time. Often in the literature denudation rates are quoted in mm/1000 years. Denudation rates which are not representative of the long term have little geomorphic significance. Sediment transport by the Narrator Brook fluctuates considerably. Suspended sediment discharge over the period of observation ranged from 131 to 0.03 gm/s. In one 24 hour period 2.6 tonnes of suspended sediment was discharged representing 13.5% of the total yield over 19 months. In this situation several years of observation are required to obtain a reliable estimate of mean annual sediment yield for computation of mechanical denudation rate. Reservoir sedimentation can provide a very valuable short cut to estimating mean annual yields and has been employed on several occasions to determine denudation rates for catchments in Great Britain (e.g. Young 1958, Cummins & Potter 1972, Ledger et al 1974). The Burrator Reservoir has been collecting sediment from the Narrator Brook and neighbouring streams since 1895. A volumetric survey of the sediment in the reservoir undertaken by the South West Water Authority in 1950, after adjustments for silt density and reservoir trap efficiency, indicates a mean annual inflow of sediment amounting to 24.3 t/km²/yr over the period 1895 to 1950. This is appreciably greater than the 4.02 t/km² discharged from the Narrator catchment over the 19 months of observation from May 1975 to December 1976.
Total yield over the period of observation, which probably exceeds mean annual yield gives a computed contemporary rate of mechanical denudation (from equation 1.1) of no more than 1.5 m³/km²/yr or mm/1 000 yr in comparison to a value of 9.2 m³/km²/yr or mm/1 000 yr derived from reservoir sedimentation up to 1950. Bedload transport in the Narrator Brook is only 2% of suspended sediment transport and does not materially affect the computed rate of mechanical denudation. Mean annual solute yield can be approximated by combining mean annual runoff with baseflow solute concentration. This gives a figure of 39 t/km²/yr. After subtraction of the non-denudational component of 70.1%, chemical denudation for the Narrator catchment is calculated at 4.4 m³/km²/yr or mm/1 000 yr.

Rates of denudation for the Narrator catchment can be usefully compared to rates established for other small catchments in Britain. In Britain, where precipitation is of low intensity and spread evenly over the year, rates of mechanical denudation are generally low in comparison to other climates, but the contemporary rate of denudation for the Narrator catchment appears low even by British standards (table 8.1). This can perhaps be attributed to the management of the Narrator catchment which restricts commercial land use to low intensity grazing and forestry thereby maintaining a dense continuous ground cover. The higher rate of denudation computed from sedimentation in the Burrator reservoir may be a result of higher rates of soil loss during the period when the reservoir catchment was privately owned farmland. The very sensitive response of mechanical denudation to land use means that differences in denudation rates between catchments in Great Britain cannot be accorded any real long term geomorphic significance. Some of the higher rates of mechanical denudation listed in table 8.1 undoubtedly reflect accelerated erosion within the catchment. The Hodge Beck catchment, for example, is characterised by active gullying (Imeson 1969).

Chemical denudation is less sensitive to land use and
Table 8.1 Rates of mechanical denudation for small catchments in the British Isles.

<table>
<thead>
<tr>
<th>Catchment</th>
<th>Rate of Mechanical Denudation (m³/km²/yr or mm/1000 yr)</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Narrator Brook, Devon</td>
<td>1.5 (contemporary rate)</td>
<td>Young 1958</td>
</tr>
<tr>
<td>Burrator Reservoir, Devon</td>
<td>9.2 (average rate 1985-1950)</td>
<td>Cummins &amp; Potter 1967</td>
</tr>
<tr>
<td>Strines Reservoir, Yorkshire</td>
<td>130</td>
<td>Hall 1967</td>
</tr>
<tr>
<td>Cropston Reservoir, Leicestershire</td>
<td>12.9</td>
<td>Imeson 1969</td>
</tr>
<tr>
<td>Catclough Reservoir, Northumberland</td>
<td>114</td>
<td>Imeson 1969</td>
</tr>
<tr>
<td>Catchwater Drain, Yorkshire</td>
<td>3.4</td>
<td>Slaymaker 1972</td>
</tr>
<tr>
<td>Drewton Beck, Yorkshire</td>
<td>0.4</td>
<td>Gregory &amp; Walling 1973</td>
</tr>
<tr>
<td>Hodge Beck, Yorkshire</td>
<td>181</td>
<td>Oxley 1974</td>
</tr>
<tr>
<td>Upper Wye Valley, Wales</td>
<td>18.1</td>
<td>Potter 1973</td>
</tr>
<tr>
<td>Five small Devon catchments</td>
<td>3.8 - 20.8</td>
<td>Ledger et al 1974</td>
</tr>
<tr>
<td>Ebyr North, Wales</td>
<td>0.3</td>
<td>Ledger et al 1974</td>
</tr>
<tr>
<td>Ebyr South, Wales</td>
<td>0.4</td>
<td>Waylen 1979</td>
</tr>
<tr>
<td>Blackbrook, Leicestershire</td>
<td>8.8</td>
<td></td>
</tr>
<tr>
<td>North Esk Reservoir, Scotland</td>
<td>12.8</td>
<td></td>
</tr>
<tr>
<td>Hopes Reservoir, Scotland</td>
<td>11.8</td>
<td></td>
</tr>
<tr>
<td>East Twin Brook, Mendips</td>
<td>1.0</td>
<td></td>
</tr>
</tbody>
</table>

consequently inter-catchment comparisons are more meaningful in geomorphic terms. The rate of chemical denudation for the Narrator catchment, which can be considered representative of Dartmoor Granite, is relatively low in comparison to other rock types in Britain (table 8.2). It is comparable to rates of chemical denudation for old resistant sedimentary
Table 8.2 Rates of chemical denudation for different rock types in Britain.

<table>
<thead>
<tr>
<th>Rock Type/Location</th>
<th>Rate of Chemical Denudation (m^3/km^2/yr or mm/1000 yr)</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Granite, Dartmoor</td>
<td>4.4</td>
<td>Oxley 1974</td>
</tr>
<tr>
<td>Silurian greywackes, Mid-Wales</td>
<td>1.9</td>
<td>Waylen 1979</td>
</tr>
<tr>
<td>Devonian sandstone, Mendips</td>
<td>1.6</td>
<td></td>
</tr>
<tr>
<td>Various sedimentary, Devonian to Permian, Exe River Basin</td>
<td>2 - 100</td>
<td>Walling &amp; Webb 1978</td>
</tr>
<tr>
<td>Limestone, S. Pennines</td>
<td>75 - 83</td>
<td>Pitty 1968</td>
</tr>
<tr>
<td>Limestone, Cheddar</td>
<td>80 - 102</td>
<td>Smith &amp; Newson 1974</td>
</tr>
<tr>
<td>Chalky boulder clay, E. Yorkshire</td>
<td>51.8</td>
<td>Imeson &amp; Ward 1972</td>
</tr>
</tbody>
</table>

Rocks which form the Mid-Wales Highlands and the Mendip Hills, but appreciably lower than the younger less resistant sedimentary rocks of the Exe River Basin. Highest chemical denudation rates of all occur in calcareous rocks, exceeding the rate for Dartmoor Granite by at least ten times. The relatively low rate for Dartmoor Granite is to be expected since according to Gorham (1961) chemical denudation of granite in Britain is slow in comparison to most sedimentary rocks. Furthermore, chemical denudation is slower for true granite, such as the Dartmoor Granite, where orthoclase is the dominant felspar, than for other members of the granite family (Garrels & McKenzie 1967). However, in warmer climates, granite appears to suffer greater chemical denudation. Rates of chemical denudation for granite in a moist tropical climate reported by Douglas (1968), are on a par with British limestone.

Acceleration of denudation rates as a result of human activities means that extrapolation of present measured rates through geologic time to assist in landscape interpretation must be approached with extreme caution. The solute system
is more robust than the sediment system in this regard. Nevertheless increase in precipitation acidity resulting from atmospheric pollution may boost natural rates of chemical denudation considerably (Johnson et al 1972). The apparent excess of sulphate in the Narrator Brook over and above that supplied in bulk fallout may indicate that accelerated chemical denudation is occurring in the Narrator catchment. However, since rates of both chemical and mechanical denudation for the Narrator catchment are small in comparison to other catchments in Britain acceleration of denudation rates is unlikely to be of major importance. Extrapolating the present rate of denudation for Dartmoor back through the Holocene, since the close of the Pleistocene some 10 000 years ago, notwithstanding climatic fluctuations during this period, total denudation (mechanical and chemical combined) has probably amounted to little more than 0.06 metres. Although this is unlikely to have been uniformly distributed over the catchment so that erosion in localised areas may have been much greater, the landscape as a whole can have changed little since the Pleistocene. This accounts for the comparative freshness of features resulting from periglacial processes operating during the Pleistocene. Relics of pre-Pleistocene landscapes have also been preserved on Dartmoor. Because of its durability Dartmoor has provided geomorphologists with unique clues in the reconstruction of the geomorphic history of Southern England. Through his activities on Dartmoor, in particular mineral exploitation, man has had a greater impact upon the landscape in a couple of centuries than 10 000 years of the undisturbed operation of geomorphic processes. This is consistent with Brown's (1979) view that physiographic evolution during the Holocene in Britain as a whole has been largely anthropogenic. The slow rate of denudation on Dartmoor is reflected in the general altitude of the region. Through differential erosion the granite area of Dartmoor has emerged as a highland region standing above the surrounding less durable sedimentary and metamorphic rocks. Walling & Webb (1978) discovered a
strong inverse correlation between chemical denudation and altitude within the Exe River Basin which they also interpreted in terms of differential erosion.

8.5 Practical implications

The slow rate of denudation in the Narrator catchment is reflected in the quality of runoff. Baseflow suspended sediment concentration in the Narrator Brook is generally below 1 mg/l and the clarity of stream water at these times is excellent. During flood periods sediment concentration and stream turbidity rise sharply, but these periods are of short duration. Flood periods accounted for only 9.7% of the total period of observation. Experiments conducted by the Water Pollution Research Laboratory (1961) reveal that suspended sediment concentrations in excess of 270 mg/l for an extended period can kill trout. Sediment concentration in the Narrator Brook exceeded 270 mg/l for a total period of less than an hour during the 19 months of observation imposing little real threat to the stream's trout population. Neither can sedimentation in the Burrator Reservoir be considered a problem. Accumulation of sediment in the reservoir occupies less than 2% of its original capacity, and if present rates are maintained at least 2 000 years will elapse before this capacity is reduced to half by sedimentation.

Despite Dartmoor's resistance to erosion when undisturbed, careful management is essential to preserve water quality and maintain low rates of sedimentation. Due to rapid saturation, peaty soils are susceptible to sheet erosion following damage to the protective cover of moorland vegetation. Several studies have reported very rapid rates of erosion on British peatlands as a result of heather burning or overgrazing (Tallis 1964, Curtis 1965, Imeson 1971a, Ledger et al 1974). The sandy growan which underlies surface peat is also subject to rapid rates of erosion once exposed. In 1962, in the catchment of the Newleycombe Lake adjacent to the Narrator catchment, an unlined drainage ditch was excavated in order to conduct overflow from the Devonport Leat.
into the stream channel. Once the overflow broke through the peat into the underlying growan erosion became very rapid and by 1976 approximately 4,500 m$^3$ of growan had been removed from the site creating a large gully. This gully has probably contributed in the region of 10% of total sediment accumulated in the Burrator Reservoir.

Although sediment production from the forested region of the Narrator catchment as a whole is probably not greatly in excess of moorland or grassland regions, it is apparent that afforestation has led to marked acceleration of bank erosion. This undesirable side-effect of afforestation can be avoided by leaving a strip of ground adjacent to stream channels unplanted. Since ground surface vegetation is sparse in forested areas, when the trees are harvested rapid rates of erosion are likely to follow. Several studies have reported large increases in sediment yield from catchments which have undergone timber harvest (Lull & Rheinhart 1963, Fredricksen 1970, Pierce et al 1970, Megehan 1972). Forest in the Narrator catchment has never previously been harvested, but soon after completion of the present research logging activities were commenced. Observed sediment yields during the period of research provide a yardstick by which to gauge the impact of these activities upon sediment transport rates.

With respect to dissolved solids, even before purchase of the Burrator catchment by Plymouth Corporation, stream water was "exceedingly pure, approaching rainwater in softness" (Sandeman 1901). Concentration of total dissolved solids in the Narrator Brook is at all times well below the highest desirable level of 500 mg/l recommended by the World Health Organisation for drinking water (Henderson-Sellars, 1979). All individual constituents are also well within acceptable limits except iron. The relative mobility of iron in the Narrator Brook is greater than normally reported from granite catchments as a result of its combination with colloidal humus which discolours stream water during flood periods. Concentration of iron in the Burrator Reservoir is almost always in excess of the highest desirable level of 0.1 mg/l, occasionally exceeding the maximum permissible
level of 1.0 mg/l, and Burrator water has to be treated with alum to remove iron in colloidal suspension. Weed on the bed of the Narrator Brook regulates transport of this colloidal material effectively limiting it to flood periods. During baseflow it is almost entirely filtered from the stream water by the weeds. In view of the detrimental effect of iron upon water quality this phenomenon deserves closer scrutiny.

Forest cover in the Narrator catchment is responsible for locally raising mean baseflow solute concentrations from a background concentration of 49.0 umhos in the moorland and grassland regions of the catchment to 110.8 umhos. This need not influence management policy on Dartmoor where low rates of chemical denudation mean that background solute concentrations are low. However, in catchments where background concentrations are higher, afforestation could well push the salinity of the stream beyond the maximum desirable level for drinking water. Careful design of the plantation can off-set this effect to some degree. In addition to the proportional area of the catchment to be forested attention should also be given to the length of forest perimeter. It appears from observation in the catchments of three streams flowing into the Burrator Reservoir that the impact of afforestation upon stream solute concentration is minimised in plantations which have a low ratio of forest perimeter to forest area.

8.6 Relative importance of sediment and solute loads

The yield of solutes from the Narrator catchment at 259 t greatly outweighs the 18.8 t of suspended sediment. After removal of the non-denudational component of stream solutes, the denudational component at 67.6 t still exceeds suspended sediment yield by three times. Comparison of global trends in sediment and solute by Gregory & Walling (1973) indicates that excess of solute yield over sediment yield is
to be expected in a humid temperate climate. However, it
appears from these trends, given a sediment yield of 4 t/km²
for the Narrator catchment, that the ratio of solute yield
to sediment yield should range from only 2.2 for plainlands
to 1.0 for mountainous regions. Separating the Narrator
catchment into three component sub-catchments, the highest
ratio of solute yield to sediment yield (15.6) occurs at St
21 above which the catchment area is almost entirely covered
by peat. For the sub-catchment areas above Sts 11 and 1,
which are only partially covered by peat, the ratios are
smaller at 11.7 and 13.8 respectively. These relatively
high ratios of solute yield to sediment yield for the
Narrator catchment may have some bearing upon the origin of
growan on Dartmoor which has been the subject of some con­
troversy in recent years. Despite the slow rate of weather­
ing under the cool climate of Dartmoor at present, continual
accumulation of decomposed granite may still be taking place,
particularly beneath a protective blanket of peat. This
lends support to the view expressed by Eden & Green (1971)
that Dartmoor growan is a product of climatic conditions
similar to present, rather than being a relic of a former
tropical climate.

The ratio of suspended sediment to total solutes dis­
charged from the Narrator catchment varied considerably over
the period of observation. On occasions, for brief periods
only, sediment yield overhauled solute yield. On 8/7/75 at
12.30 am, close to the peak of a small flood event generated
by a short duration high intensity rainstorm, sediment yield
exceeded solute yield by a factor of 5.3 (130.7 and 24.8 gm/s
respectively). At the other extreme, during low baseflow in
the Narrator Brook, sediment yield is generally exceeded by
solute yield by a factor of more than a 100 (0.02 and 2.5
gm/s respectively).

Overall, transport of sediment as bedload in the
Narrator Brook amounts to only 2.3% of the transport of sedi­
ment in suspension (0.43 and 18.8 t respectively over the
period of observation). This is in accord with observations
in other small catchments in Britain where bedload is insignificant in comparison to suspended load (Walling 1971a, Imeson & Ward 1972). With respect to long term denudation, therefore, bedload transport is relatively unimportant. Over individual flood events, however, the contribution of bedload to total sediment load varies considerably, depending upon the nature of the flood. The highest relative rate of bedload transport occurred during the period 3-17/2/76. This period included a single flood event which reached a peak discharge of 1 845 ℓ/s, but was generated by relatively low intensity precipitation (maximum 2 hr precipitation - 6.3 mm). Bedload transport during this period exceeded the capacity of the bedload trap, and thus accounted for at least 5.0% of total sediment transported during the period. By contrast, for the period 17-31/8/76, which included a single event of low peak discharge (169 ℓ/s), but generated by high intensity precipitation (maximum 2 hr precipitation - 21.0 mm), bedload comprised only 0.16% of total sediment transported.

Overall, therefore, stream solutes constitute the most important component of fluvial transport in the Narrator Brook, followed by suspended sediment, with bedload forming a very small proportion of the total.
APPENDIX I

DETAILED LONG PROFILE OF THE NARRATOR BROOK

The profile is separated into 30 sections between randomly selected stream sampling stations. Intervals on the vertical scale represent 1m and on the horizontal scale 10m. The lower line on the profile is the stream bed while the upper line is the water surface corresponding to normal baseflow.
APPENDIX II

BASIC DATA EMPLOYED IN MULTIVARIATE ANALYSIS
pnO[j
1-2/12/75

5- 7/10/76

1/11/76

5-8/12/76

1-2/12/76

66.8
55.5
55.5
55.5
57.4
50.0
55.5
55.5

5.5
12.7
3.7
6.6
12.9
17.5
4.2
20.2

1303

610

1079

623

526

528

646

2

'30/11-1/12/76

838

65.2

2.8

^

28-29/11/76

1202

72.7

15.9

-

6- 7/11/76

305

465

2125

s ssS

24-25/10/76

21/10/76

17-13/10/76

14.1V10/76

a/lO/76

58.1

63.5

37.3

3-4/10/76

66.5

526

98.6

35.5

30/9-1/10/76

s s

9.1

24A

62.9

2s

31.2

169
200

152.5

22.3

29/8/76
21-22/9/76

795

7 ,7

S

78.2

1459

51.8
50.7

31.1

ssS

21-22/3/76

12-13/3/76

12-13/2/76

3 s

30/1/76

28-29/1/76

1845

5.7

52.1

26.3

27- 2 8 / 1 1 / 7 5
28- 2 9 / 1 1 / 7 5

15.7

50.1
47.9

6.3

221

55.5
47.2

26.7

23-21/11/75
25-26/11/75

85.4

1713
1230

61.7

27.2

3/11/75

14.8

610
254

55.5

12.5

2/10/75

48 7

395

55.5

6.5

27/9/75

2146

244

55.5

11.6

25-26/9/75

55.5

208

55.5

32.3

13- 1 4 / 9 / 7 5

ss ss5S

65.4

376
300

55.5

11.1

IB-30/8/75

" - SS S 2 S 2

32.4

120
235

55.5

6.4

16-17/8/75

15/8/75

4-5/8/75

9ajn.p«,Q

21.8

101

55.5

37.4

p31<|3|an oSitnistio UTDH
96

( I/SB) noi J i s i n t )
68.7

Oo53
JB ai3/aoi|Bi It) f t o i j i i s i n t )
JO 3.iu*i3n(iun,-) 3 | j t 3 a d s
paii|D|>n a9j(m:)iio uoo^

72.1

(•/I)

22.5
12.4

6.1
5.9

10.8

5.6

10.3

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31.3

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7.0

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<td>Retention Potential 1</td>
<td>Overland Flow (m, of occurrence)</td>
<td>Organic Content of Matted A horizon (% dry weight)</td>
<td>Ill &amp; Clay Contents (% dry weight)</td>
<td>Altitude (feet above O.D.)</td>
<td>Slope (°)</td>
<td>Residual Physiographic Factor 2</td>
<td>Distance from Catchment Boundary (km)</td>
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1 total number of thistles filled over 18 period of observation (total possible = 108)
2 spreading slopes = 0 uniform slopes = 1 gathering slopes = 2
3 accelerating slopes = 0 straight slopes = 1 decelerating slopes = 2

11.5 Analysis of soil and topographic characteristics influencing soil saturation potential at 20 sites in the narrator catchment.
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<th>Location</th>
<th>pH</th>
<th>EC (dS/m)</th>
<th>TDS (mg/L)</th>
<th>Total Dissolved Sp. Cond. (µS/cm)</th>
<th>Ultrasound</th>
<th>Conductivity (µS/cm)</th>
<th>Heat Dissipation Specific (µS/cm)</th>
<th>Biotreatment Eff. (%)</th>
<th>Total Bio-Eff. Area (m²)</th>
<th>Total Stream Reach (m²)</th>
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Note: The table continues with similar data for other locations.
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<th>Stream Stage at St. 27 (ft)</th>
<th>Stream Stage at St. 39 (ft)</th>
<th>Seasonal Index</th>
<th>Antecedent Precipitation API 30 (cm)</th>
<th>Antecedent Suspended Sediment Discharge (lbs)</th>
<th>Multiple Correlation Coefficient</th>
<th>Suspended Sediment Concentration at St. 27 (mg/l)</th>
<th>Difference in Specific Conductance between Sts. 29 &amp; 30 (µmhos/cm at 25°C)</th>
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### Notes
1. Stage in each case is related to an arbitrary datum.
2. Calculated on a 30-day period basis as in the case of sediment precipitation.
3. Calculated by converting concentration to specific conductance for each sampling date with concentration data.

### Specific Conditions

**Catchment Exit**
- (Funnel Covered by Nylon Mesh)
- (Open Funnel)
- Control Catchment (Open Funnel)

**Sample Period**

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**Mean precipitation intensity (mm/hr.)**

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<td>( L )</td>
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\( L \) = length of forest margin (km).  
\( C_Y \) = stream baseflow solute concentration (\( \text{mg/L} \) at 25\(^\circ\)C).  
\( C_A \) = solute concentration of groundwater in non-forested region of catchment (\( \text{mg/L} \) at 25\(^\circ\)C).  
\( A_A \) = area of catchment unforested (\( \text{km}^2 \)).  
\( C_P \) = solute concentration of groundwater below forested region of catchment (\( \text{mg/L} \) at 25\(^\circ\)C).  
\( A_Y \) = area of catchment under forest (\( \text{km}^2 \)).

CT-10. Analysis of the effect of evapotranspiration by a forest cover upon downstream variations of baseflow solute concentrations in three streams draining to the Narrator Reservoir, July 1976.
<table>
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<th>TOTAL RUNOFF (mm)</th>
<th>TOTAL PERIOD SURFACE</th>
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<th>TOTAL ANNUAL CATCH</th>
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II. 12. Analysis of temporal variations in mean discharge weighted sediment concentration of quickflow at Sts 11 and 21, 26/5/75-13/12/76.
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