GEOMORPHIC AND HYDROLOGIC PROCESSES IN

COOMBS BROOK, MACCLESFIELD FOREST

by

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ABSTRACT

The sources of solutes and sediments entering the Coombs Brook in Macclesfield Forest, Cheshire, reflect the legacies of past climates, present day climate, land use, and the changing chemistry of precipitation. The legacies of past climates are related to Quaternary glacial deposits and periglacial loess which are actively being eroded by streams. Sixty per cent of the length of stream banks in Coombs Brook shows signs of erosional activity. Six processes contribute to the detachment and transport of soil material on stream banks and valley slopes: lateral corrasion (bank scour), subsoil fall, soil creep, overland flow, mass movement, and splash erosion. Sediment transfer out of the drainage basin dominantly occurred as suspended load (92%), while bedload contributed only 8%. Strong seasonal contrasts in bank erosion rate could be identified, with most material being removed between the months of November and April. The frost action consistently emerged as the variable most strongly active. The behaviour of suspended sediment concentration was extremely variable, and seven different types of response were recognised. The free availability of suspendable material appears to be an important limiting control on sediment concentration, and this, related to different responses, such as soil moisture, conditions the activity of bank erosion.

Present land use, largely as coniferous forest, affects the water chemistry. The pH of the throughfall had a mean pH of 3.9 ($0.126\ H^+$), indicating acidification as the rain washes through the coniferous trees.

Precipitation was weakly acidic (pH 5.2), dominated by H^+, Na^+, Cl^-, SO_4^{2-}, and NO_3^-: its composition varied in time. Stream water was alkaline (pH 7.5); Ca^{2+} and Mg^{2+} are relatively more important in stream water than in precipitation: Ca^{2+}, Mg^{2+}, Na^+ and pH vary in the same way; they decrease in concentration with increasing discharge, but NO_3^- tends to increase with increasing discharge. The concentration of K^+, Cl^-, SO_4^{2-} and PO_4^{3-} vary independently. The water balances reveal a net output of Ca^{2+} and Mg^{2+}, but a considerable proportion (about 70% Na^+, 88% K^+, 55% SO_4^{2-}, 94% PO_4^{3-}, 75% NO_3^-, and 56% Cl^-)

of the input of these elements does not pass out of the catchment in
solution.   Uptake of such nutrients in solution by a catchment system
is to be expected.   The budgets on a monthly scale show three differ-
ent patterns of input-output:

(a)   Those in which output exceeds input in every month (Ca^{2+}
      and Mg^{2+});

(b)   those in which input exceeds output (NO_3^-, Na^+ and Cl^-); and

(c)   those which show transition patterns (K^+ and SO_4^{2-}).

ACKNOWLEDGEMENTS

ABBREVIATIONS   USED

n.d.	not determined
O.D	Ordnance data
n.s.	not a significant correlation
Independent variable	Discharge
Dependent variable	Chemical species
s.s.c.	suspended sediment concentration (mg l^{-1})
dis (Q l s^{-1})	discharge
Con	Conductivity (μS cm^{-1}) unit
pH	pH unit
g	gas
Stand. Dev.	Standard deviation
M	Mean

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CHAPTER ONE

INTRODUCTION

1.1 THE CONTEXT OF THE STUDY

This dissertation reports the results of a study of sediment and solute sources and outputs in the Coombs Brook Catchment, in Macclesfield Forest, Cheshire, England. Such studies contribute to the understanding of geomorphic and hydrologic processes, but are also relevant to current practical problems of the impact of afforestation on drainage and sediment yield; the effects of acid precipitation on ecosystems, soils and streams; and the prediction of solute and pollutant behaviour in relation to stream discharge.

The relationship between dissolved solids concentrations and discharge in rivers has frequently been seen as an inverse association (Hem, 1970) with solute rating curves developed to calculate total dissolved loads and to predict pollutant concentrations and the quality of drinking water. Such knowledge of the solute loads of streams is now considered important for several reasons:

(i) Calculation of regional rates of chemical denudation facilitates comparisons between different areas and the assessment of the roles of such independent factors as climate and parent materials on solute discharges (e.g. Durum et al., 1960).

(ii) Studies at the local scale of small drainage basins help to identify the roles of vegetation and the nature of the hydrological cycle in solute discharges (e.g. Bormann et al., 1969).

(iii) Knowledge of the solute loads carried by streams into lakes, reservoirs and oceans helps estimate the environmental impact of pollutants, especially of non-point source discharges (e.g. Ongley et al., 1977).

(iv) Process rate investigations may indicate temporal and spatial
      variations in solute transfer and provide empirical data
      to test broad-scale theories of denudation rates (e.g.
      Schumm, 1963; Carson and Kirkby, 1972).

Rates of denudation may be assessed in a number of ways. For example,
many studies attempt to isolate the nature, magnitude and relative impor-
tance of specific processes in a single environment, usually on the basis
of hillslope studies including measurement of soil creep and surface wash
(e.g. Rapp, 1960; Young, 1963, 1969; Young and Saunders, 1986). One
of the most common methods of determining denudation rates is by means
of river water quality data collected systematically over a period of
months or, preferably, years. The exact time interval employed for
sample collection depends on a number of constraints, particularly the
size of the catchment and the rate at which streamflow responds to preci-
pitation. During periods of stable flow, samples collected on a daily
basis may be considered adequate, but intensive sampling is required
during individual flood events. Sampling must pay attention to seasonal
changes in the nature of precipitation, especially if there is winter
snowfall.

In order to compute total denudation rates, continuous streamflow
records must be used in conjunction with water quality data. The product
of instantaneous stream discharge and solute concentration, summed over
the year, will provide an estimate of total load removed from a drainage
basin above the point of sampling (Douglas, 1964). These studies do not
reveal, however, the relative significance of specific processes operating
within a drainage basin, and thus provide only a gross estimate of denuda-
tion rates for an entire area. If a drainage basin is large, and geolo-
gically complex, a study of material lost from a single point can only
reflect a general regional rate of process operation.

Identification of the significance of contemporary process rates is
by no means new. For example, Reade (1885), on the basis of water
chemistry data, calculated rates of denudation for many of the major river
basins in the two Americas. Calculation of denudation rates using river
chemistry data is common in the literature of most areas of the world
(e.g. Kazarinov et al. (1965) in the U.S.S.R.; Hembree and Rainwater
(1961) and Marchand (1971) in the U.S.A.; Brinson (1976) in Central
America; Douglas (1973) in Australia; Pulina (1972) in Poland; Rapp

(1960) in Finland; Arnett (1978) and Walling (1978) in the United Kingdom). Many of these studies attempt to map the spatial distribution of denudation rates and relate these areas to rates of weathering process associated with changing geological and environmental conditions (e.g. Walling and Webb, 1978).

A variety of data bases have been used to calculate total stream load in these studies, varying from collection of monthly streamflow and chemistry data to continuous measurements of specific conductance which are converted into values of total dissolved solids (Walling, 1978). With the exception of the latter investigation, few attempts have been made to assess the relative accuracy of different methods of load calculation, or the variability in estimates resulting from changes in the annual runoff regime.

Sediment-discharge relationships vary with the particle-size distribution of material supplied to the stream; the seasonal vegetation cover; the availability of material to be carried into suspension or transported as bed material load, and the degree, timing and nature of disturbance of the catchment by people. A wide variety of relationships have been observed, including lead or lag effects of peak sediment concentration in relation to peak discharge; a variety of forms of hysteresis loops with differing sediment loads on the rising and falling stages of storm runoff events; 'flushing' effects at the onset of storm runoff periods; and 'exhaustion' effects when one storm discharge event quickly follows another (e.g. Heidel, 1956; Guy, 1964; Dragoun and Miller, 1966; Kunkle and Comer, 1972; Gregory and Walling, 1973, pp.215-219; Allen, 1974; and Walling, 1974).

Further understanding and prediction of suspended sediment yields and their relationship with discharges and other significant factors should come from more realistic modelling of catchment sediment dynamics, as in the Stanford sediment model (Gregory and Walling, 1973, pp.231-232). The success of such models closely depends on, among other things, an adequate appraisal of the field processes. Here two sets of factors may be identified. Firstly, there are essentially hydraulic ones responsible for the erosion and transport of sediment, and proxy variables for some of these derived from readily available weather or streamflow data can be used in catchment modelling exercises. Others, for example, involving flow on hillslopes, may be less easily approximated. Secondly, the

availability of transportable sediments has to be assessed, and this is
certainly not straightforward.   Suspended sediment concentrations rarely
approach capacity levels and are strongly dependent on sources available
and operating during particular runoff events.   Thus the identification
of sources appears highly pertinent to the effective modelling of sedi-
ment production systems.

As Grimshaw and Lewin (1980) state:

> "A number of methods can be used to identify sediment
> sources within a catchment;   these may involve field
> survey of sites manifestly producing sediment and an
> estimate of the relative importance of source types in
> contributing to catchment sediment yield (e.g. Glymph,
> 1957) allowing for sediment within catchments (Roehl,
> 1962).   Such methods depend on extensive and expensive
> field survey, and it would be a matter of great conven-
> ience if sources could be identified in some measure
> from the characteristics of the yielded sediments them-
> selves.   Some possibilities exist through examination
> of the mineralogy of yielded sediments, or through the
> use of tracers (e.g. Klages and Hsieh, 1975; Wall and
> Wilding, 1976; Lewin and Wolfenden, 1978)."

Broad reviews of present technology for the study of sediment and
solute yields provided by Ward (1984), Onstad (1984) and Walling (1984)
indicate that many aspects of variation water chemistry, sediment yield
and denudation rates are still not properly understood.   There is still
no generally accepted method to determine the rock-derived or denudational
component of the total solute load.   Although contributions in precipi-
tation from dry fall-out and anthropogenic pollutants may be subtracted,
detailed knowledge of soil and bedrock geochemistry may be necessary to
decipher the importance of solutes derived from rock weathering and pedo-
genetic processes.   Furthermore, only a thorough analysis of sediment
sources and transport through a catchment system can explain the relation-
ship between particle detachment and sediment yield at a catchment outlet.
It was in the context of such considerations that a detailed small catch-
ment study in the Macclesfield Forest was planned.

1.2 OUTSTANDING RESEARCH QUESTIONS

The various sources of solutes and sediments in streams may be
hypothesised in terms of atmospheric and lithospheric inputs and the
deduction of the atmospheric input from the net output is frequently

taken to indicate the input from the lithosphere.   The precise ways in
which this lithospheric component enters the stream remain unknown.
Solutes may pass from groundwater, from soil water or through the vege-
tation and litter layer.   Sediments may be derived from erosion of the
surface by overland flow, by headward extension of minor channels, from
bed material in existing channels or by bank erosion.   Some of the
derived sediments may not reach the catchment outlet, being trapped in
the channel, comminuted or dissolved away.   Particular attention should
be paid to bank erosion, especially in environments like that of Britain
where bank materials may reflect not only the catchment bedrock, but a
variety of Pleistocene and Holocene glacial, periglacial and fluvial
materials.

As Cryer (1976) states:

> "It has been repeatedly demonstrated in recent years
> that the atmospheric supply of plant macro-nutrients
> to the ground surface is a factor which must be con-
> sidered in most biogeochemical investigations.   These
> inputs should be evaluated as 'external credit factors'
> in complete nutrient-cycle studies of ecosystems (Ovington,
> 1965).   The Hubbard Brook Ecosystem study in the U.S.A.
> has shown that in a cool, temperate, high-rainfall environ-
> ment and on resistant bedrock the 'terrestrial ecosystem
> is heavily dependent on precipitation as a source of
> nutrients' (Bormann and Likens, 1969).   This and other
> similar catchment nutrient-budget studies (Eriksson, 1960;
> Crisp, 1966; White and Turner, 1970; White et al., 1971)
> has also shown indirectly that dry deposition accounts for
> about 2-4 times as much of the total nutrient input as wet
> deposition.   The fact that rainfall is not a 'pure' solvent
> can also be important in studies of 'catchment solute dyna-
> mics' (Gregory and Walling, 1974) in geomorphology where
> dissolved constituents of stream water are often used as
> tracers or 'labels' for water of particular origin or from
> a particular subsurface flow route.   Atmospheric inputs
> must be subtracted as 'non-denudation components' when
> estimating rates of chemical denudation of rocks from the
> dissolved load of a river (Meade, 1969; Goudie, 1970;
> Janda, 1971).   The atmospheric nutrient inputs must be
> carefully evaluated, with adequate attention to problems
> of measurement and interpretation."

The size, shape, morphology, parent material, vegetation and land
use of any catchment influence its hydrograph response to rainfall, but
the space, time, duration, frequency aspects of precipitation largely

control variations in discharge:solute and sediment load relationships.
The precise nature of such relationships in given environments deserves
greater attention.   Generally, clear positive relationships exist
between load and instantaneous discharge, as Wolman and Miller (1960)
indicated for rivers in the U.S.A.   However, the slope of the regression
line is often a discriminating factor.   In the U.S.A. example, it was
less than +1.0 as the concentration of the dissolved solids was inversely
correlated with discharge.   In other catchments the slope may differ,
particularly if suspended sediments form a large part of the total load.
Load:discharge relationships require careful study, especially in terms
of the hysteresis, lag, flushing and exhaustion effects described in the
previous section.

The roles of seasonal changes in weather, type of precipitation,
status of the vegetation and dominance of geomorphic processes, require
attention, particularly in terms of processes which may be episodic or
reflect particular events.   Bank erosion is one such episodic process
which has received some attention in the geomorphological and hydrologi-
cal literature.   Investigations in south-west Scotland revealed that
93 per cent of the total sediment removed from a mountain grassland basin
resulted from erosion of river banks (Kirkby, 1967).   Other studies
suggest that the various processes of bank erosion may contribute 25 to
60 per cent of the sediment load, even in drainage basins which contain
considerable areas of cultivated land (Anderson, 1954, 1975; Robinson,
1977; Smith and Hicks, 1982).

Considerable information is available from the results of direct
and indirect measurements of erosion on the relationships between erosion
and meteorological, hydrological and bank material variables (e.g. Wolman,
1959; Turnbull et al., 1966; Hill, 1973; Knighton, 1973; Hooke, 1979;
Grissinger, 1982), and on the consequences of bank erosion for channel
morphology and water quality (Klimek, 1974; Knap and Mildner, 1978;
Thorne and Lewin, 1979; Andrews, 1982).   Nevertheless, little informa-
tion is available concerning the relative importance of the various bank
erosion processes and the contributions these make to sediment output.

The chemical changes to waters in their passage through vegetation
litter and the soil to streams are a major influence on water quality
and need to be seen in the context of the nutrient cycle.   Chemicals

accumulating on leaf surfaces by evapotranspiration are readily soluble and quickly leached (from leaf surfaces). The greatest concentrations in throughfall occur in the initial stage of a storm. The importance of throughfall as a source of chemicals is illustrated by Carlisle et al. (1966, 1967) in a table comparing annual deposition rates in incident rainfall and throughfall beneath a sessile oak canopy (Table 1.2.1). Monthly figures show that solute leached from leaf surfaces is greatest in autumn. Studies by Attiwill (1966) in Australia, Madgwick and Ovington (1959) in south-east England, and Eaton et al. (1973) in New Hampshire, also show increased solute concentrations in throughfall over concentration in incident precipitation. In forested areas stemflow may also contribute significantly to the amount of solutes reaching the soil surface. Douglas (1972) quotes Duvigneaud and Denaeyer-Desmet (1970) on the relative importance of stemflow and throughfall in the return of nutrients of the soil in mixed oakwood at Virelles, Belgium (Table 1.2.2). To distinguish the portion of the chemical elements carried to the ground by throughfall and stemflow derived from atmospheric dry fallout or by retention from precipitation from that portion taken up by plants from the ground is difficult. Consequently, many researchers assume that any quantity of chemical elements in throughfall or stemflow which exceeds that in precipitation in the open is part of the internal nutrient cycle of the ecosystem. Work to distinguish these two portions is clearly needed.

Overall catchment nutrient and sediment budgets have been established for many areas, classic examples being the Hubbard Brook studies (e.g. Bormann et al., 1969) and the many ecosystem studies carried out under the International Biological Programme. Sediment budgets have been established for a variety of areas and purposes; for example, for determining the relative importance of high magnitude, episodic events (Rapp, 1960; Schick, 1977; Kelsey, 1980; Lehre, 1982); to examine changes in properties of soil and sediment movement through drainage basins (Dietrich and Dunne, 1978); and to analyse the effects of management practices on soil erosion, sediment yield and water quality (Madej, 1982; Megahan, 1982; Smith and Hicks, 1982; Swanson and Fredriksen, 1982; Trimble, 1983). The majority of these studies have paid most attention to sediment transfer on hillslopes, while often the contribution of sediment from streambanks has been either neglected, or estimated as a residual term. As a consequence, few of the available budgets measure both

TABLE 1.2.1   COMPARISON OF CATION IN INCIDENT RAINFALL AND
THROUGHFALL BENEATH A SESSILE OAK (Quercus petraea)
CANOPY   (kg ha^{-1} y^{-1})   (after Carlisle et al., 1966)

	Incident rainfall	Throughfall	Period of most
K^+	2.96	28.14	Max. June-October
Na^+	35.34	55.55	Max. Sept.-October
Ca^{++}	7.30	17.18	Max. October-November
Mg^{++}	4.63	9.36	Max. October-November

TABLE 1.2.2   RETURN OF NUTRIENTS TO THE SOIL BY VARIOUS ROUTES IN
MIXED OAKWOOD AT VIRELLES, BELGIUM   (kg ha^{-1} y^{-1})
(after Duvigneaud and Denaeyer-Desmet, 1970)

	K^+	Ca^{++}	Mg^{++}	N	P
Throughfall	1.6	6.2	5.6	0.9	0.6
Stemflow	0.8	0.9	0.6	0	0
Leaf litter	21.0	110.0	5.6	50.0	2.4
Ground flora	15.0	10.0	1.5	11.0	1.7

hillslope and channel contributions in detail. Probably the best documented studies are those of Leopold et al. (1966), who measured rates of slope and channel processes in a semi-arid area to aid analysis of arroyo filling and cutting, and Kelsey (1980), who established a sediment budget for a steep forested catchment in northern California receiving high annual rainfall amounts. Up to now, no budget has been presented for a forested catchment in a humid, temperate area.

1.3 CHEMISTRY OF NATURAL WATERS AND CATCHMENT ECOSYSTEMS

Introduction

Water chemistry research in both the purely academic and the public health and pollution control fields has a long history. The emphasis has varied from worker to worker according to their individual interests and the particular waters they examined.

The hydrological processes in a catchment ecosystem (Fig. 1.3(a)) involve the distribution of precipitation inputs through a number of stores by a series of transfer processes leading to outputs as streamflow, evapotranspiration, and deep groundwater seepage. Thus, in simple terms, water entering the catchment is intercepted by several types of vegetation and subsequently evaporated, or reaches the ground surface as throughfall and stemflow. In the absence of vegetation, the precipitation reaches the ground directly, although interception by surface litter may still occur. At the soil surface, water infiltrates into the soil or is retained in surface storage. The surface water may move downslope as surface runoff or be slowly evaporated. Moisture held within the soil is subject to surface evaporation and plant transpiration, to downward percolation to the water table, and to downslope movement as throughflow and interflow.

The stream channel receives variable contributions of surface runoff, throughflow and inter-flow and base-flow, which together contribute to the time-variant outflow hydrograph of the drainage basin.

As water moves through this system of stores and transfer pathways, its quality is modified, and the quality of the water leaving the drainage basin will differ considerably from that of the moisture entering the

Water Quality in Catchment Ecosystems

(a)

Water in the Catchment Ecosystem

(b)

PRECIPITATION

EVAPOTRANSPIRATION

Interception loss

INTERCEPTION STORAGE

Throughfall
Stemflow

Evaporation

SURFACE STORAGE

Surface runoff

Infiltration

Evaporation

SOIL MOISTURE STORAGE

Throughflow

Transpiration

and Interflow

Percolation Capillary rise

Evaporation

GROUNDWATER STORAGE

Baseflow

Transpiration

Influent seepage and Bank storage

Evaporation

CHANNEL STORAGE

Transpiration

CHANNEL RUNOFF

PRECIPITATION QUALITY

BIOMASS

Vegetation & Litter Leaching

Erosion and Surface Wash

Nutrient uptake

Weathering Mineralization Other interactions

Decomposition

Leaching

Nutrient uptake

Weathering Other interactions

Nutrient uptake

Channel erosion
Solute/Sediment interaction
Thermal equilibrium
Photosynthesis & Aeration

Decomposition

RIVER WATER QUALITY

INPUT

Process Mechanisms

OUTPUT

INPUT   STORE   OUTPUT

FIGURE 1.3 (a) & (b)   Quantity and quality processes. A simplified representation
(a) of the hydrological processes operating in a catchment, and
(b) of the major mechanisms influencing the quality of the water involved
(after Gower, A.M. (1980)

catchment as precipitation. The modifications of water quality involve a series of changes (Fig. 1.3(b)) through interactions with the rock, soil, sediment and biota of the catchment ecosystem. Comprehension of these interactions is necessary if spatial and temporal variations in stream quality are to be fully understood. Furthermore, it must be appreciated that the various processes controlling stream water quality may be in a delicate balance easily altered by a change to any one component of the catchment ecosystem. Thus, in this section, the sources of elements in precipitation will be discussed first, and the changes in the composition of river water associated with changes in discharge second.

1.3.1 Factors Affecting the Chemistry of Precipitation

Rain and snow are not pure water; they contain a wide range of dissolved constituents which vary greatly in concentration from place to place. Three major sources of these constituents have been identified (Sugawara, 1967): oceanic spray, terrestrial dust, and industrial pollution (see Table 1.3.1). Some elements are derived dominantly from one source, such as Na^+ from oceanic spray, while others come from several sources, such as S^{2-} from industrial pollution and oceanic spray, and the composition of precipitation at any one point may thus vary widely in time, depending on the origin of the airstream producing precipitation.

1.3.1.1 Oceanic spray

Salts are transferred from the ocean to the atmosphere by the action of breaking waves. The aerosols so released are carried mainly in the sub-cloud layer and may be dissolved or 'washed out' by precipitation. The latter process is responsible for most of the Na^+, Mg^{2+} and Cl^- in precipitation, and contributes appreciable quantities of SO_4^{2-}, Ca^{2+}, K^+ and organic matter (Sugawara, 1967; Eriksson, 1960).

Further reactions may then occur between the aerosols and chemical compounds in the atmosphere. The most important of these are reactions between gaseous oxides of S^{2-} and salt particles (Eriksson, 1960). This leads to the formation of

TABLE 1.3.1   SOURCES FOR CHEMICAL SPECIES IN PRECIPITATION
(after Sugawara, 1967)

Oceanic source		Terrestrial source		Industrial source	
Major	Minor	Major	Minor	Major	Minor
Na^+		SiO_2		SO_4^{2-}	
Mg^{2+}		Fe^{2+}		$SO_2(g)$	
Cl^-		Al^{3+}		NO_3^-	
	Ca^{2+}	Ca^{2+}		Pb^{2+}	
	K^+	K^+		Zn^{2+}	
	SO_4^{2-}	$NH_3(g)$		Ni^{2+}	
	organic C		$H_2S(g)$	Cu^{2+}	
			$N_2O(g)$	H^+	
			$CO_2(g)$		Cl^-
			SO_4^{2-}		K^+
					Ca^{2+}
					organic C

g = gas

Na_2SO_4 and release of gaseous HCl, which causes significant changes in the $Cl^-:Na^+$ ratio of precipitation.

1.3.1.2 Terrestrial dust

The influence of terrestrial dust on the composition of precipitation is practically the reverse of that for oceanic spray, ranging from virtual dominance in continental areas to subordination to oceanic spray at the coast.   It is the main source of SiO_2, Fe^{2+} and Al^{3+} in precipitation (Sugawara, 1967) and also contributes large amounts of CO_3^{2-} , SO_4^{2-} and cations, particularly Ca^{2+} and K^+.

Dust is transferred from the ground to the atmosphere by the action of the wind.   Normally, however, dust consists mainly of quartz and silicate minerals, and the acids in atmospheric moisture attack the latter, releasing some soluble cations and SiO_2 to the precipitation.   On the regional scale, differences in the composition of the dust derived from areas of different bedrock may affect the chemistry of precipitation falling on these areas.

No single current theory adequately explains the variation in NO_3^- concentrations in rainfall.   Possible sources include soil dust, lightning fixation of atmospheric N_2 , photochemical production of oxides of N_2 in the stratosphere, organic processes in the soil and industrial pollution (Gambell and Fisher, 1966).

1.3.1.3 Industrial pollution

Practically all the elements found in precipitation can be produced by man's urban and industrial activities, but this source is particularly important for the gaseous oxides of C , S^{2-} and N_2 , and for heavy metals such as Cu^{2+}, Pb^{2+} and Zn^{2+} (Sugawara, 1967).   These gases are released in vast amounts by the combustion of fossil fuels and can significantly increase the acidity of precipitation (Douglas, 1972).   This may have a major effect on the biota and pedogenic processes of an area,

particularly where the soils have a low buffering capacity.

The influence of this factor on the chemistry of precipitation at any point depends on the nature and extent of urban and industrial activity in the surrounding area. Thus industrial areas such as the Midlands of England show very high concentrations of S^{2-} in the air and SO_4^{2-} in precipitation relative to rural areas of Britain (Stevenson, 1968). Even where heavy industry is absent, precipitation in urban areas is affected by local pollution; Andersson (1969) demonstrated that precipitation in Uppsala, Sweden, had higher concentrations of Ca^{2+}, K^+, Cl^- and S^{2-}, and lower pH, than that in the surrounding countryside.

1.3.1.4 Variation with time

The chemical composition of precipitation at a station will depend on the relative importance of the various solute sources, not only on proximity to the sea and sources of pollution, but also on wind direction at any one time. Thus Gorham (1958) investigating precipitation in the Lake District, found that when the wind was from the sea, Cl^- was the dominant anion, but when the wind was from the industrial areas of the Midlands, SO_4^{2-} and NO_3^- were dominant. Such major fluctuations in composition are, however, mostly short-term. Areas where industrial pollution is important may experience rapid changes in precipitation chemistry due to changes in the nature or amount of pollutant being emitted.

1.3.2 Factors Affecting Stream Water Quality

The chemical composition of stream water is derived from a number of sources which are interrelated and vary in space and time. As all these sources are also related to the discharge of the river, they are best viewed in the context of hydrological cycle. As the ultimate source of water to rivers is precipitation, solutes brought down in rainfall or snow influence stream water chemistry. Stream catchment hydrology, geochemistry, soil, geology, vegetation, climate and land use will determine the amount and space-time variation of water

discharge and the concentration and chemical form of each dissolved species in the river. The sum of all these processes, modifying precipitation hydrologically and chemically, at any point on a stream, may be referred to as the biogeochemistry of the catchment supplying water to that point.

The extent to which these sources can be assessed depends on the scale of the investigation. On the global scale the chemistry of river water, like hydrological regime and soil type, is determined by climate; concentration of total dissolved salts increases from the polar regions to the arid zone and decreases again in equatorial regions (Douglas, 1972). On the continental scale, variations between areas of contrasting geology can be seen, as in Australia (Douglas, 1972). Here, waters draining sedimentary, granitic and basaltic terrains can all be distinguished chemically. Within any climatic zone, variations in water chemistry due to lithology are apparent. For example, waters draining limestone areas have higher solute concentrations, particularly of Ca^{2+} and HCO_3^-, than waters draining more resistant rocks (Hem, 1959).

The content of dissolved solids of river water tends to increase from source to mouth, and the downstream sections of rivers tend to be fairly similar within a region, due to the mixing of tributaries flowing over differing bedrock (Livingstone, 1963). The composition of smaller tributaries reflects differences in underlying geology. At this scale, however, the effects of glacial till, alluvium, soil type, vegetation and land use may mask some of the variation due to weathering of bedrock. These factors are usually interrelated, however, so that differences in water chemistry between differing catchments can still be detected. It is with catchments on this scale, from about 10 to 0.01 km^2 in extent, that we are concerned in this project. The rest of this section will be concerned with discussing the influence of these factors - precipitation, bedrock and soil, vegetation, biota, land use and hydrology - on the chemistry of river water in such 'representative' or 'experimental' catchments (Gregory and Walling, 1973).

1.3.2.1 Precipitation

In areas of hard crystalline bedrock with little or no vege-
tation, precipitation can be the dominant source of elements in
lake and river waters.   An example of such an area is the
Cairngorm Mountains of Scotland, which are composed of granite.
Several small lakes in these mountains were found to be dilute
solutions of NaCl and SO_4^{2-}, derived directly from precipitation
(Livingstone, 1963).   In a vegetated small catchment in the
hills of mid-Wales, concentrations of individual ions in a stream
were related mainly to their concentration in antecedent rainfall
events (Lewin et al., 1974).   Usually, however, precipitation
has an indirect influence on the chemistry of river water, the
water being modified chemically during its passage through the
soil, so that, even in areas where precipitation is the main
source of elements in river water, the patterns of concentration
shown by those elements are regulated by the properties of the
soils and bedrock.

1.3.2.2 Soil and bedrock

Soil and bedrock grade into one another, often via glacial
till or weathered material, and their effects on the hydrology
and chemistry of river water are also closely interrelated, and
so they will be considered together here.   During a storm, water
is precipitated over a catchment.   If the ground surface is
impermeable or if the soil is saturated, water will flow over it
as surface runoff.   Otherwise it will infiltrate the soil and
percolate downwards through it.   Evapotranspiration will reduce
the amount of water in the soil.   Depending on the precipitation
intensity and the antecedent soil moisture conditions, some of
the water may flow laterally through the near surface horizons as
throughflow, while the rest percolates to the deeper soil horizons
before moving downslope towards the stream net.   If the bedrock
is not impermeable, some water will percolate down to the water
table and be slowly carried along to the stream as the ground-
water.   At each of these stages the chemistry of the water is
greatly altered by reaction with the surrounding medium, and

water from each of these horizons may contribute to stream flow
at various times.

In dry weather, a perennial stream network is maintained by
groundwater and water from the lower horizons of the soil.
During a storm, however, the drainage net expands, through inter-
mittent and ephemeral channels and pipes in the soil (Gregory and
Walling, 1973).   In humid temperate well-vegetated areas of the
world, the infiltration capacity of the soils is almost always
greater than the intensity of the precipitation (Kirkby, 1969).
Thus, even water comprising a storm flow has been in contact with
the soil for some time, gradually working downslope towards the
stream net.   Hence, differences in river water chemistry at
flood stage and at base-flow level reflect the properties of the
different soil horizons out of which water is flowing at the time,
and result from the pedogenic processes active in the soils.
Natural pipes in the soil are of great importance in the trans-
mission of storm flow into the stream network, and their presence
has been reported from a wide range of soils, including hill peat
(Lewin et al., 1974), acid brown earth (Oxley, 1974) and silt
loam (Jones, 1971).

Surface runoff is characterised by very high turbidity and
low dissolved solids concentration (Davies, 1971).   Unless it
occurs on exposed stream banks, much of it may not flow directly
into the drainage net, but percolate into the soil lower down the
slope, possibly at the edge of the floodplain.

Where precipitation falls on vegetation, it will pick up
salts before it infiltrates the soil by washing down dry deposits
of oceanic aerosols which have impinged on the plants.   In addi-
tion, elements may be leached from the leaves by ion exchange
reactions with H^+ ions in precipitation.   This is particularly
important in woodland areas, where precipitation collected under
the forest canopy has significantly higher concentrations of ions
than precipitation collected in the open (Attiwill, 1966).   Thus
the chemistry of water which infiltrates the soil will be differ-
ent from that of precipitation collected in rain gauges.

Once water has infiltrated the soil, its composition will
be altered by reactions with the organic and inorganic cation

exchange complex, weatherable minerals, soluble salts, decomposing organic matter, gases in the soil atmosphere, chemical species in the soil solution, and with the plant and animal content. The extent of these reactions will depend on the composition and volume of precipitation, the physical, chemical and biological properties of the soil, and the extent of leaching and drainage. For the release of elements to river water from weathering reactions, the mineralogy, extent of leaching, and cation exchange capacity of the soil are the most important factors.

The mineralogy of the soil gives a measure of the extent of weathering reactions taking place; the primary mineralogy indicates the nature of the material available to be weathered, and the secondary mineralogy the extent to which the primary minerals have been weathered. Only rarely are soils derived solely from weathering of the underlying bedrock. In areas like the Macclesfield Forest, soils have developed on aeolian loess, alluvium and glacial materials which have been transported considerable distances from their original parent rocks. Their mineralogy is thus not closely related to that of the underlying rocks. Only where the surface materials have not been transported far from their source rocks, as in the glacial drift and periglacial solifluction deposits which mantle much of the north-east of Scotland, is soil mineralogy, and thus stream water chemistry, closely related to that of bedrock (Glentworth and Muir, 1963).

Weathering is more intense in the upper horizons of the soil, where minerals are subject to attack from organic acids and carbonic acid in the soil solution. As water percolates to the lower horizons, some of the products of weathering are redeposited. Water which percolates to the lower horizons generally will have a higher pH than that in the upper horizons, because the H^+ ions, both those brought in by precipitation and those generated by decomposing organic matter within the soil, have been used up in weathering reactions and replaced by basic cations, allowing the formation of HCO_3^-. Where such buffering occurs, water from the lower horizons of the soil has higher concentrations of cations, SiO_2 and HCO_3^-, but lower concentrations of Fe^{2+}, Al^{3+} and organic

matter, than water from the upper horizons, which yield quick
return flow during storm runoff events.   This is more marked in
rivers draining areas of podzolic soils than areas of brown earths,
because the differences between horizons are much more marked
in podzols.   The greater amounts of weatherable minerals in brown
earths result in the rivers draining them containing higher con-
centrations of cations, SiO_2 and HCO_3^- than those draining areas
of podzols or peat.

Water which percolates below the soil to groundwater develops
high solute concentrations due to solution of the aquifer or its
cementing material, ion exchange reactions, or mixing with deep-
seated brines.   If the aquifer is extensive, the water may under-
go major changes as it progresses through it, usually from a hard
$Ca(HCO_3)_2$ water to a soft alkaline Na^+-rich water (Rodda et al.,
1976).   Groundwater from more restricted aquifers, with one domi-
nant rock type, reflects the composition of the aquifer more
closely.   Thus, "water from igneous terrains usually has a high
proportion of silica.   Water from resistate sediments is strongly
influenced by solution of cementing material, water from hydroly-
zates is often affected by connate salt and ion exchange, water
from precipitates is usually proportionately high in calcium and
magnesium bicarbonate, while water from evaporites is high in
other dissolved salts.   Waters may be considerably altered in com-
position by chemical precipitation, adsorption or ion exchange,
reduction of sulphate, admixture of other waters, life processes
of plants and animals, and activities of man."   (Hem, 1959.)

The variation of river chemistry with lithology within a
fairly small region is illustrated by a study of rivers within
the basin of the river Exe, in Devon.   Here, Walling and Webb
(1975) found significant differences between the specific conduc-
tance of waters flowing over Permian marls, Carboniferous shales,
and Devonian sandstones.   Variations in climate and topography
were closely linked to geological variations, and all these fac-
tors were important in soil formation.   Even in areas of crystal-
line rocks, variations in water chemistry due to geology can be
detected.   In the Genoa river basin in south-east Australia, two
types of surface water were present (Reinson, 1976);   a Na^+-Cl^-

type draining granite-adamellite terrain, and a mixed ions HCO_3^-
- Cl^- type draining quartz diorite-granodiorite and adamellite
terrain. The latter suite contains more minerals which are
readily weathered, such as biotite and horn-blende, than the
granite-adamellite terrain. Hence the rate of chemical
weathering is higher and the waters are characterised by a
mixture of atmospheric salts and soluble weathering products.
The chemical weathering rate is lower on the granite-adamellite
terrain, and hence the surface waters are dominated by atmos-
pheric salts.

1.3.2.3 Biota, vegetation and land use

Biotic processes are strongly controlled by temperature,
light, and moisture availability, and directly affect water
quality by cation exchange, CO_2 production, chemical reduction
and organic acid production. Plants obtain many nutrients by
the process of cation exchange between roots and mineral particles.
Chelation is another important process affecting mineral break-
down and release of solutes.

The most immediate effect of catchment vegetation and
organisms on river water is to reduce the amount of water leav-
ing the catchment by evaporation and transpiration. This
results in an increase in the concentration of dissolved solids
in the river relative to rainwater, but the effect is not a simple
one. Plants and animals take up nutrients as well as water, and
the cycling of elements within the biomass adds to the buffering
capacity of the catchment in regulating the composition of the
river. The more diverse and stable the ecosystem, the better
regulated is the quality and quantity of the runoff. Thus
forested catchments, where water and nutrients are utilised very
efficiently by the vegetation, are characterised by lower total
runoff, with lower extremes of flood and drought, and much cleaner
water with lower concentrations of dissolved solids, than catch-
ments under pasture or agriculture, or which have been deforested,
in the same area (Pereira, 1973; Pierce et al., 1970).

The activity of organisms plays an important part in regulat-
ing both the concentration and form of several elements in soil

and river water. Organic compounds are brought into solution by the microbiological breakdown of soil organic matter. In gley soil, microbiological processes are very important in reducing Fe^{2+} and Mn to the mobile, divalent state (Bloomfield, 1964).

Storage of elements within the biomass may thus be significant, depending on land use. Likens et al. (1977) have shown how, in the Hubbard Brook Experimental Forest, New Hampshire, an area of aggrading northern hardwood forest, the annual storage of elements in the biomass accounts for 50% of the products of weathering. In forested ecosystems this accumulation of nutrients will be a major feature until the forest reaches maturity (Ovington, 1965). In areas of pasture land, grass or heather, the amounts of elements stored in vegetation are much smaller but may still be significant. The pattern of land use may affect this; regular burning of heather speeds up the cycling of nutrients within the soil and leads to loss of some constituents, mainly K^+, by leaching of the ash, while about half the C, N_2, and S^{2-} in the heather are driven off with the smoke (Allen, 1964; Robertson and Davies, 1965). Offtake of nutrients in sheep and other animals is minimal compared with the nutrients found in vegetation and those exported in river water in areas of low productivity (Crisp, 1966; Robertson and Davies, 1965). In lowland areas of high productivity or arable agriculture, the offtake of elements in livestock and crops may be highly significant.

The effect of different forms of land use on river water quality can be illustrated by the study of the Exe basin by Walling and Webb (1975) referred to in Section 1.3.2.2. Significant variation was found in the specific conductance of water flowing over different bedrock, but within each bedrock type there was also significant variation due to land use. Waters draining areas of farmland had higher specific conductance than those draining woodland, while streams draining moorland had still lower specific conductance. Thus, on the small catchment scale, vegetation and land use may be as important as geology in determining the chemical composition of river waters.

1.3.2.4   Topography

Topography influences water quality by controlling the
degree of leaching; and through its influence on erosion and
its impact on rainfall, temperature and wind.   The relevant
topographical factors are relief, slope and aspect.   Where in-
filtration rates are low, moisture intake by the soil depends on
slope angle.   The proportion of precipitation moved as surface
runoff will be greater on steep slopes than in flat areas, where
water may stand on the surface.   Slope also affects the rate of
erosion and weathered erodible material on steep slopes will be
stripped off to expose fresh material to biotic and chemical
weathering.

1.3.2.5   Human activity

Direct point discharges, indirect non-point source flows,
and transfer through the atmosphere all convey pollutants to stream
channels and affect river water quality.   Even those catchments
devoid of local pollution are affected by atmospheric pollution.
Much evidence suggests that SO_4^{2-} and Cl^- concentrations in rain-
fall are higher in industrial areas.   The main effect of dilute
H_2SO_4 and HCl in the atmosphere is to depress the pH of rainfall
below its CO_2 equilibrium values, therefore increasing its reacti-
vity in the water quality system.   Not all the chemicals washed
off plants by rain are derived from the nutrient cycle of the eco-
system.   Some are from dry fallout from pollution which has
collected on the leaves.   Where the addition of atmospheric
pollutants influences the total solute discharge, such increments
must be deducted before catchment denudation rates are calculated.
Often these non-denudation components (Fig. 1.3.2.5.1) are only
partially considered in estimates of denudation rates derived
from the total dissolved loads of streams.   In terms of the hydro-
chemical cycle within a small catchment area it is difficult to
distinguish the origin of solutes in bulk precipitation.

Undoubtedly most of the chemicals in precipitation will be
derived from outside the catchment area, particularly in the case

FIGURE 1.3.2.5.1   PRINCIPAL SOURCES OF DISSOLVED SALTS WHICH COMPRISE
DENUDATION AND NON-DENUDATION COMPONENTS OF THE
TOTAL DISSOLVED LOAD OF STREAMS

(After Janda, 1971)
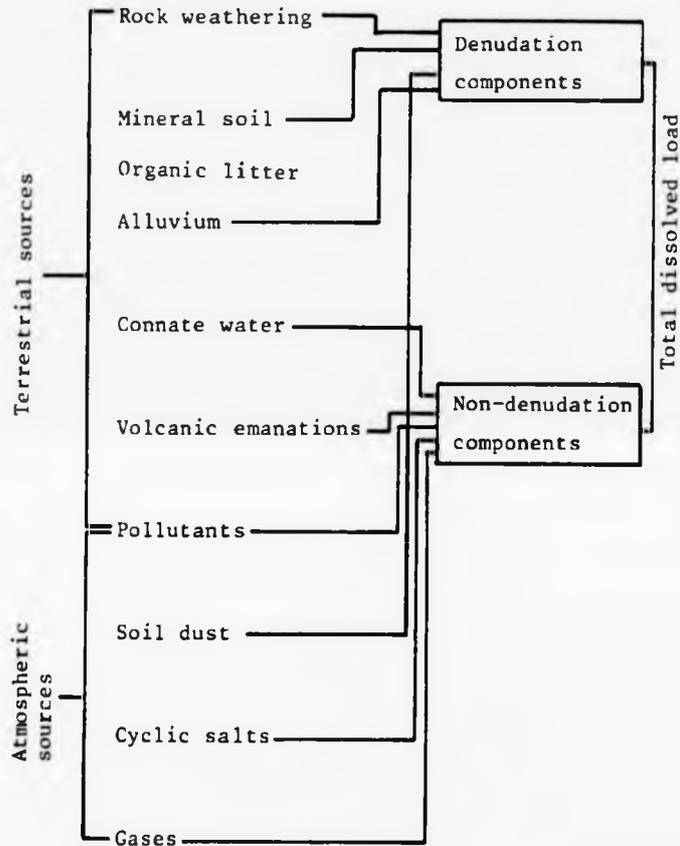
of rainfall solutes. However, some of the dust particles in
dry fallout may have originated within the catchment boundaries.
Before reaching the soil, precipitation may pick up additional
solutes from vegetation.

Measurements of nutrient return to the soil in the form of
leaf fall, throughfall and stemflow, are commonly taken to rep-
resent nutrient uptake, but even then nutrient return by the
decay of roots and large structures is difficult to estimate.
The humus layer also represents a large reservoir of nutrients
within the system.

Not all soluble products of the system leave the system as
dissolved solids in stream flow. There is evidence to suggest
that suspended sediment has the ability to absorb and adsorb
dissolved constituents in stream flow. This may be important
where concentrations of particulate organic and inorganic matter
are high, especially if the material possesses a large number of
available exchange sites. In the last two decades acid rain
has been recognised as causing increased leaching of nutrients
from foliage, disruption of leaf physiology and growth, and
increased leaching of soil cations.

1.3.2.6 Discharge and time

In most rivers the concentration of dissolved solids tends
to decrease with increasing discharge, though the relation is
seldom simple (Douglas, 1972; Livingstone, 1963). This is
because, during storms, the bulk of the flow is quick return
flow from the ground surface or the upper horizons of the soil.
Such water contains lower concentrations of most salts than the
deeper soil water or the groundwater which makes up the base
flow (Section 1.3.2.2).

Not all substances in stream water will vary in the same
way in any river. While species such as Na^+, Ca^{2+}, Mg^{2+}, HCO_3^-
and SiO_2 tend to decrease in concentration with increasing flow,
other substances such as suspended sediment, organic matter, Fe^{2+},
Al^{3+} and NO_3^- may increase in concentration because of the flush-
ing effect on the upper layers of the soil. Other constituents,

such as Cl^-, may show no fixed relationship between concentration and discharge. The patterns in any river will depend on several factors: the relative amounts of species contributed from precipitation and weathering; the buffering capacity of vegetation; the extent to which groundwater has picked up elements from weathering reactions at depth; and the relative amounts of surface runoff, soil water and groundwater contributing to stream flow. The effect of these factors is illustrated by the behaviour of river water at Hubbard Brook (Johnson et al., 1969). Discharge here varies over four orders of magnitude, but because all the water contributing to stream flow has passed through the podzolic soils of the area, the chemical composition of the stream is well buffered. Concentrations of Na^+ and SiO_2 may be diluted up to threefold at times of high flow, and Al^{3+}, H^+ ion, dissolved organic carbon, NO_3^- and K^+ concentrations increase. The concentrations of Mg^{2+}, Ca^2, SO_4^{2-} and Cl^-, change very little. The authors explained this behaviour by assuming that the stream water was a mixture of two components: groundwater of high salt concentration which is added to the stream at a steady rate; and relatively dilute precipitation water added on a variable basis, depending on meteorological conditions. The model predicts quite successfully the changes in stream water chemistry following a storm or dry period. A number of other workers have attempted to explain the variation of stream water chemistry with discharge by means of 'mixing models' of varying degrees of complexity (Hall, 1970, 1971; Pinder and Jones, 1969). In view of the complex hydrological and chemical processes involved, however, these models are at best approximations.

During an individual storm, the concentrations of most ions show little change until well after the river has begun to rise. They then fall abruptly and slowly rise back to their pre-storm levels after the flood subsides. This phenomenon is known as the 'lag effect' (Glover and Johnson, 1974), and is illustrated for Na^+ in Fig. 1.3.2.6(a). It arises because of the expulsion of soil water from the lower horizons of the soil before more dilute water from the upper horizons begins to enter the river, in response to the hydraulic gradient created by the precipitation inputs. Pipe flow and throughflow are very important in
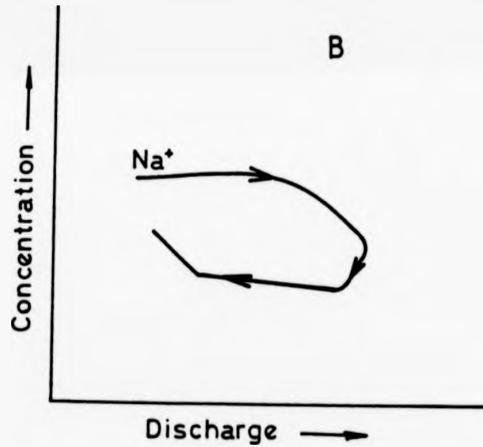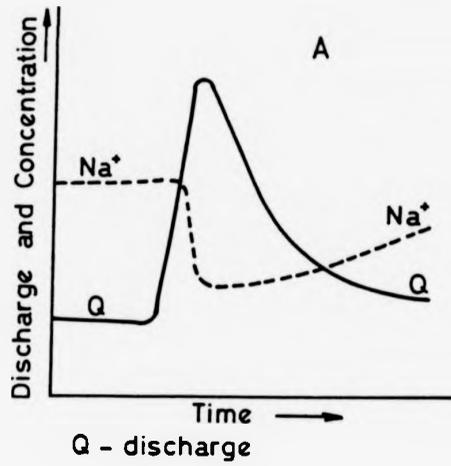
FIGURE 1.3.2.6

Variation in Na$^+$ concentration during a storm

A   Hydrograph showing lag effects

B   Hysteresis loop on concentration-discharge graph

the generation of flood flow (Lewin et al., 1974; Oxley, 1974).
The length of the 'lag time' and the extent of the drop in con-
centration after it vary from storm to storm, depending upon pre-
cipitation intensity and the antecedent soil moisture conditions.

This effect leads to hysteresis loops in graphs of concen-
tration against discharge during storms; the relationship depends
on the path the water has taken through the soil (Fig. 1.3.2.6(b)).
For species such as suspended sediment or organic matter, the
trends shown in Figs. 1.3.2.6(a) and (b) would be reversed, with
the lag followed by a rapid rise in concentration. During storm
events in a stream draining an arable agricultural area in the
Lothians, the hysteresis loops reflected changes in the origin of
water in the stream as the storm progressed (Davies, 1971).

Such variation is well illustrated by the variation of SiO_2
concentration during storms in the Mattole river in northern
California (Kennedy, 1971). Here, SiO_2 is more concentrated in
subsurface soil flow than in overland flow or groundwater. Thus,
during a storm, SiO_2 concentration decreases at first, as stream
flow consists mainly of overland flow on the rising stage. It
then increases as subsurface flow becomes the main component of
stream flow towards the peak of the flood. With decreasing flow
after the peak, groundwater becomes increasingly important and
SiO_2 concentration slowly decreases. The overall correlation
between SiO_2 concentration and discharge is poor. This example
illustrates the influence of the different sources of SiO_2 in
this river, and how patterns may vary for the same species in
catchments with differing soil, geology, land use and hydrology.

As well as variations associated with discharge, some
species may show distinct seasonal variations in concentration.
This may be due to biological activity, as at Hubbard Brook,
where K^+ and NO_3^- concentrations are significantly depleted dur-
ing the growing season (Johnson et al., 1969). In woodland
areas, there is often an increase in concentration of several
species in autumn, after the leaf fall. For example, in a
forested catchment at Pond Branch, Maryland, Cleaves et al.
(1970) found a short-term increase in the concentrations of

SiO_2, HCO_3^-, Ca^{2+} and K^+ in river water in autumn, due to leaching of fallen leaves. These examples again illustrate the importance of vegetation ion and organisms in regulating the chemical composition of natural, unpolluted waters.

1.4 AIMS AND OBJECTIVES

This thesis describes the results of water quality and sediment transport observations in the Coombs Brook catchment in Macclesfield Forest, England, from April 1984 until April 1986. The relationships between discharge and sediment and solute concentrations at seven sites in the catchment were investigated statistically. The constituents analysed were Ca^{2+}, Mg^{2+}, Na^+, K^+, SO_4^{2-}, PO_4^{3-}, NO_3^-, Cl^-, Fe^{2+} and Mn. These data, as well as those from throughfall, groundwater and more intensive sampling, are used in a discussion of the geochemical and erosion processes operating in the catchment.

In this study a number of hypotheses about the geomorphic and hydrologic processes in forested temperate catchments are tested in terms of both sediment supply and water chemistry and transport. The primary aim of the research is to study the geomorphic and hydrologic processes in a forested area, and to identify and examine those processes which affect sediment loads and water quality. Hydrological and geochemical budgets are established in order to determine the rates of chemical and mechanical denudation.

As a geomorphological unit, the Coombs Brook drainage basin provides a sound framework for the determination of chemical denudation rates using a geochemical budget as inputs and outputs of both chemicals and water can be readily monitored. By examining water quality and sediment concentrations at seven sites some of the problems caused by variations in geology, soils, and vegetation, may be eliminated and sources of solutes and sediments may be identified more readily than in studies based on a single sampling site. Identification of sources is a major focus of this study. For example, bank erosion was studied in terms of the sources of sediment rather than the patterns of channel change over short timescales.

These aims could be fulfilled by long periods of field work involving instrumentation, monitoring and experimentation. One crucial element in this type of project was the presence of the researcher in the field when processes were actually operating. With these points in mind, a catchment not too far from Manchester, Coombs Brook in Macclesfield Forest, was selected as an area sufficiently small (800 ha) for various field experiments and measurement sites to be established, which might have been too much for a single person to manage in a larger catchment. The catchment had been instrumented in 1981 by Stott (1985) and further investigated by Seiler (1984).

When this project was planned in 1984, it was clear that previous studies of gross sediment yield and spatial variations in solute concentrations needed extending and explaining in more detail, preferably in terms of the relationship between sediment and water quality.

One object of this thesis is to study the at-a-station variations in concentration and load of a number of dissolved constituents collected at weekly intervals during 1984-1986 at seven water discharge gauging stations, with more detailed observations at the catchment outlet. In particular, the relationship between water discharge, sediment and solute concentrations and load is investigated empirically with regard to two processes: dilution of baseflow by high discharges and the leaching of accumulated weathered products in the soil. The second object is to construct an approximate solute budget for the catchment. The contribution of the input from rainwater has also been estimated by determining the composition of samples collected weekly from a single collector.

Thirdly, the thesis relates variations in the amount of material carried by the catchment stream to variations in those factors likely to influence erosion. This involves the assumption that the load of a stream responds to changing hydrometeorological and catchment surface conditions. The way in which hydrometeorological and catchment surface factors influence the load of a stream may be considered within the context of a conceptual model describing variations in suspended and dissolved load in time and space.
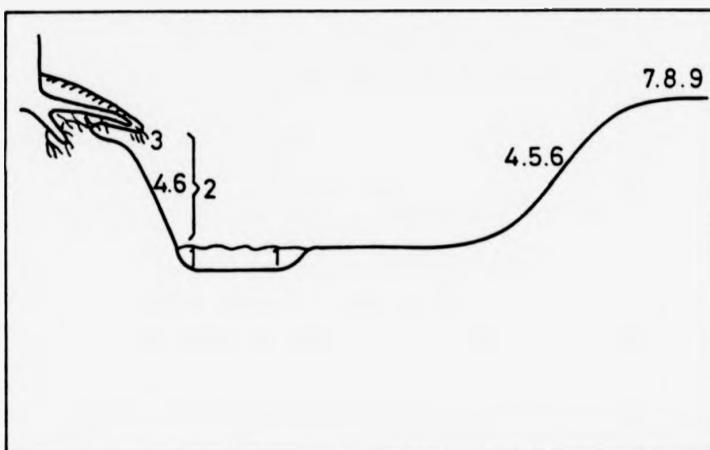
FIGURE 1.4.1

Schematic representation of valley cross-section
showing the active zones of the erosion processes

Stream bank processes   Valley slope processes

1.   lateral corrasion   7.   rainsplash erosion
2.   mass movements   8.   throughflow
3.   subsoil fall   9.   overland flow
4.   splash erosion
5.   soil creep
6.   overland flow

As bank erosion is probably an important, if not dominant, aspect of sediment supply (Section 1.2), the present study aims to:

- determine the seasonal and spatial variations in the sediment supplied by bank erosion processes;

- analyse the relative contributions of the stream-bank processes to catchment sediment output;

- quantify the relative contributions of non-channel sediment sources.

As channel widening is significant in many parts of the catchment, a stream-bank is defined in this thesis as the entire steep slope situated between the lower end of the valley slope and the channel floor (Fig. 1.4.1). It includes, therefore, the river channel bank and the steep slope above directly influenced by fluvial processes. River bank erosion, sediment discharge from slopes and sediment transport by the stream were measured to provide data for the construction of a sediment budget. A sediment budget may be defined as a quantitative description of the rates of production, storage and transport of sediment through a simple landscape unit such as an entire drainage basin or a first order stream channel (Swanson et al., 1982). The prime goal of constructing a sediment budget is to increase understanding of geomorphic and ecological systems and to determine the absolute and relative importance of the various identified sediment sources and sediment supplying processes in order to gain insight into the spatial and temporal variations in sediment production and storage. As indicated in Section 1.2, a budget assessing both hillslope and channel contributions is necessary. Such a sediment budget is attempted in this study.

1.5 HYPOTHESES

A number of hypotheses about the geomorphic and hydrologic processes in forested temperate catchments will be studied.

Geomorphic "hypotheses"

(1) That the bulk of sediment is supplied from defined discrete sources, or from critical parts of the catchment, and the bank erosion and channel processes are dominant sources of particulate matter (Sections 5.1 and 5.2).

(2) That the frost action plays a vital role as an agent of bank erosion (Section 5.3).

(3) That sediment yield varies in space, seasonally, and within storms (Chapters 5 and 6).

Hydrologic "hypotheses"

(1) That the solute content of precipitation varies within narrow limits (Section 7.1.2).

(2) That the cations and anions in precipitation originate from a variety of sources (Section 7.1.3).

(3) That the stream water quality intimately reflects the overall structure and operation of the catchment ecosystem. Broadly, the dissolved solids loads reflect vegetation type, soil-soil water, and bedrock conditions (Chapters 7 and 8).

(4) That the stream water quality varies in space, seasonallly, and during storm events (Chapters 8 and 9).

(5) That the relationships between concentration-discharge and input-output will show different patterns of variation.

The Coombs Brook catchment and the adjacent Bollin and Winshaw catchments were all afforested to protect the water supply for Macclesfield. Information collected in this study will help water engineers to know the quantity and sources of sediment entering the reservoir and the type of filtration the water needs. It may also help them find ways of minimising reservoir sedimentation and of reducing sediment supply to the stream. Several attempts have already been made by the Water Authority to reduce sediment inputs. The discussion of sources of sediment in this thesis will throw further light on the problem.

CHAPTER TWO

GENERAL PHYSICAL GEOGRAPHY

2.1   Coombs Brook Catchment: Geology and Historical Geomorphology

2.2   Coombs Brook Catchment: Land Use

2.3   Description of Coombs Brook

2.4   Soil in the Study Area

2.5   The Field Evidence of Geomorphic and Hydrologic Processes

      2.5.1   Hydrologic evidence

      2.5.2   Geomorphic evidence

2.6   Results of Previous Investigation in Coombs Brook

CHAPTER   TWO

GENERAL   PHYSICAL   GEOGRAPHY

2.1   COOMBS BROOK CATCHMENT: GEOLOGY AND HISTORICAL GEOMORPHOLOGY

The Macclesfield Forest covers the catchment at the Langley
Reservoir and lies at the eastern edge of the Cheshire Plain in the
foothills of the Pennines (Fig. 2.1.1).   The Pennines themselves are
a region of steep slopes and escarpments, deep valleys and broad
moorland plateaux with altitudes varying from 152 metres in the
western foothills to 480 metres O.D. on the open moorland summits.
The vegetation changes from predominantly grassland on the gentler
slopes, with wooded valleys and hawthorn and scrub on steeper slopes,
to bleak windswept open moorland of matgrass, heather and cotton grass.
Exceptions to this rule are woods and hedges in sheltered valleys,
and plantations such as Macclesfield Forest.   The chosen study area
of the Coombs Brook catchment lying within the forest, is about 7.2 km
south-east of Macclesfield in Cheshire and has been described previously
by Stott (1985), whose work is the basis of the bulk of the following
description.

The Coombs Brook catchment forms a U-shaped basin in the gritstone
escarpment of the south-western Pennines (Fig. 2.1.1).   It traverses
one of several north-south anticlines which dominate the geological
structure of the Pennine margin in Cheshire (Fig. 2.1.2).   Outcropping
within the catchment are gritstone and mudstone cyclothems of the
Roaches Grit Series (Namurian R2b), dipping steeply (30°) to the east
and west of the anticlinal axis.   Three terrain units can be recognised
in the 800 ha catchment (Figs. 2.1.3 and 2.1.4), though their geomor-
phological origins are poorly understood and not well documented.
The first unit comprises the summit plateaux of High Moor (442m) and
Buxtons Hill (446m), separated by a shallow col or meltwater channel
(Johnson, 1965).   The plateaux surface has a superficial cover of
peat, whilst the col is floored by glacial drift.
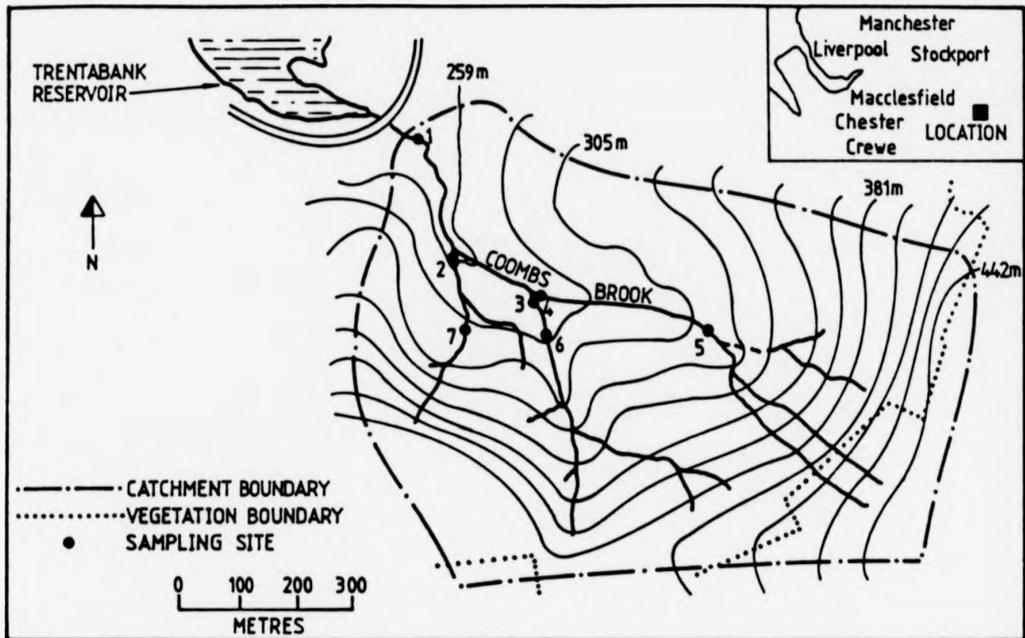
FIGURE 2.1.1   Coombs Brook: location of study area, the research
catchment, and sampling site

after Stott   (1985)
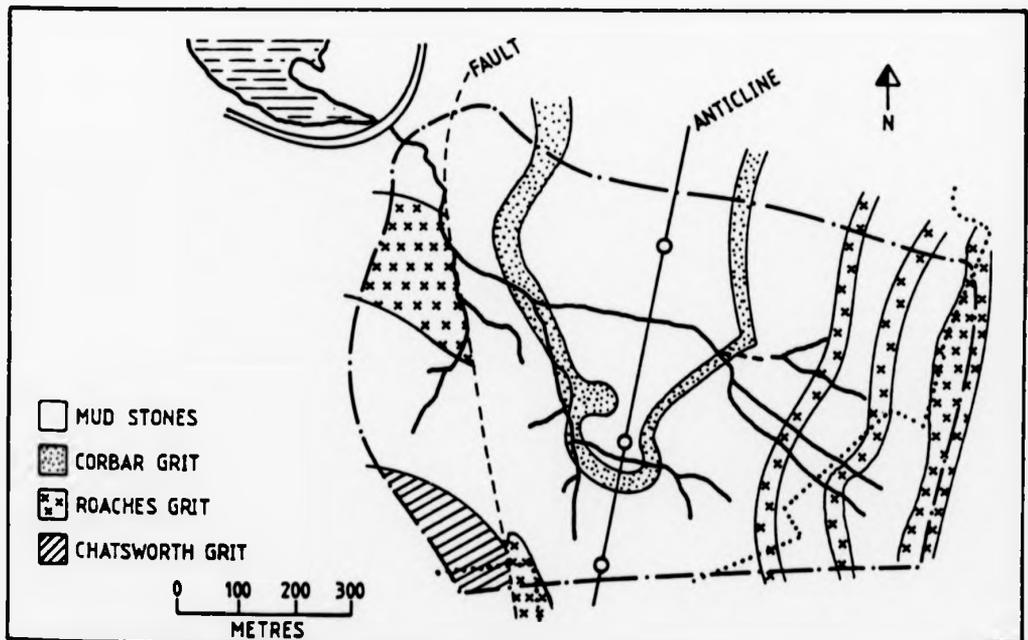
FIGURE 2.1.2   Coombs Brook catchment: solid geology

after Stott   (1985)
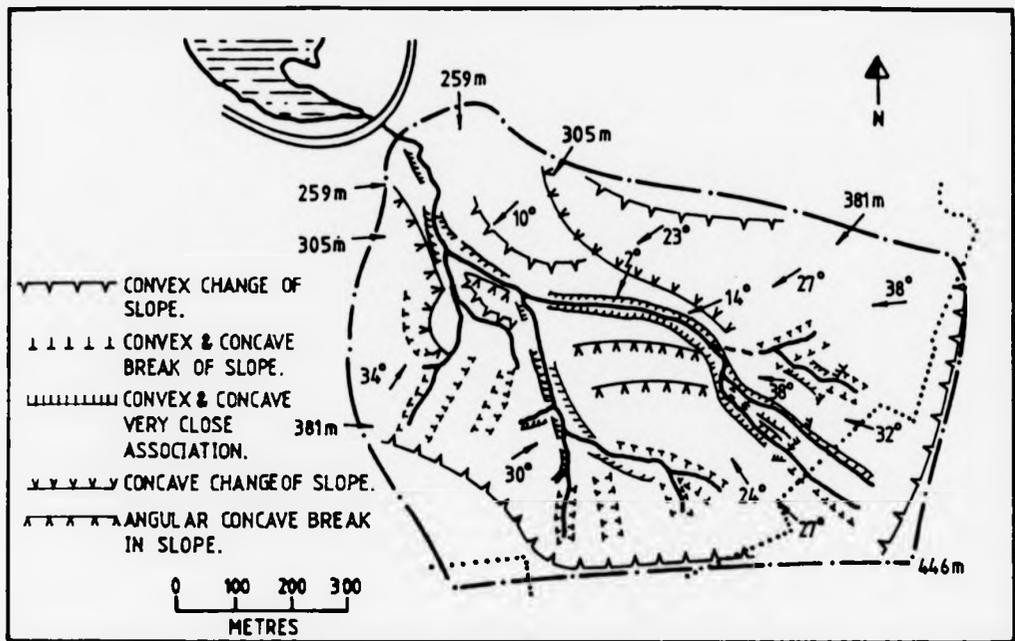
FIGURE 2.1.3   Coombs Brook catchment: morphological map

after Stott   (1985)
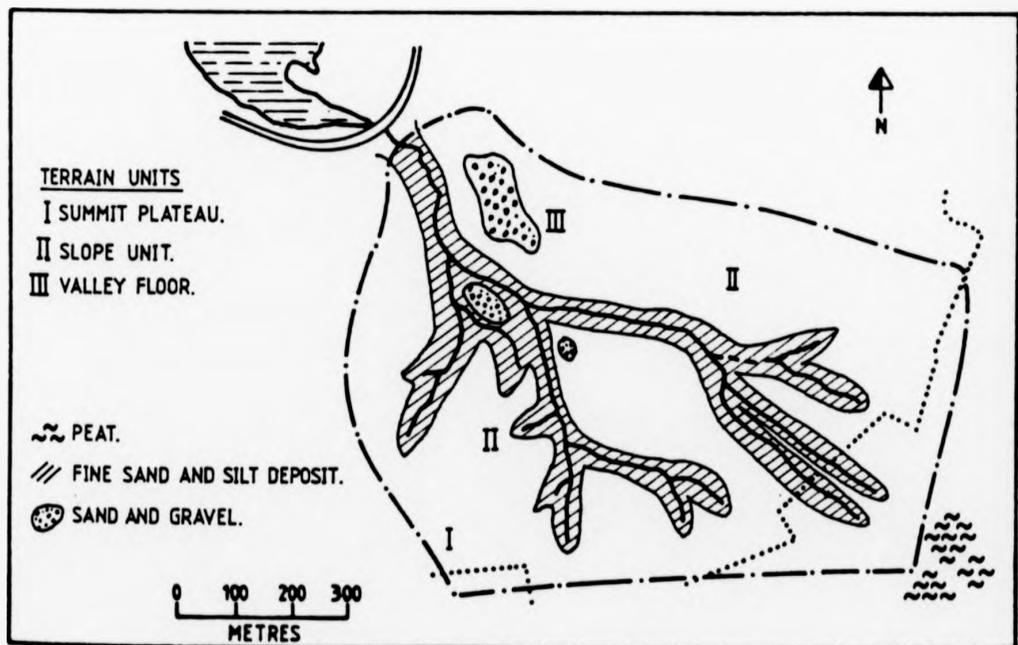
FIGURE 2.1.4   Coombs Brook catchment: drift deposits and terrain units

after Stott   (1985)
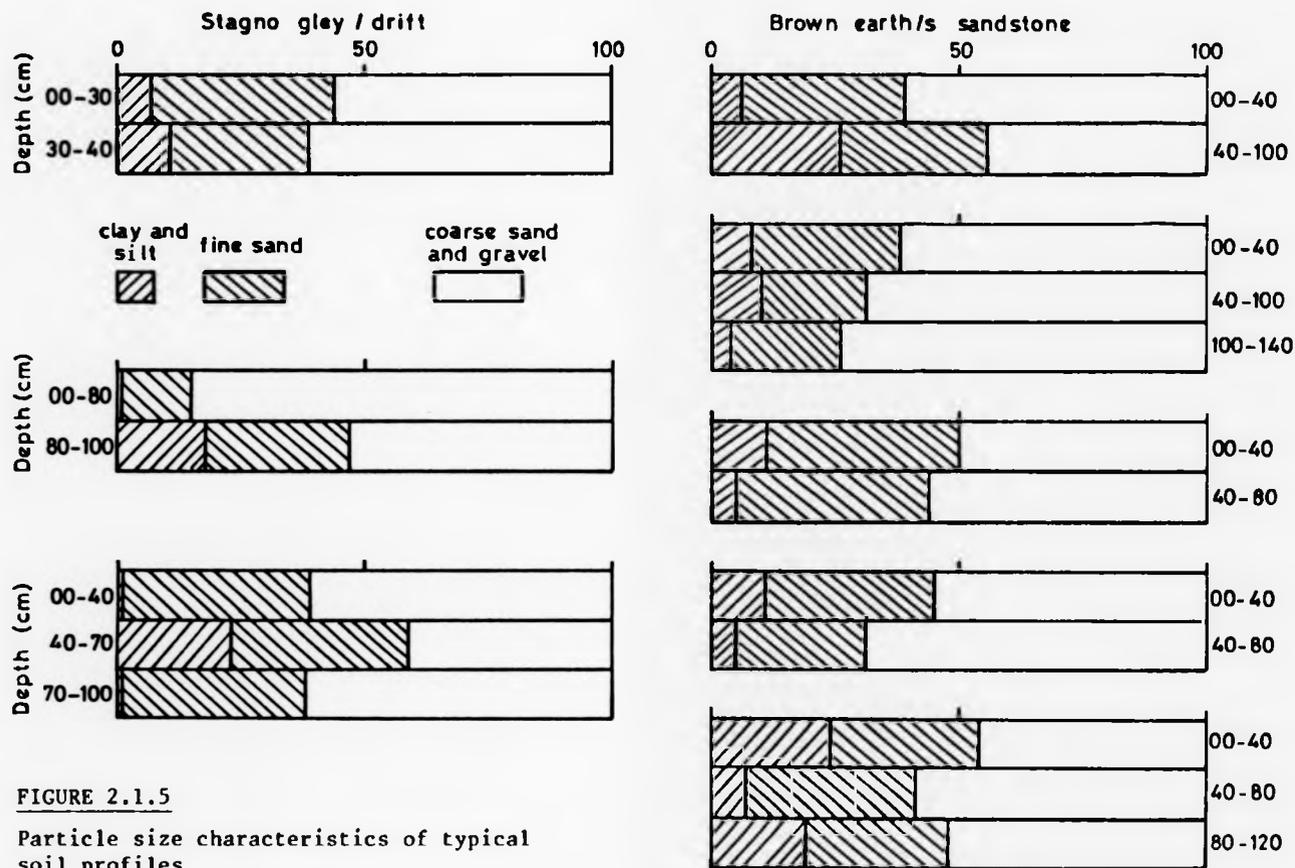
FIGURE 2.1.5

Particle size characteristics of typical soil profiles

The second terrain unit encompasses the predominantly rectilinear slopes which enclose three sides of the basin. Slopes are steep, 22° to 40°, and long, 200 to 400m, interrupted occasionally by gritstone outcrops. The easterly dip of the strata into Buxtons Hill reinforces the slope and accounts for the steepness and the absence of large landslides. This unit is marked by shallow, 2 to 4m deep, linear depressions orientated downslope and occupying the full length of the slope. These chutes are generally infilled with a deposit of fine sands and silt up to 2m thick which may be of wind-blown origin (Lill and Smalley, 1978). Active erosion in several of the depressions has exhumed a well-rounded bedrock surface beneath the drift deposit, suggesting earlier fluvial processes. Soils on these drift deposits are humose stagnogleys, whilst the adjacent well-drained, drift-free slopes support thin sandy brown earths (Figs. 2.1.4 and 2.1.5).

The rectilinear slope unit is bounded downslope by a marked concave break of slope which defines the third terrain unit, the valley floor. This unit embraces a complex zone of ice-marginal and periglacial deposits dissected by the main arteries of the present drainage system. Relief varies between hummocks of fluvio-glacial sands and gravels and low angle slopes formed on a homogeneous silty-sand drift deposit.

In broad terms, the three units may be distinguished by their age and sensitivity to landscape change. The plateaux summits are probably remnants of a pre-Glacial erosion surface (Clayton, 1979), modified by meltwater erosion at a glacial maximum and, in Holocene times, subject to the cycle of peat development. The slope unit reflects a long geological history of drainage incision into the Pennine block, uplifted relative to the Cheshire basin, though the detailed form relates to the sequence of glacial and periglacial climates towards the end of the Pleistocene. The youngest element is the valley floor, a Late-Glacial product of a downwasting ice mass intersected by the developing Holocene drainage network.

The geomorphic system can be viewed as a fossilised landscape most recently modified during the last phase of deglacierisation with only superficial adjustments achieved by processes operating in the prevailing temperate episode. The stresses required for the alteration of landforms and deposits formed under periglacial or glacial

regimes are infrequently exceeded in the present-day environment unless through disturbance by human activity.

The poorly consolidated deposits exposed to fluvial erosion in the hillslope chutes, the valley floor, and the degraded peat on the interfluves, are the most sensitive elements of the landscape. Stability results from an excess of internal resistance of the landforms over the stress imparted by external forces; any factors which act to alter this relationship, to increase stress or reduce resistance, can initiate instability and adjustment.

Geology of Macclesfield Forest

The Macclesfield district may be divided into two areas of contrasting geology. To the east lie the deeply dissected Pennine foothills, mainly formed of steeply folded sandstones and mudstones of the Millstone Grit series. To the west lies the Cheshire Plain which falls westwards across the district from about 120m O.D to less than 30m. The Macclesfield Forest is drained by the Bollin, which flows across the plain north-westwards to the River Mersey, but most of the plain further west is drained by the rivers Dane and Wheelock. The Cheshire Plain is a graben structure filled by Permo-Triassic rocks which are virtually completely overlain by Quaternary sands and gravels (Evans et al., 1968).

The Millstone Grit series formed during the Carboniferous age is made up mainly of argillaceous rocks, although in its lower part beds of quartzitic sandstone locally associated with ganister are prominent. The massive coarse sandstones, so characteristic throughout this series in the central Pennines, are restricted to the upper part of the sequence. Much of the series seems to represent the sedimentary infilling of quite a shallow sea. It is probable that earth movements which started at the end of the Carboniferous age continued well into Permian times. The result was that the pre-existing rocks were folded and the downfaulted graben in which the Permo-Triassic rocks of Cheshire were deposited was accentuated (if not initiated).

During the Pleistocene, ice from the north entered the district on at least two separate occasions, leaving extensive glacial and fluvio-

glacial deposits on the lowlands.   However, the Pennines have thin
drift deposits which are generally restricted to the gentler slopes
and through which the Carboniferous rocks protrude.   Deposits of
Boulder clay fill most of the valleys, extending up the hillsides to
about 425m O.D east of Macclesfield, and are only absent from the
highest peaks of Macclesfield Forest.   East of Macclesfield, marine
shells have been recorded from some of the gravel mounds and are
assumed to have been transported from the Irish Sea by the ice sheet
and washed out by its meltwaters.   The catchment area also contains
several large erratic boulders, mainly granites and volcanic tuffs
from the Lake District and southern Scotland.   They are most notice-
able near the upper limit of glaciation and may lie isolated from other
drift deposits.   Evidence of this type, along with the absence of any
glacial drift above the level of 425m, indicates that the higher part
of Macclesfield Forest was not overtopped by ice.   This view was
expressed by Pocock in 1906 and Worsley in 1967.   Patches of sand
and gravel were found in high-level boulder clays in Macclesfield
Forest.   It is presumed that they were deposited by outwash from the
ice-sheet when it was near its maximum development.   The Carboniferous
sandstones in the Pennines have a distinct effect on the fills which
are stony and of clay loam or sandclay loam.   Clayey fill is limited
to areas adjacent to shale outcrops.   Glacio-fluvial sands are rest-
ricted to deposits which thin westwards away from the Pennines, and
they were probably outwash deposits laid down during periods of glacial
retreat.   In the area under study there is only a small patch of these
sands on the eastern bank of Coombs Brook.

2.2   COOMBS BROOK CATCHMENT: LAND USE

Before the 1930 afforestation scheme, the land use of the catch-
ment was improved pasture, principally for sheep grazing.   Improvements
included enclosure and field drainage, usually by sub-surface tile
drain built from local stone.   A small area provided deciduous coppic-
ing for the three farms in the catchment, Parting Gap, Coombs, and
Ferriser.

The decision to extend the water supply system in the Bollin head-

PLATE 2.2.1

General view of Macclesfield Forest.

PLATE 2.2.2

Coombs Brook outlet and Trentabank Reservoir.
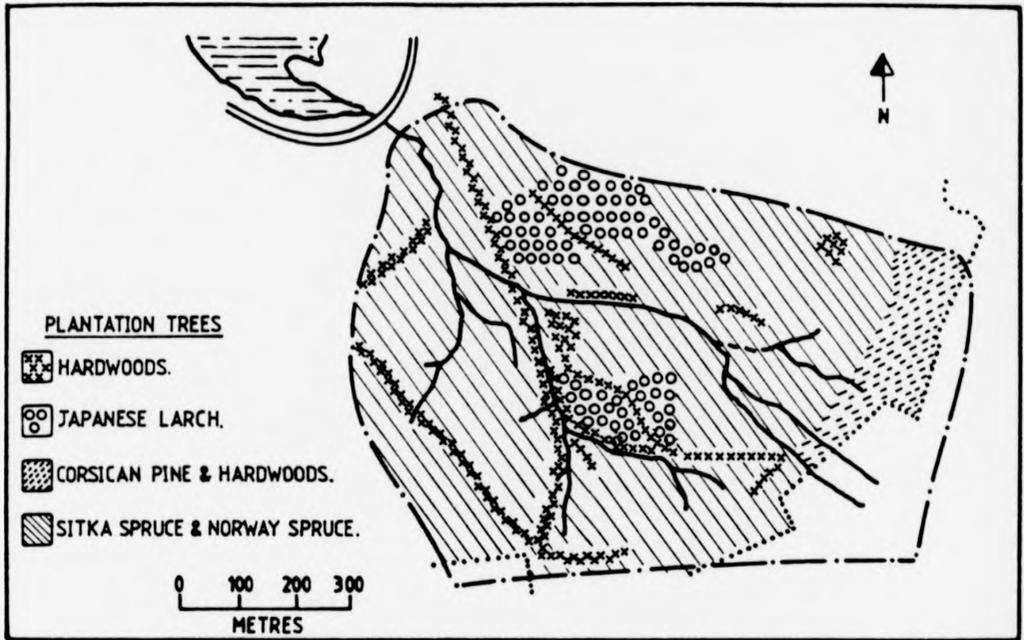
FIGURE 2.2.1   Coombs Brook catchment: plantation tree varieties
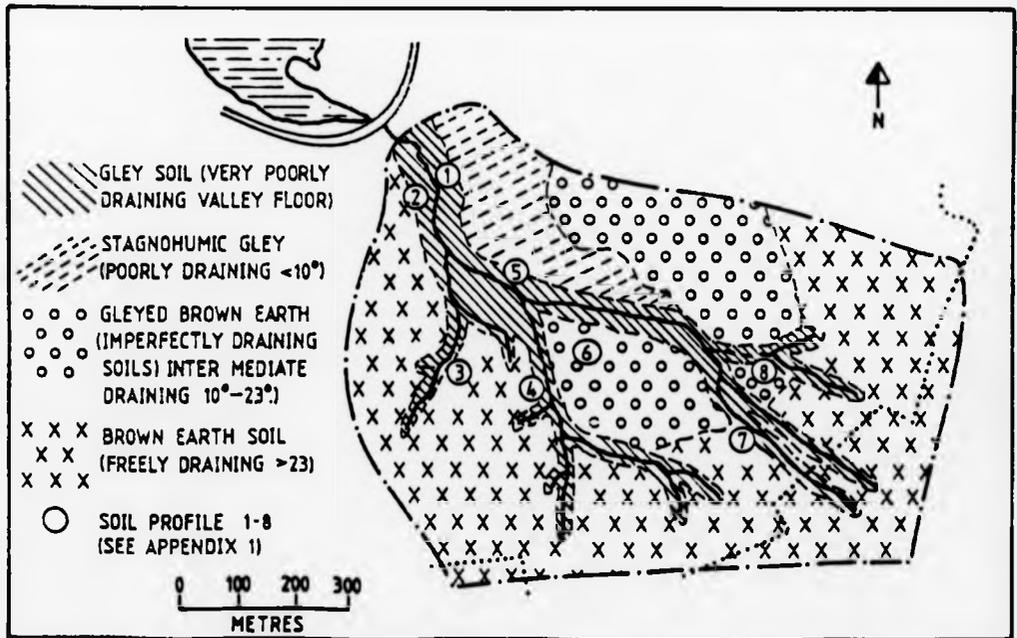
FIGURE 2.4.1 (A)   Coombs Brook catchment: soil map

unit 30 (gley soil)

396m —
213m —


```
[peat dots] peat          [shale hatch] shale
[head vertical] head      [grit dots] grit stone
[till blank] till
```

a Cambic stagnohumic gley soil
c Cambic stagnohumic gley soil and typical
   humic gley soil.

unit 35 (peat soil)

396m —
183m —


```
[peat dots] peat          [till blank] till
[head vertical] head      [grit dots] grit stone
```

a Raw peat soil
b Bare rock, humic ranker
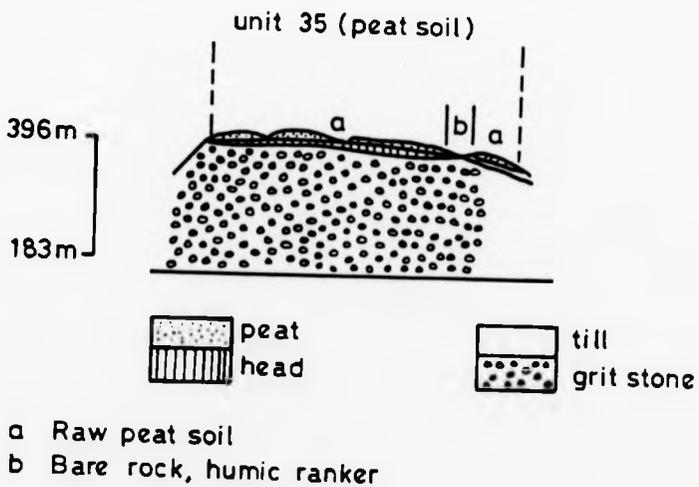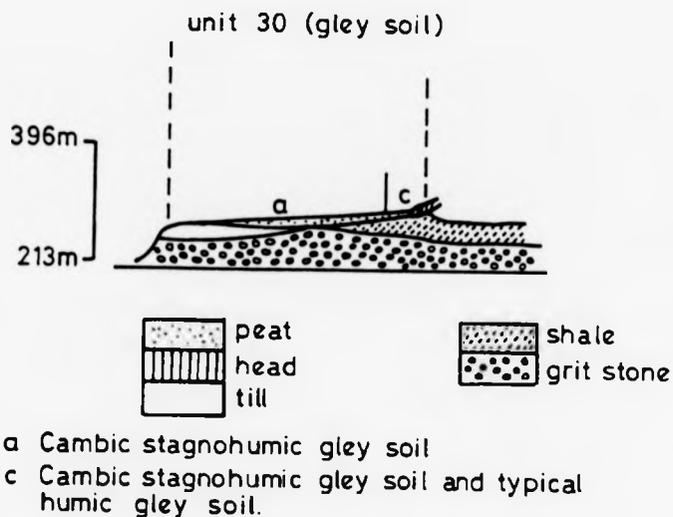
FIGURE 2.4.1 (B)

Distribution of the principal soils in map units 30, 35
(see Fig. 2.4.1 (A))

Map Unit 18   (Brown earth)

18
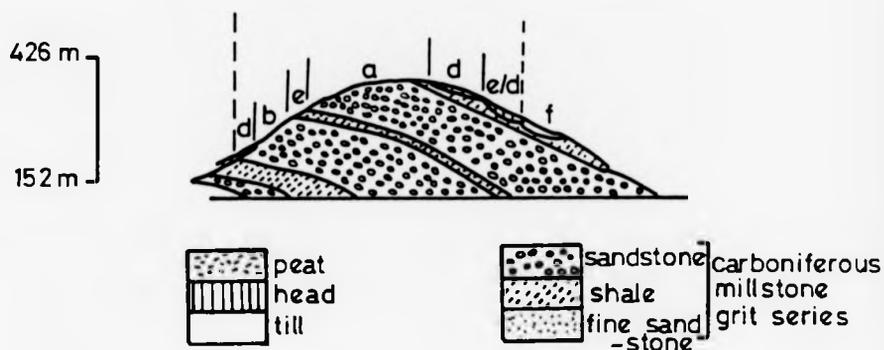
Field map unit	Subgroup
a	Typical brown podzolic soil and typical brown earth
b	Typical brown earth
d	Typical brown earth
e	Stagnogleyic brown earth
f	Cambuc stagnohumic gley soils

FIGURE 2.4.1 (C)

Distribution of the principal soils in map unit 18 (see Fig. 2.4.1 (A))
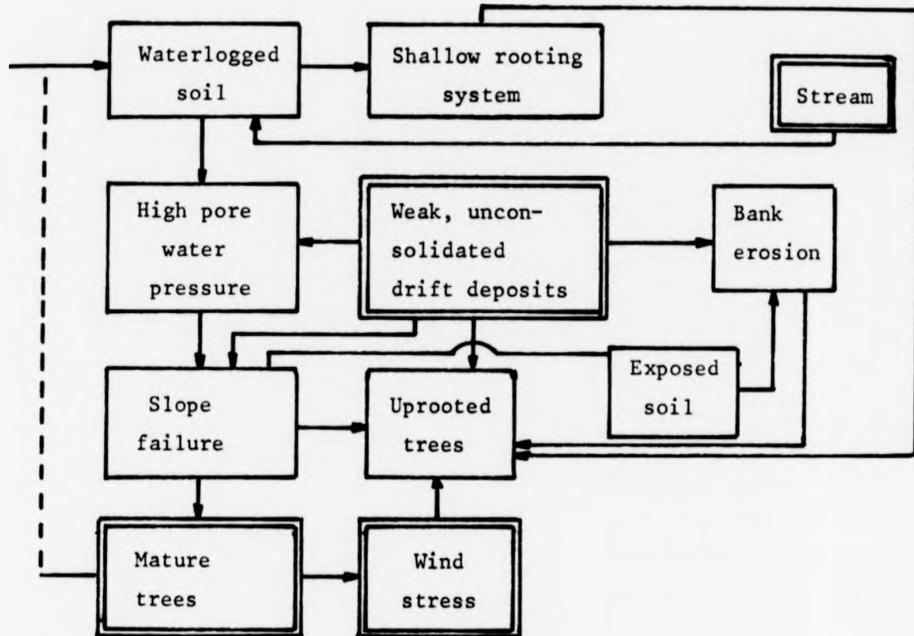
FIGURE 2.2.2   Model shows interrelationships between factors affecting slope failure and the uprooting of trees in an afforested catchment. Principal independent factors in bold boxes, dependent factors in light boxes, and the direction of causal relationships indicated by arrowed lines.   (After Stott, 1985.)

PLATE 2.2.3 (a)   PLATE 2.2.3 (b)

Coombs Brook catchment. Fallen trees (frequently associated with channel bank erosion).

PLATE 2.2.3 (c)

PLATE 2.2.3 (d)

Fallen trees with very shallow roots.

PLATE 2.2.4

The non-afforested part of the catchment of Coombs Brook, illustrating the typical land use up to the 1930s.

waters by the construction of Trentabank Reservoir in 1929 initiated
a radical change in land use.   In response to a predominant concern
for water quality, an afforestation scheme was proposed to replace
the pre-existing farming community.   Afforestation commenced in 1930
on land to the north of Trentabank Reservoir, and the Coombs Brook
catchment was planted in the period 1935-1939 (Plates 2.2.1 and 2.2.2).
Various species were used to provide diversity and improve the recrea-
tional amenity of the forest, including avenues of broad-leaved trees,
mainly sycamore (Acer pseudoplatanus) along public rights of way, and
plots of deciduous conifers, Japanese larch (Larix kaempferi), amongst
more extensive plantations of sitka spruce (Picea sitchensis), Norway
spruce (Picea abies) and Corsican pine (Pinus pinaster) (Fig. 2.2.1).
A small area of the plantations adjacent to the gauging station on
Coombs Brook failed and was replanted in 1965.   Up to the present
time, falling trees and uplifted rootstocks have been frequently
associated with channel bank erosion and mass movements, but the
nature of the relationship suggested by field observations is complex
(Fig. 2.2.2 and Plate 2.2.3 A,B,C,D).   Root development is inhibited
in soils where the water table is near the surface for a large part
of the year, thus making mature trees vulnerable to wind throw.   High
water tables occur in soils adjacent to the stream courses, but high
moisture contents are also associated with the dense plantation canopy,
probably because of reduced air circulation and cooler temperatures.
Mature stands of trees with shallow rooting systems exert a downslope
stress on surface soil horizons which may have contributed to slope
failure.   Gully development beneath rooting systems has been respon-
sible for some tree throw, and this could have been multiplied by the
domino effect as one tree falls onto another.   Thus, apart from a
limited area of open moorland (Plate 2.2.4) on the interfluves which
supports a Fescue/calluna heath community, 92% of the catchment is
presently forested.

Selected areas of poorly drained soils, principally the gleys on
drift deposits of the valley floor, were ditched at the time of plant-
ing.   Stone-pitched channels were laid in the downstream reaches of
Coombs Brook, indicating an early awareness of, or concern for, bank
erosion and high sediment loads.

2.3 DESCRIPTION OF COOMBS BROOK

During field work from April 1984 onwards, a detailed geomorpho-
logical map was constructed (Fig. 2.1.3).   A brief description of the
features is given to avoid congestion on the map.   The source of the
stream is just above the location where the forest road crosses it at
about 336m.   This road was surfaced with stone before the survey was
carried out.   The road improvements caused disturbed soil to be
washed further downstream.   Where the stream crosses the road, it
plunges down an almost vertical face to beds of sandstone and shales
which are characteristic of the Millstone Grit upon which the stream
flows.   Dense undergrowth closely surrounds the stream, and trees,
in places, have been pushed over by a combination of gravity and
accumulation of soil at the uphill side, due to creep.   The stream
proceeds along a deeply cut channel which is criss-crossed by fallen
trees, due mainly to gravity, at certain times running alongside (and
below) old dry stream channels which have not been able to cope with
increased flows of water.

Evidence of marshy ground starts as soon as the channel gradient
lessens and it is no longer deeply incised.   Crossing the length of
the stream are coarse sandstone bands of the Roaches Grits, which are
interbedded with the shales and form resistant ledges and waterfalls
in a stepped fashion.   Mass movements in different places are likely
to fail, with upturned trees lying in marshy areas, and at the base it
slopes with water seeping out from beneath the soil into the adjacent
stream.

Downstream from this location is another road bridge and an area
that has been recently deforested.   The trees cannot stop the mass
movement processes, caused by gravity which, when large-scale soil creep
on steep slopes is combined with flashy storm runoff in the streams,
produce much bank erosion and collapse.   Soil creep causes much
erosion, leading to increases in sediment concentrations.   Certain
tributaries cut a well-defined channel down to the main stream, with
no evidence of waterlogging on the surrounding ground, but some create
expanses of waterlogged marshy and peaty seepages.   The slopes are
very wet and, together with the thick carpet of pine needles, make the

surface materials very unstable.

The walls of sandstone along the stream constructed by the Water
Authority have not solved the problem (Plate 2.3.1 A,B,C). The channels
protected by stonework differ considerably in hydraulic geometry from
the natural water courses further upstream, being generally wider and
shallower (Plate 2.3.2). This increase in width means that low and
moderate flows may be shallower and possibly lower in velocity than in
the narrower natural channels. Thus, on bends, where velocity across
the channel is unevenly distributed, slack water or low velocity deposits
of sand carried from upstream are often found in the stone-lined
reaches.

After high flows, such sand is frequently absent, having been
removed. Subsequent smaller flows may well cause such deposits to
redevelop. Evidence of flash floods is provided by large stones and
boulders lodged in the undergrowth at the top of the protected banks.
In other locations, the ground immediately behind the protected bank
is waterlogged, causing trees to be uprooted due to lack of grip.
The rest of the stream length is through this protected channel, with
occasional breaks. Ponded water, on the flood plain surface, tribu-
taries along well-defined channels and dry channels also occur. Often
dry and flowing channels run alongside each other and criss-cross, follow-
ing in part the drainage lines made when the forest was planted.

Towards the end of its length, the stream enters a system of pipes
(Plate 2.3.3) which carry it underground until it emerges just above
the V-notch weir (Plate 2.3.4). Below the weir, the stream flows in
a culvert beneath the tarmac road bridge to enter Trentabank Reservoir
(Plate 2.3.5).

2.4 SOIL IN THE STUDY AREA

As yet, no detailed soil map of the Macclesfield Forest area is
available, although it is shown on a general soil map of Cheshire.
North-west England is dominated by fine and medium-textured soils
derived from a wide range of Pleistocene drift deposits, such as those
shown in Fig. 2.4.1(a)(b) and (c). The effects of the Pleistocene

PLATE 2.3.1 (a)   Coombs Brook catchment.   Stone-pitched channels laid in the downstream reaches.
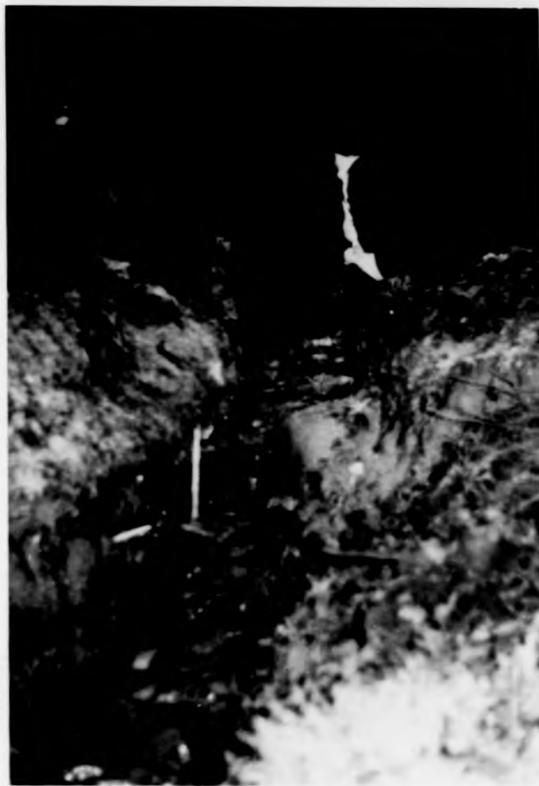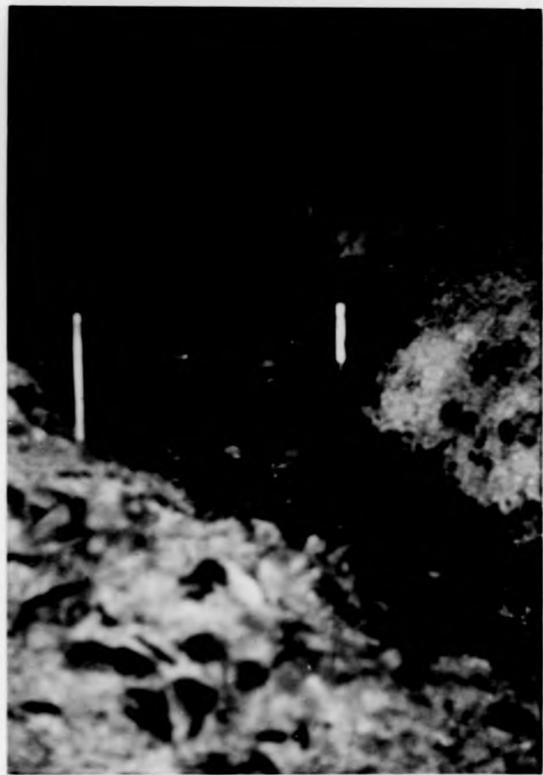
PLATE 2.3.1 (b)   Coombs Brook catchment.   The unprotected channel and bank erosion activity.

PLATE 2.3.1 (c)   Coombs Brook catchment
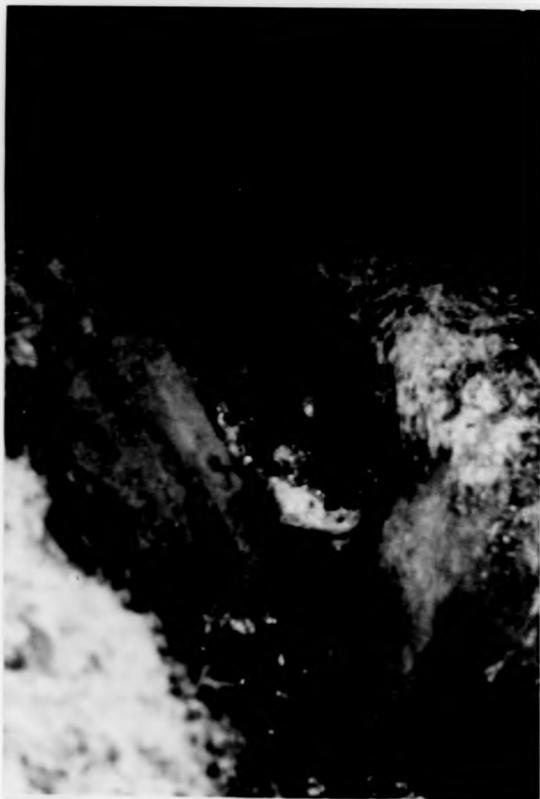
The unprotected channel, indicating an early
concern for bank erosion and high sediment
loads.
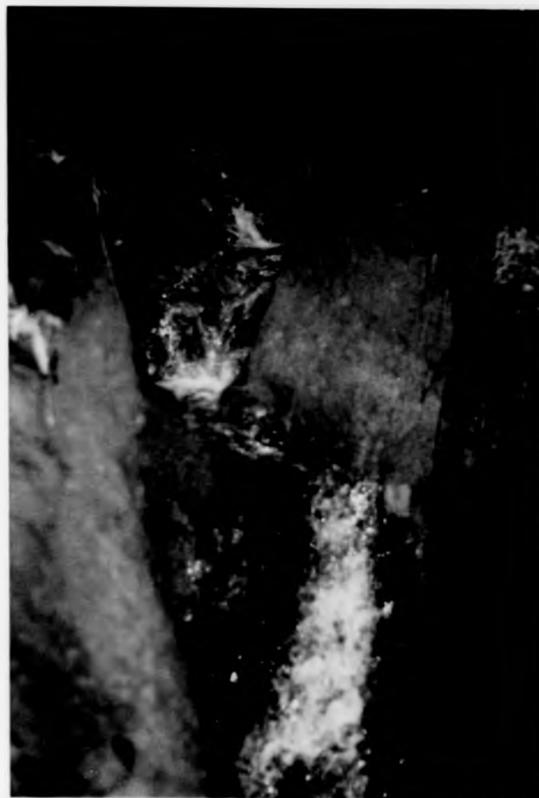
Valley-side slumps.

PLATE 2.3.2 (a)
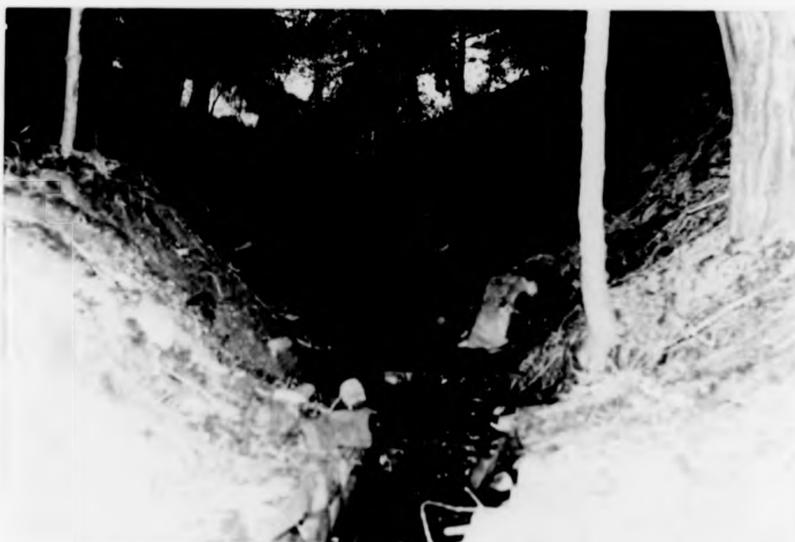
PLATE 2.3.2 (b)

Coombs Brook catchment. Channels situated upstream are
generally wider and shallower and subject to active
erosion processes.

PLATE 2.3.3

Coombs Brook catchment. The stream enters a system of pipes
which carry it underground until it emerges a short distance
above the V-notch weir.

PLATE 2.3.4

Coombs Brook catchment. The V-notch weir gauging station
downstream.

PLATE 2.3.5

Coombs Brook catchment. Below the weir the stream flows in a
culvert beneath the tarmac road bridge, to enter Trentabank
Reservoir.

glaciations and intense Devensian periglacial activity virtually obliterate any Tertiary or inter-glacial soil profiles.

Soil associations in Cheshire (Furness, 1978) comprise soil sequences in which the intensity and extent of gleying in the soil profile are determined by topographic position and site drainage. Each soil association is related to a particular parent material and the geographical name of the dominant, or most commonly occurring, soil (soil series) in the association is given to the whole association as on the recently published national 1:250,000 soil maps.

The soil associations of the Macclesfield Forest are closely related to the Carboniferous bedrock and the overlying Pennine drift, the medium and fine-textured till material already described (Fig. 2.4.1). Furness (1978) classifies each series of the soil into units (Table 2.4.1 and Fig. 2.4.1(a) and (b)).

The Brickfield association, recognised up to about 230m, is dominated by soils which are slowly permeable and seasonally waterlogged with fine loamy textures. They are generally stagnogleys (surface water). Furness (1978) recognises these soils, in Map Unit 29, as being predominant in the Macclesfield area. He restricts these soils to the lower slopes of the Pennines. They occur on moderately undulating country, mainly with slopes 0-70°, though in the field work survey this figure seems to be rather low, and in fact would appear more reasonable at around 0-10°. Annual rainfall is moderate at 1000-1038 mm and is augmented by runoff from adjacent slopes, which intensifies the surface wetness problem.

The soils within Map Unit 29 range from the stagnogleys and gleys to gleyed brown earths (mostly found on the steep slopes at slightly higher altitudes) which overlap with Map Unit 18 (Furness, 1978). The soils of this Brickfield association are formed on greyish brown medium and fine-textured, often stony, till and head. This is only slowly permeable and results, under high rainfall, in the formation of stagnogley soils characterised by strong mottling, particularly in the surface and immediate sub-surface horizons.

Above 230m, cooler temperatures and higher rainfall (1020-1520 mm) lead to the formation of acid root mats and peat accumulation, particu-

TABLE 2.4.1   COOMBS BROOK CATCHMENT SOIL UNITS
                (after Furness, 1978)

Map Unit	Principal Soil Series	Soil Sub-group
18	Rivington	Typical brown earth
	Withnell	Typical brown podzolic
	Swindon bank	Typical brown earth
	Heapey	Stagnogleyic B.E.
29	Brickfield)	
	Hallsworth)	Combic stagnogleys
30	Wilcocks)	Combic stagno humic
	Ruddlesworth)	gleys
	Unnamed)	Typical alluvial gley

larly on the highest, gently sloping surfaces. The upland soils
formed under these conditions, termed the Wilcocks association, are
slowly permeable, seasonally waterlogged peaty surface water gleys,
with very dark grey clay loam topsoils over grey, distinctly mottled
clay loam or clayey subsoils. These wet and acid peaty soils are
colonised by moorland plants, including mat gross (Nardus stricta),
purple moor grass (Molinia caerulea) and cotton sedge (Eriophorum
vaginatum). Peat becomes extensive with increasing elevation, and
organic soils of the Winter Hill association occur. Depending on the
local site conditions, aspect and rainfall, the change takes place
between 300 and 550m. The Wilcocks association is included in Map
Unit 30 (Furness, 1978) as peaty stagnohumic gley soils.

The Rivington association of soils is associated with the
Carboniferous mudstones, shales and the more resistant sandstones and
grits. It occurs on moderate or steep slopes below about 260m,
generally between 167 and 396m O.D (Furness, 1978). This soil asso-
ciation includes the typical brown earths found in Macclesfield Forest.
These free-draining brown earths have dark brown stony topsoils
passing into yellowish brown weathered B horizons. Fragments of sand-
stone usually increase with depth, so that between 40 and 60 cm they
dominate the solum. Furness (1978) also notes that south of Macclesfield
some red fragments and reddish staining down the profile occurs, which
he attributes to a relic feature of an eroded Triassic cover. These
soils are generally slightly moderately acid. The Withnell associa-
tion, at about 260m, is dominated by brown podzolic soils. These soils
are often distinguished by their sesquioxide enriched subsoils. These
soils follow on from those of the Rivington association. They are
free-draining soils. Furness (1978) includes them also under Map Unit
18, with the Rivington association soils. These complex patterns of
soil in and around Macclesfield Forest obviously reflect the diverse
soil-forming conditions and the wide range of parent materials on which
the soils lie. Often the overwhelming influence of the heterogeneous
drift deposits dominates the pattern of soil associations (Johnson, 1985).
Some soil sequences reflect the hydrological conditions, so that some
associations are dominated by free-draining, especially those developed
on drift diverse hydrological conditions related to altitude and slope.

2.5 THE FIELD EVIDENCE OF GEOMORPHIC AND HYDROLOGIC PROCESSES

2.5.1 Hydrologic Evidence

Hydrologically, the catchment area may be sub-divided into an upper and a lower basin. The area has high infiltration capacity, such that infrequent heavy storms produce overland flow, caused by saturation building up above the A horizon, until it reaches the surface, where detention storage and finally overland flow occurs. When overland flow does not occur, water moves as throughflow into the organic infill of the upper stream bed, or into the brown earth. Throughflow is the dominant pathway for runoff to streams in the area. Even the largest storms failed to produce overland flow in parts of the area, as the infiltration capacity is much greater in brown earth soil than gley soil.

The soil-forming processes are part of the overall biogeochemical processes affecting movement of solutes in the catchment system. All the water that eventually flows into the Coombs Brook passes through or over the soil, except the small amount of direct channel precipitation. Much of the stream flow has spent a considerable period of time as soil moisture. Among the factors influencing chemical composition of soil moisture are the solution or alteration of soil minerals, selective removal and circulation of nutrient elements by plants. Water moving through soil dissolves some CO_2. The H^+, HCO_3^- and CO ions are potent forces in controlling the pH of the water and in attacking rock minerals. The ultimate source of most dissolved ions is the mineral assemblage in rocks near the land surface.

2.5.2 Geomorphic Evidence

Sediment supply in the catchment appears to be dominated by channel bank and mass movement associated with bank collapse and drainage net-work. Field evidence suggests that the geomorphic system is respond-ing dramatically to land use change; sediment deposition in Trentabank Reservoir may provide further evidence to support this contention. The observations suggest supply-limited sediment transport, with sedi-ment being made available either by overland flow during storm precipi-

tation, or by the evacuation and erosion of sediments within the channel, in addition to sediment being made available by needle ice during periods of freeze-thaw activity, especially from January to March. Exposed soil and substrate beneath rootstocks are particularly vulnerable to further erosion by rainsplash or surface runoff.

2.6 RESULTS OF PREVIOUS INVESTIGATION IN COOMBS BROOK

The previous studies by Stott (1985) showed the accumulation of sediment in the reservoir at a measurement point downstream. His results indicate that:

(1) Over 60% (1.84 km) of the permanent channel network provides evidence of active erosion, including bank erosion, incision and valley-side slumps.

(2) The Coombs Brook has a very flashy response to storm precipitation characterised by a sharp rise from baseflow of 10 to 30 1 s^{-1} to stormflow discharges of 60 to 200 1 s^{-1} with a lag time following effective precipitation of less than three hours.

(3) Maximum suspended sediment concentrations of 1600-2000 mg 1^{-1} coincided with peak storm runoff.

(4) Within storm variation is characterised by a clockwise loop, with lower sediment concentrations, at equivalent discharges, on the falling stage.

(5) Successive rising stages during multi-peaked runoff events recorded lower rate of increase of sediment concentration with discharge.

(6) Increases of sediment concentration after peak discharge can be explained by bank collapse or the bursting of temporary debris dams within the stream channel.

(7) High sediment concentrations occurred during relatively small storm flows following long periods of baseflow recession, for

example on 18.6.82, suggesting the accumulation or preparation
of sediments within the channel and slopes between storm events.

(8) Significant correlation ($r = 0.66$) between log transformations
of predicted suspended sediment load and bed load over the same
time interval.

(9) Variations in the sediment load of Coombs Brook were observed
on three timescales, each related to the characteristics of
storm events.

   A. Within storm events sediment concentration increased
rapidly on the rising stage to over 200 mg 1^{-1} at
discharges in excess of 80 1 s^{-1}, up to a maximum of
2000 mg 1^{-1}, before falling to about 30 mg 1^{-1} at a
discharge of 40 1 s^{-1} on the recession limb.

   B. Daily suspended sediment load estimates vary from
negligible amounts during periods of baseflow to a
maximum of 1.5 t during the heaviest rainfall day of
the year, 25.6.82, which received 31.5 mm of rainfall
in 24 hours.

   C. Seasonal contrasts in sediment transport events are
indicated by the different rating curves obtained for
the two halves of the year.

Seiler (1984), studied the chemistry of water at seven sites in
the catchment area for one year, and concluded that:

"The pH figures of rainfall are quite high in an environment
near to a highly urbanised area. This is presumably caused
by fairly high concentration of Ca^{2+}, Na^+, and K^+ buffering
the chemical properties of the rainwater. The Ca^{2+} values
during summer exceeded other ions in stream, but the K^+
values in rainfall are higher than other ions.

The comparison between the summer period (April-September)
and the winter period puts the idea forward that the pH
decreases during the winter period. Especially after 21st
October, a distinct fall of pH can be seen, which seems to

be related to a sharp decrease of temperature."

These stages may be phrased as general hypotheses in the catchment area:

- Spatial variation in water quality may be quite marked, even in an area of apparently uniform vegetation. Temporal changes due to variations in hydrologic inputs, and seasonal conditions, may also vary within a small catchment area.

- Natural variations in stream chemistry are primarily controlled by hydrological and geochemical processes and the interaction between them.

CHAPTER   THREE

EXPERIMENTAL   DESIGN

Introduction

CHAPTER   THREE

EXPERIMENTAL   DESIGN

INTRODUCTION

To understand the hydrochemistry of a small catchment, a wide
range of parameters indicating water and chemical circulations has
to be measured.   This chapter describes the field instrumentation
and sample collection procedures adopted to measure the quantity and
quality of precipitation, throughfall, soil water and stream discharge.
Procedures for sampling soil, vegetation and bedrock are also described.
The principles governing the design of the measurement network, type
of instruments and sample collection are considered for each compon-
ent of the system in turn.   The system used in this study is shown
in Table 3(a).   The resulting data will be discussed in subsequent
chapters.

3.1   SAMPLING FREQUENCY

"By necessity the sampling schedule adopted is usually a compro-
mise between the accuracy and detail desired and the funds and person-
nel available." (Rainwater and Thatcher, 1960, p.7.)   As spatial
variation in sources of solutes and sediments was a prime concern of
this study, and as the pattern of seasonal variation was unknown at
the start of the study, a once-weekly sampling system for visiting
each of the seven selected sample stations between 0930 and 1100 every
Wednesday was adopted.

Daily and, on two occasions, hourly sampling was used to investi-
gate the likely magnitude of shorter interval changes in some consti-
tuents.   An interval of less than one week would have produced an
excessive number of samples for analysis.   In the weekly sampling pro-
gramme, which ran for the 24 months from May 1984 to April 1986

TABLE 3(a)   THE COOMBS BROOK CATCHMENT SYSTEM

(1) Independent Variables	Parameters Used	
	Measured	Derived
1. Precipitation	Pluviograph Chart Daily-read gauges	Maximum 30-minute intensity Daily precipitation Precipitation in previous 5 days
2. Temperature	Thermohydrograph	Days of frost
3. Climate	Seasonal temperature change Causes of rain/snow	

4. Hydrometeorological	Daily precipitation (rain/snow)
	Daily/hourly throughfall
	        overland flow
	        water depth in wells
	Stream flow	

5. Geology: Lithology	Bedrock lithology Soil grain size Soil chemistry Soil profile characteristics	
6. Vegetation	Type and density	
7. Relief or volume of system	Above base level	
8. Hydrology	Runoff characteristics and erosive potential of each terrain unit	
9. Drainage network morphology		
10. Hillslope morphology		

TABLE 3(a) (Continued)

(2) Dependent Variables   Parameters Used

Dependent Variables	Measured	Derived
1. Discharge	Water level chart Stick gauges	daily mean flow water level and instantaneous discharge at time of sampling baseflow flood to peak interval lag time
2. Throughfall		
3. Water quality	Ca^{2+} Mg^{2+} Na^{+} K^{+} SO_4^{2-} PO_4^{3--} NO_3^{-} Cl^{-} Fe Mn	
4. Sediment concentration	Suspended sediment Bed load particle size Bed load characteristics	Chemical composition of sediment

inclusive, the time lapsing between the collection of the first and last sample was usually not more than two hours.

A weekly time interval was used in the Hubbard Brook Ecosystem study (Likens et al., 1967) and by Steele (1968) in his study of discharge concentration relationships in a Californian catchment. Park et al. (1970), however, collected samples from the Colorado River basin only once a month in an investigation of the variations of nutrient concentration.

In his discussion of the frequency of sampling and the number of samples needed to give a representative description of the dissolved load of a river, Hem (1959, pp.14-18) states that samples should be collected frequently enough to ensure that no important cycle of concentration is missed. Since, in practice, the dissolved load of a stream varies principally with the discharge, the frequency of sampling should be determined by variability of the discharge. A stream such as Coombs Brook, characterised by rapid fluctuations in discharge, requires more frequent sampling than others where the groundwater discharge is relatively steady. A sample from the Coombs Brook could not be extrapolated to represent more than one or two days' runoff, while on other streams a sample might be representative of several weeks.

As samples were at weekly intervals, they do not provide an uninterrupted or continuous record of the dissolved load concentration. Lack of time and automated sampling equipment made more frequent sampling impossible, but a Northants automatic vacuum sampler was installed at Station 1 to collect samples every eight hours. This record enabled storm-period changes to be compared with seasonal variations in water quality.

3.1.1 Position of Collection in Channel

A true solution consists of a perfectly homogeneous dispersion of molecules or ions in a solvent. Sampling dissolved load should not pose the problems of variations in concentration with velocity in the channel cross-section which affect suspended sediment sample collection. However, on major rivers there is the problem of mixing of water from

different tributaries in the main river.

An extreme example of this is recorded by Mackay (1970) in northern Canada, where the water from the Laird River can still be identified 330 km downstream from its confluence with the Mackenzie. Such problems are minimal in small catchments, such as the Coombs Brook, where samples were collected by US DH 48 depth-integrating hand suspended sediment sampler where the water was deep enough. Otherwise, a bottle was held by hand in the most turbulent part of the stream at each of the seven sampling sites.

3.1.2 Sample Containers

Samples were collected in 250 ml polyethylene bottles, which were first rinsed several times in the stream. The time of collection was noted. Polyethylene bottles are both more convenient than glass ones and are not known to have any reactions with the constituents to be analysed. The samples were usually returned to the laboratory within 1.5 hours of collection. Immediately after arrival at the laboratory, pH and conductivity were determined, the samples were filtered and a sub-sample was placed in deep freeze.

3.1.3 Sampling of Water for Quality Determination

The main problems encountered in water sample collection were:

(1) During the cold winter period, from December to February, frost action affected the Northants Automatic Sampler, breaking many glass bottles and blocking the inlet pipes with ice. Freezing of the surface stream water made sample collection difficult, and rainwater samples also were frozen at times.

(2) During the summer period, the tributaries dried out at some stations, particularly at Station 3. Lack of continuous samples at these critical times was a handicap.

3.1.4 Discharge Measurement

At Station 1 an Ott weekly chart recorder was installed to pro-
vide a continuous record of water stage. The 90° V-notch weir,
installed by A.P. Stott and the North West Water Authority in 1981,
provided a means of calculating discharge from the stage record, using
the weir formula:

$$Q = 0.0138 \ H^{2.5}$$

where Q is discharge in $l \ s^{-1}$ and H is water depth over the V-notch
in cm.

(Based on Barnes' formula as given in the Manual of British Water
 Engineering Practice, Fourth Edition, 1969.)

Daily means were derived from the calculated values.

At Stations 2 to 7, simple stick gauges were installed and the
water level noted at the time of sampling. Current meter gauging,
using a Pygmy Ott current meter, enabled a stage-discharge rating curve
to be established for each station.

No data are available on the accuracy of the discharge records
from these stations, but data from other areas suggest that the record
from a good control structure, such as a flume, should be accurate to
within ±1-2%, while that from a good rated section should be about ±2%
(Gregory and Walling, 1973).

3.1.5 The Collection of Sediment

Suspended sediment sampling involved the sample collection proce-
dures described in Section 3.1. More frequent sampling would have
been desirable for storm event studies, but this was not possible in
the context of present work. Bed material sampling, necessary to cal-
culate the bedload, involved episodic evacuation of material trapped
behind the weir at Station 1. In this way, the volume accumulated over
a given time period was able to be calculated. Sampling of bed material
at Stations 2-7 at different times of the year gave information.

3.2 PRECIPITATION

During the study period precipitation was measured, using a standard

British Meteorological daily-read gauge 12.7 cm, W5006, and also was monitored continuously by a recording gauge, both situated close to Station 1 (Plate 3.2.1). Additionally, six rain gauges were installed further upstream. The locations of the gauges are shown in Fig. 3.2.1.

Rain is not the only form of precipitation and snowfall also must be measured. Snow that entered the gauge was measured as precipitation, but not all the snow may enter the gauge; some may fall off it and lie outside it, and so not be measured. From the recording rain gauge charts, hourly rainfall was determined. On the few occasions when the rainfall recorder did not operate properly, hourly rainfall at the North West Water Authority River Division's gauge, 0.8 km from the catchment in Macclesfield Forest, was interpolated, corrections being made for differences in total rainfall.

Although the solute content of precipitation is unlikely to vary significantly over an area as small as the Coombs Brook catchment, rainfall samplers were located throughout the catchment area in locations as far from trees as possible. Precipitation collectors were of two different types. Rain collectors consisted of open polyethylene funnels connected to polyethylene reservoir bottles. Wide-mouthed polyethylene buckets served as snow collectors. The collectors, similar to those used by Gore (1968), comprised a polyethylene funnel of 300 mm diameter, fitted into a polyethylene bottle. Nylon gauze of 0.30 mm mesh size was placed over the end of the funnel to prevent insects, leaves and large particles getting into the bottle. The apparatus stood 40 cm above the ground. Every week the collector was returned to the laboratory and replaced by an identical collector. In the laboratory the container was emptied, cleaned with dilute HCl and had the gauze replaced. The rainwater was filtered and analysed following the same procedure as that adopted for stream water samples.

The material of the collector may significantly influence the composition of rainwater. Juang and Johnson (1967) found that polyethylene screens adsorbed appreciably more Cl^- than metal ones. The height of the collector above the ground is also important, as those near ground level will be more affected by splash-in and dust than those placed at greater heights, such as the 3m standard used in the U.S.A. network.
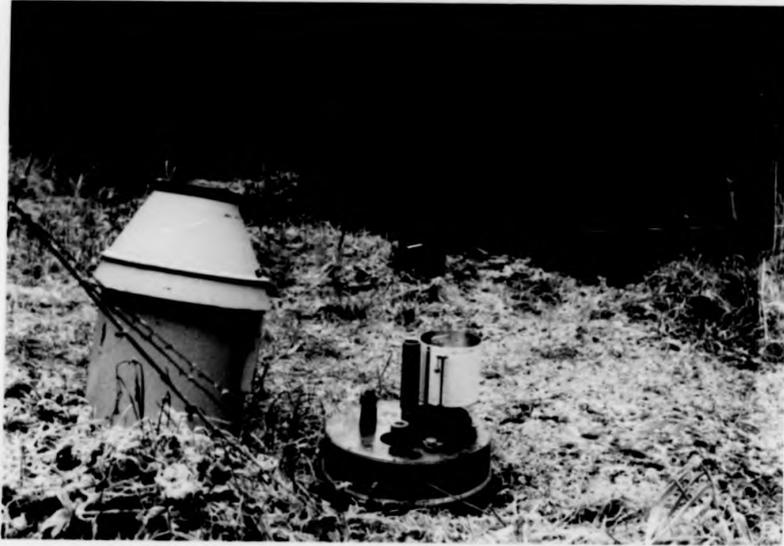
PLATE 3.2.1

Recording rain gauge situated above the outlet of the catchment.

PLATE 3.3.1

Collecting stemflow by placing collars around the stems of trees.
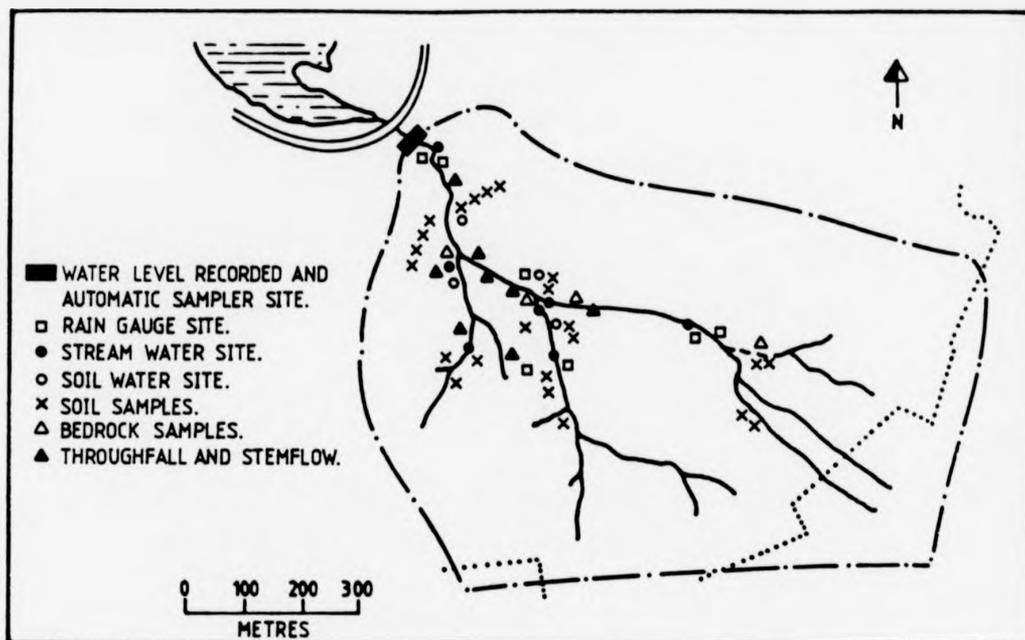
FIGURE 3.2.1   Coombs Brook catchment.
Instrumentation and field work site
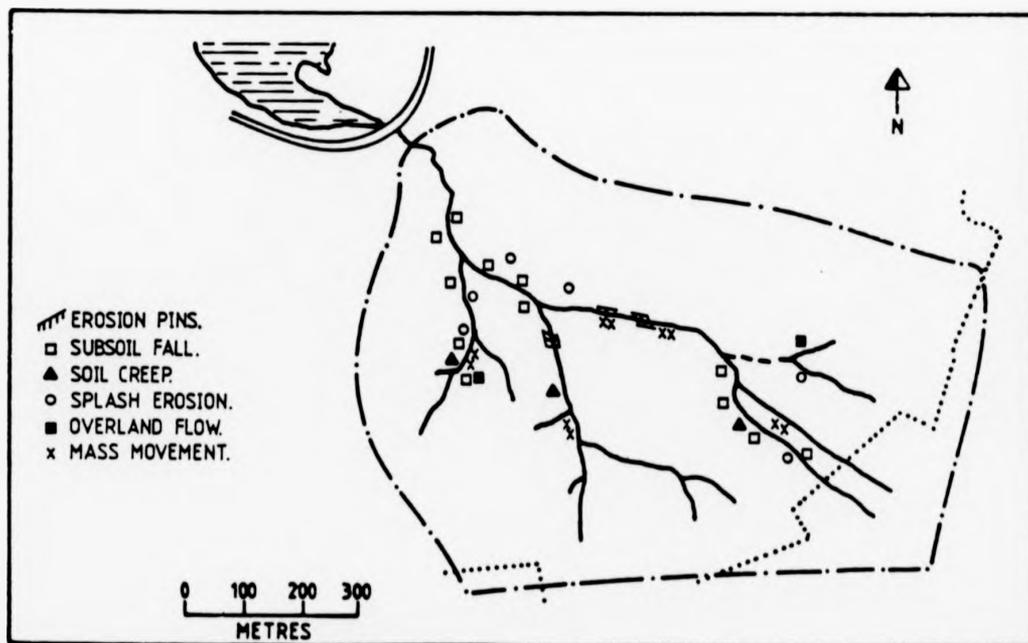
FIGURE 3.6.1   Coombs Brook catchment. Field work – experimental location
of erosion processes measurements

Although the network of gauges within the catchment is relatively sparse, it was considered adequate to record the amount and variability of precipitation for the purposes of this project. The gauges are well spaced within the catchment (Plate 3.2.1) and an analysis of variance showed no significant differences between the weekly amounts of precipitation recorded at the four gauges.

Rain gauges made out of metal, such as the standard gauge, are not suitable for collecting samples for chemical analysis, as contamination of the sample by reaction with the metals could lead to serious changes in composition, especially of metallic constituents such as iron. Gauges constructed entirely of polyethylene cause least contamination of the sample and have been used in many studies of precipitation chemistry (e.g. Allen, 1974; Gore, 1968; Likens et al., 1967). Accordingly, four all-polyethylene rain gauges were constructed and sited beside the standard gauges in the catchment. Like the standard gauges, they were visited weekly. The data from the standard gauges were used to compute the amount of water entering the catchment, and samples of the precipitation caught by the polyethylene gauges were taken back to the laboratory, analysed, and used to assess the concentration of chemical species in the precipitation.

Finally, three main problems were associated with precipitation sampling:

1. The rain gauges inevitably sampled dry fallout, but whether that dry fallout was an addition from outside the catchment or was derived from within the catchment was unclear. In practice, it is impossible to separate chemical inputs of external origin from those derived from within the catchment.

2. The samples collected in the precipitation samples suffered contamination from three sources: particles of vegetation blown into the sampler; insects falling into the sampler; and dust blown into the sampler. The ground-level position of the samplers possibly aggravated this contamination.

3. As samplers were collected only once a week, there could have been some loss from containers by evaporation.

3.3   THROUGHFALL, STEMFLOW AND LEAF SAMPLES

Nutrient losses from plants carried to the ground by throughfall or stemflow are a significant component of the catchment geochemical budget.   Material is both leached from the leaves and washed off their surface.   Dry fallout often accumulates on foliage to be washed off by rain.   Throughfall was sampled by placing three collectors under each of six trees (Fig. 3.2.1 and Table 3.3.1).   One collector was placed 1m from the stem, another was placed in the 'drip zone' at the edge of the trees canopy, and the third collector was placed midway between the other two (Fig. 3.3.1(a) and (b)).   Stemflow was collected from each of the six trees with polyurethane collars and led into polyethylene collection bottles, as described by Likens and Eaton (1970).

Throughfall and stemflow samples were collected and filters changed weekly.   During periods of high rainfall, collections were made more frequently to prevent the collection bottles from overflowing. Samples collected in the field were brought back to the laboratory as soon as possible.   The pH and conductivity of the samples were determined immediately on returning to the laboratory.   Samples were then stored until a batch of 30 was ready for the analysis of Ca^{2+}, Mg^{2+}, Na^+, K^+, PO_4^{3-}, SO_4^{2-}, Fe and Mn by plasma (200), NO_3^- and Cl^- by titration.   Falling leaf litter was collected in six traps distributed in different parts of the catchment area.   Each trap was a plastic basket of 0.2 m^2, positioned 0.5m above the forest floor.   Collections were made once, in autumn (October to mid-November 1985), while the rate of litter fall was high.

The redistribution of leaves through wind action may affect the structure and function of forest and stream ecosystems.   Loss of litter from the forest floor in the upper stands on a surface slope should lead to a reduction in soil organic matter in all horizons. Concomitantly, the concentration of soil nutrients may also reflect surface slope leaf transport.   Structurally bound elements, such as Ca^{2+} and PO_4^{3-}, should have higher concentrations in soils at the base of the slope, where leaves are accumulating, while a readily leached element, such as K^+, may have near-uniform concentration in soils along the entire slope.   Finally, downslope leaf movement may strongly

TABLE 3.3.1   MAIN TYPES OF TREE FOUND IN THE CATCHMENT AREA

A. Coniferous (softwood) tree species

    1. Japanese larch (Larix leptolepis)

    2. Corsican pine (Pinus nigra var. calabrica)

    3. Norway spruce (Picea abies)

    4. Sitka spruce (Picea sitchensis)

B. Deciduous (hardwood) tree species

    1. Common alder (Alnus glutinosa)

    2. Common hawthorn shrub (Crataegus monogyna)

    3. Ash (Fraxinus excelsior)

    4. Sycamore (Acer pseudo-platanus)

C. Other species

    1. Buckler fern (Dryopteris dilata)

    2. Guelder rose shrub (Viburnum opulus)

    3. Lesser found sedge (Carex acutiformis)
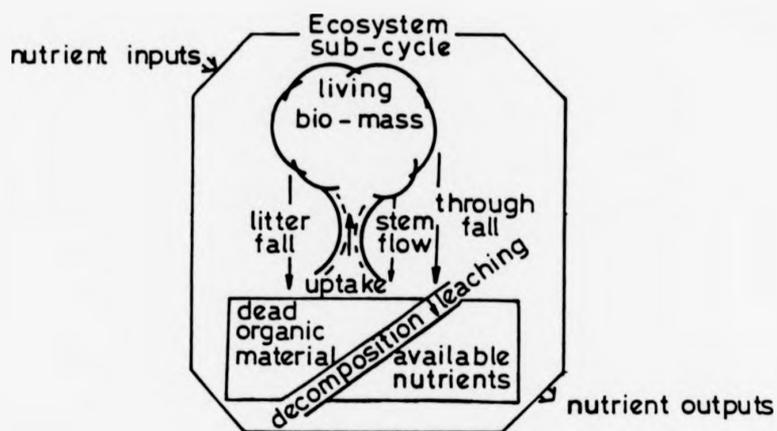
FIGURE 3.3.1 (A)

Relationships for a sub-system of the intra-system nutrient
cycle for a terrestrial ecosystem
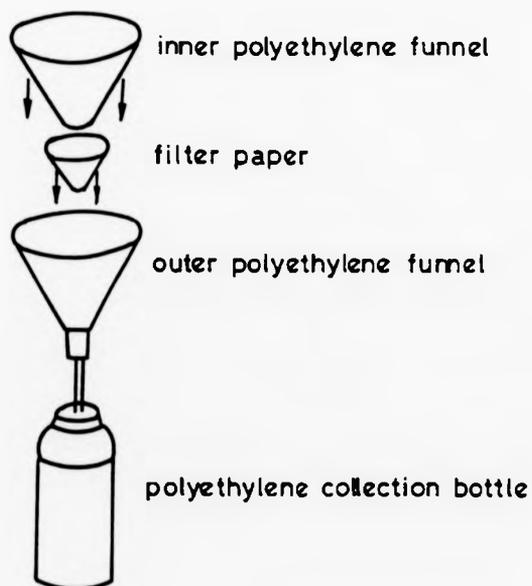
FIGURE 3.3.1 (B)

Polyethylene throughfall collector

influence the energy budgets and nutrient dynamics of small forest streams by increasing the allochthonous inputs (Triska and Sedell, 1976; Webster, 1977).

Problems arising during sampling of throughfall and stemflow include:

1. Throughfall collectors suffer all the problems experienced by rain gauges, but the litter fall and contamination beneath the vegetation is much greater.

2. Containers were sometimes blown over in high winds.

3. Leakage between the trunk and polyurethane collars of stemflow collectors limited the value of these samples. Stemflow data are therefore unreliable, only providing a qualitative indication of the importance of stemflow in the catchment geochemical budget (Plate 3.3.1).

3.4 SOIL WATER SAMPLES

In the Coombs Brook catchment restricted zones of marked surface saturation occur in the lower parts of the catchment, particularly between Stations 1 and 2 at all times of the year. These zones indicate the importance of subsurface water movement downslope towards the stream channel. To ascertain the nature of these subsurface water fluxes, subsurface water monitoring wells were constructed.

Three holes were augured to depths of 20 cm, 50 cm and 90 cm at four sites close to the mean channel in the lower part of the catchment (Fig. 3.2.1). Areas of both gley soils and brown earths were sampled. The 90 cm deep holes were used to distinguish between shallow subsurface and groundwater (Fig. 3.4.1(a) and (b)). In the chosen locations, the soil at 90 cm is almost permanently saturated, so that changes in water level in the 90 cm wells reflect fluctuations of the water table proper.

Although measurement at water table level is inherently simple, one practical problem arose occasionally. When the water table was

-78-
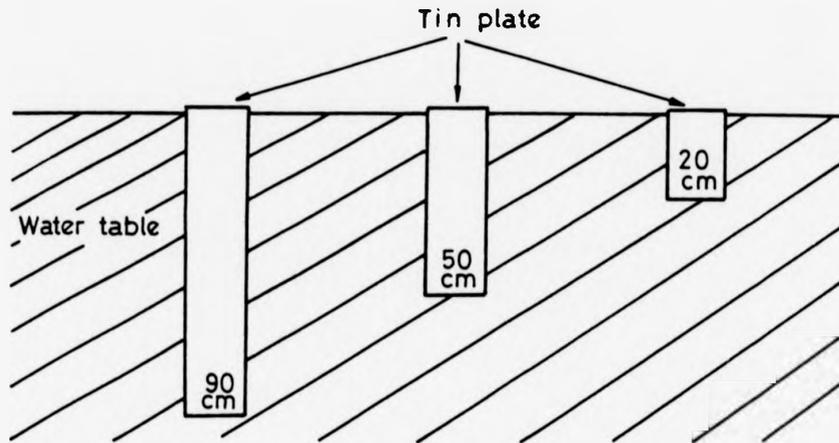
FIGURE 3.4.1 (A)   Measurement of the water table level by
the dip-well method
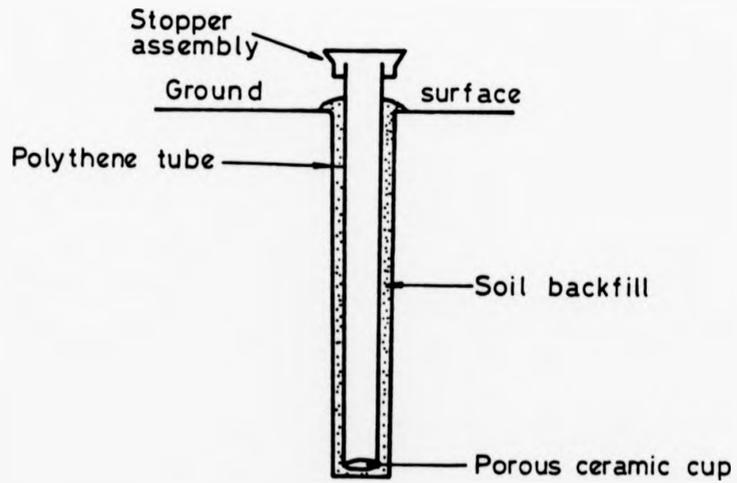
FIGURE 3.4.1 (B)   Soil water sampler in position of the
field work

low, the water surface in the hole was not clearly visible and some
inaccuracy in measuring the depth to the water table was inevitable.
Sometimes, in extremely wet periods, the saturated zone reached the
ground surface and water appeared to flow out of the top of the well
tubes.

3.5 SOIL SAMPLES

The aim of studying the soil is to examine the soil sequences and
profiles of the Coombs Brook catchment.   This examination was made
through both physical and chemical analysis of the soil.   The analysis
will produce information about nutrient content (exchangeable bases Ca^{2+},
Mg^{2+}, K^+ and Na^+), organic matter content, and pH determined.   Six
slopes were chosen (Fig. 3.2.1), some with a coniferous tree cover, and
others with a deciduous cover.

On each slope, four soil pits were dug at strategically chosen
positions along a slope catena sequence.   Samples were taken at 5-10 cm
intervals down each profile to a depth of between 50 and 100 cm.   At
each profile, site descriptions and soil profile descriptions were made.
These included elevation, aspect, angle of slope, soil texture, soil
structure and soil colour; other environmental factors, such as climate,
vegetation and parent material, were also noted.   The samples were then
analysed in the laboratory.   From the results obtained a full account
of the changing soil characteristics within a profile and between pro-
files, according to changes in vegetation drainage, was made.

3.6 MEASUREMENTS OF EROSION

One objective of this thesis is to locate the areas supplying sedi-
ment to the catchment streams.   Sixty per cent of the streambank
length in the Coombs Brook shows signs of erosional activity (Stott,
1985).   Six erosion processes were distinguished as being active on
the streambanks in detaching and transporting soil material (Fig. 1.4.1):
lateral corrasion (bank scour), soil creep, subsoil fall, rainsplash
erosion, overland flow and mass movements.   Many techniques for

measuring erosion in the field have been developed in recent years; those used in this study and the processes affecting stream banks at different sites (Fig. 3.6.1) are outlined in Table 3.6.1.

(1)   Erosion pins

Bank erosion has been studied because it represents a significant contribution to the sediment output of a stream system and undoubtedly influences stream water chemistry.   Although the contribution of river banks to the total sediment budget of a stream is highly variable in space and time, it may account for over half the total supply of sediment to the channel (Carson et al., 1973;   Richards, 1982).

Bank retreat was monitored at five sites, using 80 erosion pins, arranged in dense grid networks, in order to define spatial variability in material removal.   An erosion pin, a length of metal rod, is inserted into the bank material 15 cm, so that only a small portion remains visible.

Lateral corrasion measurement sites

Site selection

It was clear that, if one of the main foci of the study was the investigation of bank erosion processes, then sites which appeared to be actively eroding would have to be sought and instrumented.   With these aims in mind, and following selection of the catchment, almost the whole length of the stream was walked in order to select appropriate bank erosion measurement sites over the 3500 m of stream involved (Fig. 3.6.1 and Table 3.6.2).

Usually four pins were installed at various heights from bank-foot to bank-top, to represent one vertical section.   The common spacing between verticals was 20 cm.   A total of 80 pins was installed in March 1985.   The location of each pin was recorded with respect to water level and flood plain tie points at the time of installation.   The pins were read at approximately monthly intervals, although difficulties of accessibility in winter led to postponement of some readings.

TABLE 3.6.1   MEASUREMENT METHODS OF EROSION AND SEDIMENT

Erosion process	Measurement technique	Units of measurement	Accuracy	Limitation
1. Lateral corrasion	Erosion pins 15 cm	Change in pins exposure in mm	±3 mm	Effect of pin insertion on soil
2. Subsoil fall	Small traps (10 x 12 cm)	Sediment supply in grams	±4 grams	Occurrence of subsoil fall, size and form
3. Soil creep	A simple wooden frame 30 x 30 cm, with 4 edges fixed in the soil, covered with 1.5 mm of nylon, and a small tray was dug into the soil.	Soil transported in g/cm	±4 grams/ 30 cm	Soil material loss, and transported by creep
4. Overland flow	Erosion pins 30 cm, troughs	Change in pins protruding length in mm	±5 mm	Effect of pin insertion on soil
5. Mass movement	Erosion pins (0.8m) & map	Change in pins exposure in cm	±1 cm	Rate of slope retreat due to rapid mass movement
6. Splash erosion	52 mm diameter funnels, buried flush with the ground surface	Sediment supply in grams	±2 grams	Soil material loss from the surface
7. Throughflow	Baseflow volumes from water level recorded	Suspended sediment concentration mg/1	-	Estimated value of baseflow
8. Bedload output	Weight by kg	kg	±4 kg/y	Output of bedload

Stream banks and valley slopes

TABLE 3.6.2   DETAILS OF EROSION PIN INSTRUMENTATION AND MONITORING AT THE FIVE STUDY SITES

Details	Site No. 1	Site No. 2	Site No. 3	Site No. 4	Site No. 5
Date pins established	7.3.1985	7.3.1985	11.3.1985	11.3.1985	16.3.1985
Date of first reading	30.3.1985	30.3.1985	30.3.1985	30.3.1985	30.3.1985
Number of days between installation and first reading	23	23	21	21	14
Last reading	31.5.1986	31.5.1986	31.5.1986	31.5.1986	31.5.1986
Length of study period (days)	420	420	417	417	411
Number of readings	14	14	14	14	14
Average intervals between readings (days)	30	30	30	30	30
Number of pins	16	16	16	16	16
Length of bank pinned (metres)	2.0	2.0	2.0	2.0	2.0
Approx. area of bank face (m^2)	4.0	4.0	4.0	4.0	4.0
Pin frequency (no. per metre of channel)	4	4	4	4	4
Approx. density of pin coverage (no. per m^2 area)	4	4	4	4	4

Details of pin networks

From the details of the erosion pin network for each site (Table 3.6.2), it can be seen that all pins were installed in the same month, and that observations finished at the end of this study on 31st May, 1986. The pins were read on 14 different occasions or approximately once a month at all sites between March 1985 and May 1986 (Table 3.6.2). The number of pins for all sites totals 80, although it is more useful to weight this figure for the size of banks involved. Thus, two measures have been adopted:

(a) pin frequency (the number of pins per metre of channel length), and

(b) areal density, which is simply the number of erosion pins per unit area (in the vertical plane) of stream bank (Table 3.6.2).

All sites had the same density network of erosion pins (which averaged about four per metre of channel). This sampling scheme was designed to facilitate a more detailed examination of the spatial characteristics of the transfer and removal of material within, and between, sections of stream bank. The precise locations of all pins at each site will become apparent when the results are presented below.

Problems with the erosion pin measurement

The following discussion deals briefly with actual drawbacks of the erosion pin measurement technique as noted by the writer in the field. The erosion promoted around pins was problematic, and was noted frequently at the Coombs Brook sites. Around some pins, usually the lower ones, it was observed, especially in winter, that cone-shaped depressions developed. These were about 40 mm in diameter and 25 mm deep, mostly circular in shape, although a few were elongated in a downstream direction to take on an elliptical form. It is tempting to associate these features with an increase in turbulence at these points during submergence, when the pins may protrude out from the boundary layer. Occasionally, some pins could not be found when the periodic measurements were due. A few instances

of burial were noted, mostly at Sites 4 and 5.

(2) Other techniques

Several other techniques were used to measure erosion processes
(Table 3.6.1 and Fig. 3.6.1).   Some of these techniques met with
success, but others proved to be less accurate.   The varied erosional
processes affecting stream banks, and the details of the techniques
used will be discussed in Chapter Five.

CHAPTER FOUR

LABORATORY ANALYTICAL PROCEDURES

4.1   Water Analysis

        4.1.1 Hydrogen ion activity pH

        4.1.2 Specific conductance measurements

        4.1.3 Filtration and storage

        4.1.4 Chemical analysis

4.2   Soil Analysis

4.3   Particle Size Analysis

4.4   Rock Analysis

4.5   Vegetation Analysis

CHAPTER   FOUR

LABORATORY   ANALYTICAL   PROCEDURES

4.1   WATER ANALYSIS

The general analytical procedures for water samples collected
weekly is outlined in Fig. 4.1.1.   In addition, samples from the
automatic sampler at Station 1 were analysed following the same
methods, but inevitably the delay between sampling time and return
to the laboratory was as much as seven days for the first sample
taken automatically.

4.1.1   Hydrogen ion activity pH

Much has been written on the advantages and disadvantages of
taking pH measurements in the field as opposed to taking them in the
laboratory.   In Macclesfield Forest the base flow of the stream is
derived from groundwater draining from the sandstone bedrock, but
storm runoff events and the falling stages of the hydrograph are
dominated by throughflow from the soil.   The relatively high concen-
tration of organic compounds present in the throughflow may influence
the stability of pH over time.   An experiment was therefore carried
out to test the stability of pH in samples under storage.

The pH of samples of stream water from the seven stations and
rain from different collectors was accurately measured twice, in the
field and then in the laboratory.   Field pH was taken with a Kane-May
digital pH meter.   The pH was measured in the bottle rather than by
putting the electrode in the river, as water velocity is thought to
affect the reading (Barnes, 1964).

The laboratory determinations were made with a Pye-Unicam (Model
291) pH meter, occasionally subject to drift and varying electrode
conditions.   The results (Fig. 4.1.1.1 and Table 4.1.1.1) have been
rounded to 0.1 pH units and are probably accurate to $\pm 0.1 - 0.2$ pH.

FIGURE 4.1.1   FLOW DIAGRAM OF THE STAGES OF COLLECTION,
                 STORAGE AND ANALYSIS

1.	Stage Fieldwork	START Rinse out 250 ml Polythene bottle Collect sample Measure pH
2.	Initial laboratory analysis	Measure pH and conductivity with Laboratory Meter Filtration Determination of suspended sediment
3.	Storage	Storage in deep freeze at $-1^{o}C$
4.	Analysis	Immediate full analysis Analysis by:

Titration
Cl^- NO_3^-
SO_4^{2-} PO_4^{3-}

Atomic absorption
spectrophotometry
Ca^{2+} Mg^{2+} Na^+ K^+

one year
1984-1985

Titration
Cl^- NO_3^-

Plasma
Ca^{2+} Mg^{2-} Na^+
K^+ SO_4^{2-} PO_4^{3-}

one year 1985-1986

Raw data

Discharge data
Meteorological data
Soil water data

Soil, Rock,
Vegetation, etc.

FIGURE 4.1.1.1

Comparison between pH measured in the
field and the laboratory

TABLE 4.1.1.1   COMPARISON BETWEEN pH MEASURED IN THE FIELD AND THE LABORATORY

Station No.	pH in the field		pH in the laboratory		Difference
	pH	°C	pH	°C	
1	7.5	10	7.3	17	0.20
2	7.49	10	7.4	17	0.09
3	7.73	10	7.7	17	0.03
4	7.45	10	7.3	17	0.15
5	7.43	10	7.2	17	0.23
6	7.49	10	7.2	17	0.29
7	7.56	10	7.2	17	0.36

TABLE 4.1.1.2   THE METHOD OF WATER ANALYSIS USED IN THIS STUDY

| Type of measurement | Unit | Techniques used | |
		Laboratory Techniques	Field Techniques
pH	pH unit	Pye Unicam Model 291 (Lab - Teach)	Kane and May Model 7001 (Field measurements)
Conductivity	μscm^{-1}	Conductance meter CM 35 WPA	-
Ca^{2+} Mg^{2+} Na^{+} K^{+} SO_4^{2-} PO_4^{3-} Fe Mn	ppm or mg/1	1.*Perkin-Elmer 360 atomic absorption spectrophotometer and 2. Inductivity coupled plasma (ICP) emission spectrometer, IL plasma 200	-
Cl^{-} NO_3^{-}		3. Titration using a Hach direct reading meter in a Hach portable water chemistry laboratory	-

*1. Used for one year (1984-1985), in the Geography Department
2. Used for one year (1985-1986), in the Geology Department
3. Used for two years (1984-1986), in the Geography Department

Both instruments were calibrated immediately before use with buffer
solutions. All measurements were made on unfiltered samples, at fre-
quent intervals over the next 1-2 hours to establish whether there
were many pH variations over time.

Allowing for the precision of the pH meter, it can be seen that
the pH of the samples taken from the catchment changed little over a few
hours. The pH measured in the laboratory of all samples was lower,
despite the increase in the temperature. These movements are not the
result of temperature change, as the meter was adjusted to the sample
temperature before each reading. Nevertheless, providing pH is read
within 1-2 hours of sample collection and samples are stored in air-
tight bottles, the variations from true field pH only just exceed the
precision of the instrument, the largest variation being 0.9 pH units
from the sample. It was therefore decided to make all pH measure-
ments in the laboratory on the more precise and accurate Pye Unicam (291)
meter, using pH 7.0 buffer solutions. No resistance thermometer was
available for automatic temperature compensation, so sample temperatures
were taken by hand and the necessary adjustments made to the meter.
The electrode was allowed to stand for five minutes in the stirred
sample before a reading was taken (Table 4.1.1.2).

4.1.2 Specific Conductance Measurements

The ability of a liquid to transmit an electric current is
measured by its conductance. Pure water is a poor conductor of
electricity and hence has a low conductivity. The pressure of dis-
sociated ions in solution increases the conductance of the water, the
magnitude of the conductance increasing with ion content and tempera-
ture for all except very saline waters. Undissociated salts do not
conduct electricity and, as these figure in the total dissolved load
of the river, the relationship between dissolved solids and conducti-
vity is not directly linear. Important factors determining how well
a solution will transmit an electric current are given by Hem (1959,
p.39) as: "the number and kinds of ions present, their relative
charge and their mobility".

Although the relationship between conductance and chemical load

is not precisely linear, the total dissolved solids (in mg 1^{-1}) are usually between 0.55 and 0.75 times the specific conductance measured in micromhos.

The specific conductance was determined with CM35 WPA, a conductivity meter where the conductivity (K) has been measured in μScm^{-1}. Conductivity is denoted by the symbol K and is given by the equation K = C/R where C is the cell constant and R is the resistance in ohms. It is expressed in microsiemens per millimetre (μSmm^{-1}) in SI units or in reciprocal ohms (ohm^{-1} or mho).

All values for water samples are reverted to $25^{o}C$ ($77^{o}F$). The response of the conductance value to temperature change differs somewhat depending on the precise salts in solution and their concentrations, but in dilute solutions for most ions an increase of $1^{o}C$ increases conductance by about 2% (Hem, 1970).

To obtain a precise measurement of conductivity, the cell constant of the probe must be measured. This can be done by making up a 0.01m solution of KCl, which gives a conductance of 1412 μScm^{-1} at $25^{o}C$

$$\therefore \quad C = 1412 \times R$$

The meter reading is calibrated in 1/R.

4.1.3 Filtration and Storage

Conductivity and pH were measured prior to filtration and storage. All samples contained a certain amount of suspended sediment, and biochemical and chemical reactions with the sediment during storage might severely affect solute concentrations in the sample. Hence all samples were filtered prior to storage.

The amount of suspended sediment in the stream water sample was determined by filtration in the laboratory. Initially, Whatman 542 filter papers were used, the papers being rinsed beforehand with distilled water to remove salts, and dried in an oven overnight at $50^{o}C$. Replicate samples showed that the accuracy of this method was only within 5 mg 1^{-1}, so in order to improve upon this, a procedure using Millipore cellulose ester filters was adopted.

The Millipore method consisted of filtering the samples in a
Millipore filter assembly, using 0.22 micron filters following the
recommendations of the Society of Automotive Engineers (1963).   In
this procedure, filters rinsed beforehand with distilled water (to
detect changes in humidity) and dried in an oven overnight at $50^{\circ}C$,
are cooled in a desiccator and weighed.   Between 200-300 ml of
vigorously shaken sample are passed through the filters with the aid
of a vacuum pump.   After filtration, the filters are placed in petri
dishes, dried in an oven overnight at $50^{\circ}C$, cooled in a desiccator
and then finally weighed.   This method is accurate to the nearest
2 mg l^{-1}.   The advantages of using the Millipore filters are that
they enable the organic combustible part of the sediment load to be more
easily determined, facilitate microscopic investigation of the sedi-
ment, and detect changes in humidity.

Following filtration, the samples were stored for various lengths
of time awaiting analysis.   Both the type of container and mode of
storage can affect the chemical composition of the samples.   Factors
that are pertinent to the selection of containers are resistance to
solution and breakage, efficiency of closure, size, shape, availability,
and cost.   There are many, and often conflicting, views on the prefer-
ence for one type of container over another, since the concentration
and type of chemical has an influence on the rate and nature of mater-
ials dissolved.

Generally, polyethylene bottles are accepted as the cheapest way
of storing large numbers of samples.   However, for certain ions,
notably phosphates, and possibly chlorides, chemicals may be absorbed
on to the sides of the containers (Edwards, 1971).

4.1.4 Chemical Analyses

Methods of chemically analysing water samples have been considered
by several authors (Rainwater and Thatcher, 1960;   The Institution of
Water Engineers, 1960;   Mackereth, 1963;   The British Standards
Institution, 1964-67;   and Vogel, 1965).   The objectives of this
thesis did not require a complete chemical analysis of each sample,
and only the major ions were determined: Ca^{2+}, Mg^{2+}, Na^+, K^+, SO_4^{2-},

PO_4^{3-}, NO_3^-, Cl^-, Fe^{2+} and Mn (Table 4.1.1.2). The accuracy of the method used is as follows:

(1) Titration Method

   (a) Nitrate

   To a 25 ml water sample, contained in a glass cell, a Nitra-Ver-5 Nitrate Reagent Powder Pillow was added. The cell was stoppered and shaken vigorously for exactly one minute. An amber colour will develop if NO_3^--N is present. At least five minutes were allowed for proper colour development, but not more than 15 minutes. Once the colour had developed, its intensity was measured in a colorimeter at 500 nm. The result given was expressed as NO_3^--N, which was converted to total NO_3^- by multiplying by the factor 4.4. The accuracy of this technique depends on whatever concentrations of other ions interfere with true colour development.

   (b) Chloride

   To a 10 ml sample, contained in a glass cell, three drops of concentrated Ferric Nitrate solution, together with three drops of concentrated Mercuric Thiocyanate were added, which gave a blood-red colour of which the intensity is directly proportional to the concentration of free Cl^- ions. Standard solutions of Cl^- were treated in a similar manner. The accuracy of this test, like that for NO_3^-, depends on whether other ions are present.

(2) Atomic Absorption Spectrophotometer and Plasma Spectrometer Methods

   (a) Atomic absorption spectrophotometer

   The four major cations were measured by atomic absorption. Standard solutions were prepared according to the instruction sheet No. S3/152/2/MC issued by the Manchester University School of Geography. Due to the low ranges of standards used to achieve linearity, dilutions of the samples were made so as to read within the appropriate standard ranges and to apply dilution factors where necessary.

(b) Plasma spectrometer

Concentrations of Ca^{2+}, Mg^{2+}, Na^+, K^+, SO_4^{2-}, PO_4^{3-}, Fe, and Mn were measured in the plasma spectrometer, for which standards were prepared according to instructions from the Manchester University Geology Department. Dilutions of the samples were not necessary.

The accuracy of both machines was examined by comparing the results of samples. The difference ranged between ± 0.001 - 0.015 mg l^{-1}.

4.2 SOIL ANALYSIS

Soil solutions were prepared according to procedures developed by Mr. B.S. Kear of the School of Geography at Manchester University. Soils, oven dried overnight, were ground to pass through a 0.2 mm mesh sieve. Ten grams of sieved soil were placed in a 250 ml conical flask with 70 ml of freshly prepared ammonium acetate solution and shaken for one hour, then filtered into a 100 ml volumetric flask, and finally made up to a full 100 ml with ammonium acetate. The pH measurements and chemical analyses for cations were then completed, the plasma 200 spectrometer being used for the majority of determinations.

4.3 PARTICLE SIZE ANALYSIS

Particle size is a parameter having dimension of length. The measurement of particle size is one of the useful techniques for determining the character of sediments and soils. Particle size distributions help in the understanding of processes of transport and deposition of sediments, both at present and in the past, and are therefore important in studies of contemporary processes. They also are a valuable tool in the description and classification of deposits and soils.

Samples collected from seven sites of the catchment were dried

and sieved on returning to the laboratory. The relative proportions of coarse and fine sand, silt and clay were determined from the weight of material collected in each sieve.

4.4 ROCK ANALYSIS

Seven thin sections prepared from rock samples taken in the stream bed were analysed microscopically. Percentage counts of the major elements were made, using X-ray fluorescence spectrometry (Phillips PW 1450) in the Department of Geology at the University of Manchester.

The main aim of the bedrock analysis was to determine the major elements present in the sandstone in order to study the relationship between soil and water chemistry and rock chemistry. No complete chemical analyses were performed on the samples, as detailed mineralogical study can provide a reasonable estimate of the bulk chemistry.

The bedrock is only exposed in the upper part of the catchment, and the thin beds are unlikely to be continuous. Additionally, the soil chemistry is unlikely to reflect the rock chemistry at a given site because much of the soil in the study area is derived from glacial drift deposits. The samples taken from the stream bed can provide only a general picture of bedrock chemistry and not a full account of the sources of all ions released by weathering in the catchment.

4.5 VEGETATION ANALYSIS

Samples of leaves were collected and washed in distilled water. After oven drying, one gram samples were cut into small pieces and placed in clean silica crucibles. The crucibles were then placed in the muffle furnace which had been allowed to stabilise at 475° - $500^{o}C$ for two to three hours. A 0.1 gram of sample was dissolved in a few drops of concentrated hydrochloric acid for ten minutes, and then transferred to concentrated nitric acid for five to ten minutes. The resultant solution was diluted with 20 ml distilled water. Then the solution was filtered and the filtrate collected in a 100 ml

volumetric flask, then made up to 100 ml with distilled water.

Cations and some anions were analysed by plasma spectrometer; NO_3^- and Cl^- could not be analysed by plasma spectrometer due to interference. They were therefore determined by using a Hach Portable Water Laboratory.

CHAPTER FIVE

EROSIONAL PROCESSES AND SEDIMENT SOURCES

Introduction

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B - A sediment budget model for the Coombs Brook catchment

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    5.4.1   Calculation of total sediment supply

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CHAPTER FIVE

EROSIONAL PROCESSES AND SEDIMENT SOURCES

INTRODUCTION

Stream channel courses may be considered to be most dynamic ele-
ments of the landscape in humid areas, and understanding the processes
of channel widening and deepening is fundamental to the explanation
of sediment yield and channel capacity changes.   Consequently, much
attention has been paid to processes of erosion, sediment transport
and sedimentation in gullies and stream channels and to effects of
land use management on channel stability and water quality.

The varied erosional processes affecting stream banks are out-
lined in this chapter, and subsequently the details of their operation
in the Coombs Brook catchment are considered.

The nature and rate of stream bank erosion depend upon two basic
groups of factors: those related to available energy and those rela-
ted to bank resistance, both of which are specific for each erosional
process.

A.   Concepts and requirements of sediment budget models

In the Proceedings of the Workshop on Sediment Budgets and Rout-
ing in Forested Drainage Basins, Swanson et al. (1982) state:
"Geomorphologists have traditionally studied erosion of landscapes by
analysis of individual erosion processes, measurement of sediment yield
at one or more points along a river system and stratigraphical analysis
of deposits.   These approaches, however, have rarely been used collec-
tively to provide a framework for understanding soil and sediment move-
ment through drainage basins.   Many current problems in basic and app-
lied geomorphology and ecology can better be addressed when placed in
a broad, conceptual framework provided by analysis of a sediment budget."

Lehre (1982) distinguishes three steps in the construction of a
sediment budget:

1.   identification of transport processes and storage sites
   and understanding of their interrelationships and con-
   trols;

2.   quantifying the contribution from each erosional process;

3.   setting up a balance sheet showing production, sediment
   yield and storage changes.

How well a budget characterises and quantifies a geomorphic sys-
tem depends on how well transfers, storages and linkages in the system
are understood, the precision and duration of field measurements and
the scale of spatial and temporal segmentation of the drainage basin
under analysis (Swanson et al., 1982).   In the following section a
model for the construction of a sediment budget for the Coombs Brook
catchment is attempted.

B.   A sediment budget model for the Coombs Brook catchment

The main processes controlling the sediment budget of the Coombs
Brook catchment are summarised in a flow chart (Fig. 5(b)).   Obviously,
not all functions and storage elements are represented;   the more com-
plete the flow chart, the more difficult it is to interpret and the
less useful it becomes as a graphical description of the system.
The diagram demonstrates how sediment transfer from the valley slopes
and the channel subsystem are related to one another by channel flow.
This flow comprises water and sediment output from the contributing
valley slopes (and channel precipitation) and acts as a major input
variable (concerning erosive force and transport medium) to the channel
incision.   Channel flow directly causes bank and bed scour whether or
not influenced by preconditioning of the bank material by frost action.
Mass failures may result from increased undercutting of the bank or
from the development of positive pore water pressures in the bank
material.   The latter process is due to water inflow during high
water stages or contribution of seepage.   Stream bank erosion processes,
such as splash, creep and subsoil fall, are only directly related to
channel flow reflecting their activity in a zone above the maximum
high water level.   Soil material supplied from the banks is tempor-
arily stored in the channel bed or transported out of the catchment
as wash-on bedload.
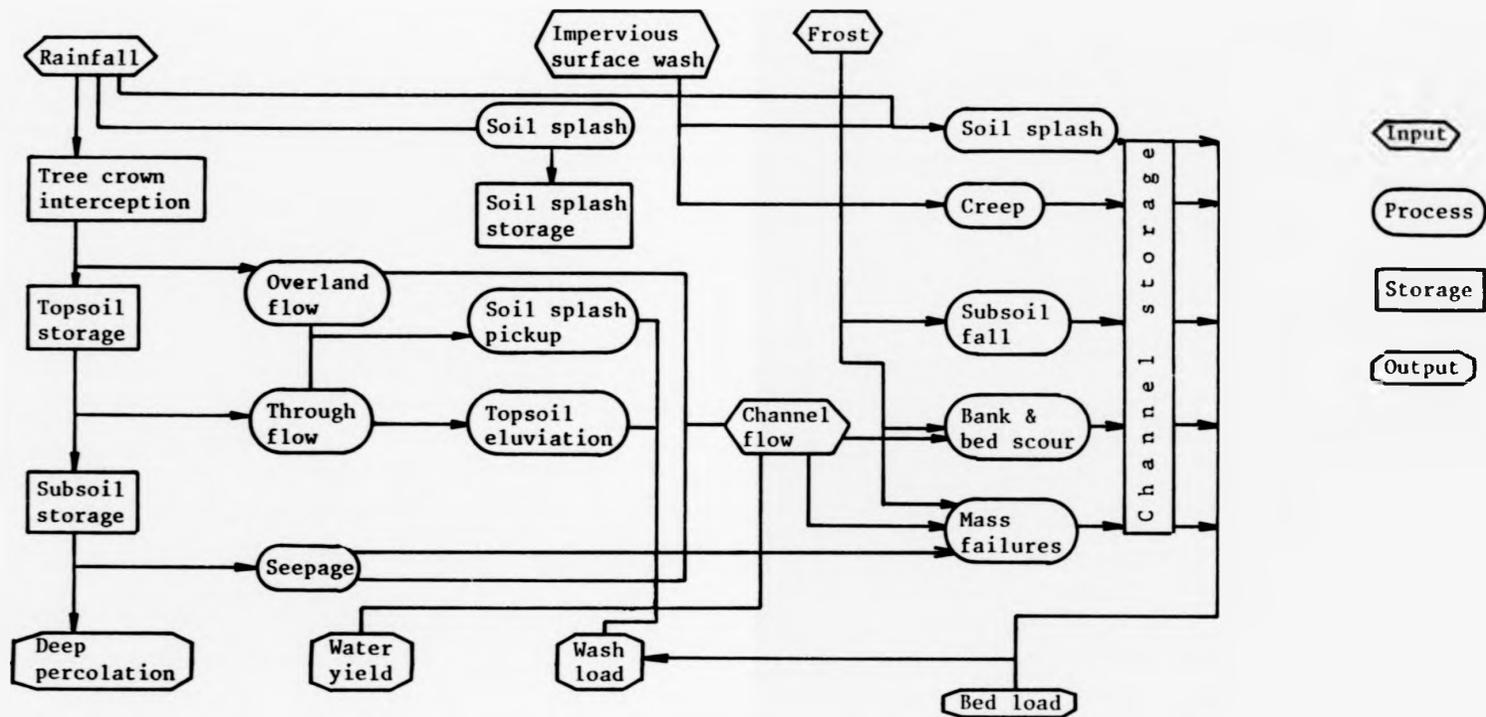
Figure 5(b)   Sediment budget model for the Coombs Brook catchment, showing the interrelationships
between the various erosion and sediment transferring processes.

The areas of occurrence of the various erosion processes are schematically represented in Fig. 1.4.1.

5.1 STREAM BANK EROSION IN THE COOMBS BROOK CATCHMENT

Sixty per cent of the stream bank length in the Coombs Brook shows signs of erosional activity (Stott, 1985).   Six processes contribute to the detachment and transportation of soil material on stream banks and valley slopes (Fig. 1.4.1 and Table 5.1.1): lateral corrasion (bank scour), subsoil fall, soil creep, overland flow, mass movements, and splash erosion.   Particular attention will be given to subsoil fall, as it is widespread and has specific effects on bank morphology.

The sources of the suspended material carried by Coombs Brook have been investigated by detailed field studies and sediment load measurements designed to:

1.   Locate the areas of intense erosion and the sources of sediment in the catchment.

2.   Determine the catchment characteristics conducive to erosion.

3.   Relate the removal of material from the ground surface to erosional processes.

5.1.1 Lateral Corrasion

Lateral corrasion, or bank scour, is the interaction between the shear stress or tractive force of the stream and the resistance of the bank material.   The shear stress is primarily a result of water forces (drag and lift forces) which try to move the sediment particles down the channel in the direction of the flow.   In addition to these forces, a secondary, transverse, motion exists in channel bends (and to a lesser extent also in straight reaches) which, superimposed on the longitudinal flow, results in a helical type of circulation (Simons, 1971).   This transverse flow is governed by the centrifugal force and

TABLE 5.1.1   MAJOR EROSION AGENTS ACTIVE ON SLOPES

Erosion Agent	Main Effect Detachment	Transport
Burrowing animals	X	
Splash	X	X
Throughflow	X	X
Overland flow	(X)	X
Rill and gully flow	(X)	X
Litter fall		X

the existence of a transverse gravity slope.

The resistance of cohesive bank materials to scour is exceedingly complex.   Soil properties not only determine the magnitude of the inter-particle forces of cohesion that resist detachment, but also influence the physical configuration of particles at the bank surface (Grissinger, 1982).   This two-fold influence implies that bank resistance is highly dynamic both in time and space.

The considerable number of studies investigating the process and effects of bank scour have consequently revealed a wide range of factors affecting the spatial and temporal variation in lateral corrasion. These factors fall clearly into three groups:

(a) Factors related to the hydraulic characteristics of the channel and channel geometry (Hooke,1980).

(b) Factors related to the erodibility of the bank material (Grissinger, 1982).

(c) Factors related to the characteristics of the eroding fluid (Arulanandan and Heinzen, 1977;   Arulanandan et al., 1980).

Erosion pin measurements

Since the locational co-ordinates of each erosion pin were known, it was possible to examine variations in erosion rate across individual stream bank sites, both in along stream and vertical direction.   This was facilitated by the density of pin coverage established (Section 3.6).

The objectives outlined earlier required measurements of soil loss from different regions of the catchment, even though these were:

(a) difficult to make;

(b) probably subject to an unknown error factor;   and

(c) could only be made over a short period of time.

The quantitative techniques employed in this study provide measurement

of soil loss or accumulation at particular points on the ground sur-
face.   As it was impossible to measure erosion at every point in the
catchment, a sample of measurement sites had to be selected (Fig.
3.6.1, Chapter 3).

Individual sites

The spatial distribution of the amounts of bank erosion
recorded from each of 16 pins at each site has been displayed in
the form of proportional circles (Fig. 5.1.1.1).   Sixteen pins
cover about 2m of stream bank and are arranged in four vertical
sections of four pins each.   Erosion pin plots were set at 2m
intervals along the stream where bank erosion appeared to be
relatively active.

At certain stations, thick lenses of coarse sands, often
throughout the bank to within 0.4m above the low flow level, made
the insertion of erosion pins impossible.   However, near Station
3, pins close to the water level, below such a sand lens, showed
considerable erosive activity.   Nevertheless, five sites (Fig.
3.6.1) show great variation in erosion from one measurement time
to the next and considerable spatial differences in erosion in
any interval between measurements (Figs. 5.1.1.1 and 5.1.1.2).

Sites C/3 and C/4 form part of the left bank at the entrance
to the middle Coombs Brook meander.   They appeared to be suffer-
ing active erosion at the time of field reconnaissance, as no
surface vegetation was apparent and many tree roots were exposed,
especially in the upper layers of the soil.   The presence of a
tree and its roots, extending more than 4m along the bank, preven-
ted pin emplacement for 4.0 metres (Table 5.1.1.1).   Site C/2
is the least active, possibly because it is the site with the
greatest protection from the overhanging tree canopy which would
break the impact of falling raindrops.   The density of the pin
cover at C/2 is also low, but this should not affect the mean
value of soil loss.

Temporal patterns of bank erosion

Temporal trends in average erosion rate will be addressed first.
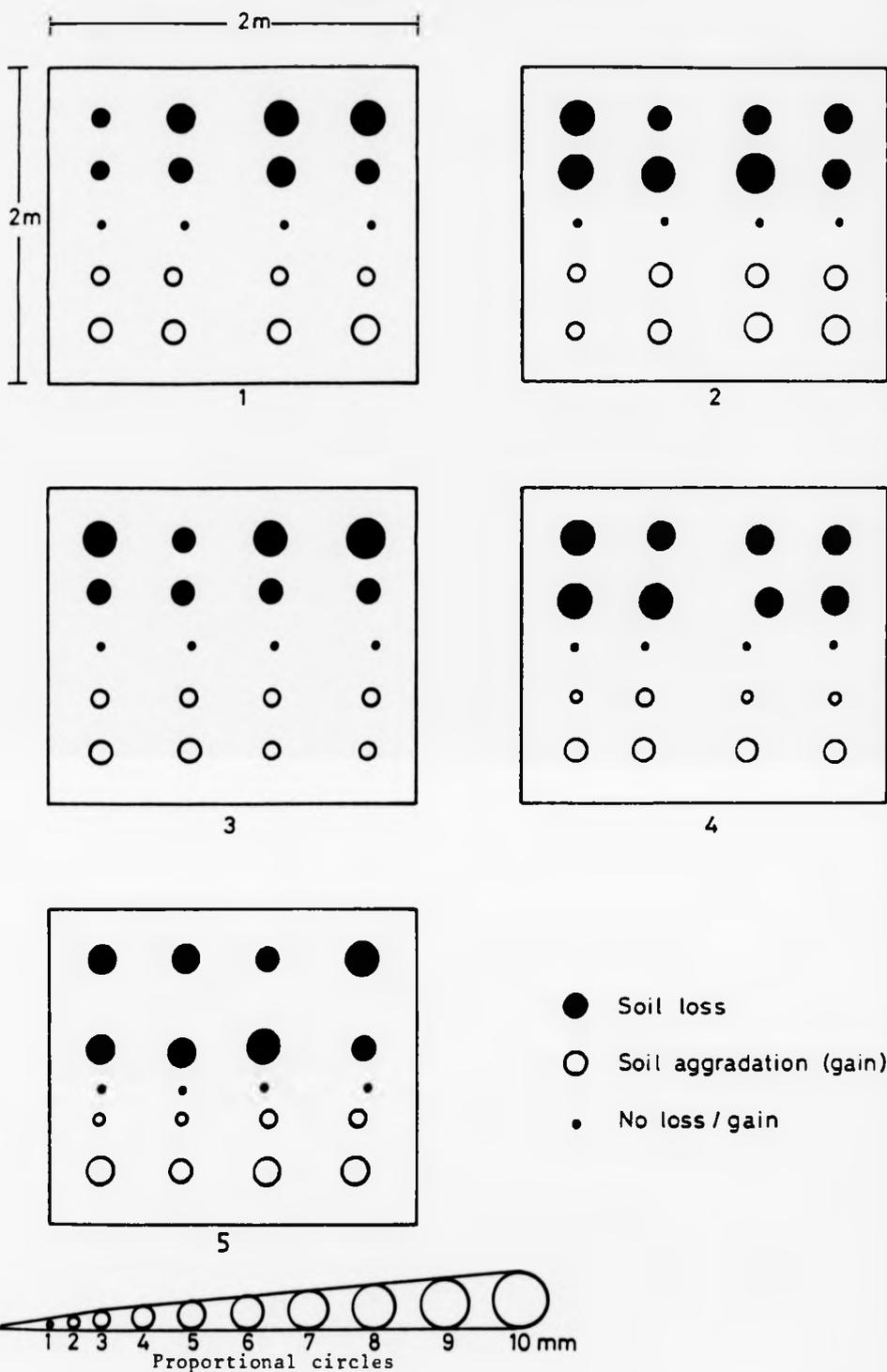
FIGURE 5.1.1.1   Circle diameter of pin erosion sites. The average
                  amount of bank erosion recorded from each of 16
                  pins at five sites

FIGURE 5.1.1.2

Average of bank erosion rate during the period
March 1985 - April 1986 for Coombs Brook

TABLE 5.1.1.1   MEAN MONTHLY SOIL LOSS DATA FOR EACH SITE

	Rainfall (mm)	Mean No. of storm events per month	Site No. 1	Site No. 2	Site No. 3	Site No. 4	Site No. 5
Mean	86.0	2.7	35.6	34.8	40.0	36.0	32.5
Median	87.0	2.0	23.0	20.5	27.0	25.0	23.0
Standard deviation	23.2	1.98	31.5	30.2	34.6	28.9	29.0
Maximum	117.8	7.0	120.0	110.0	130.0	115.0	112.0
Minimum	48.0	0.0	2.0	2.0	3.0	2.0	1.0

CORRELATION MATRIX FOR PRECIPITATION EVENTS AND BANK EROSION AT DIFFERENT SITES*

	Rain	Storm	Site No. 1	Site No. 2	Site No. 3	Site No. 4
Storm	0.789	-	-	-	-	-
Site 1	0.671	0.507	-	-	-	-
Site 2	0.721	0.582	0.995	-	-	-
Site 3	0.693	0.551	0.994	0.995	-	-
Site 4	0.663	0.473	0.990	0.981	0.985	-
Site 5	0.665	0.480	0.993	0.989	0.991	0.992

*All correlations are significant at P = 0.05 (95% confidence level)

March 1986 witnessed the most active erosion (130 mm), with April, November and December 1985 having average rates above the mean of 35 mm.   Examination of average rates immediately raises the question of how well such mean figures summarise the changes which occur.

Bank erosion rates vary by three orders of magnitude on a seasonal basis, with most erosion in the late winter (Fig. 5.1.1.2). For many months of the year negligible erosion occurs and, in some periods, net accretion was recorded.   These relatively insignificant changes, characteristic of the summer and autumn months, were the result of a very small number of pins registering erosion or accumulation. At all sites, the winter of 1986 proved about twice as erosive as the preceding one (Fig. 5.1.1.2).   The difference between winters reflects prevailing temperature and snow conditions.

Spatial patterns of bank erosion

Comparisons between erosion pin sites and analysis of the spatial pattern of bank erosion is valuable, as Gregory (1978, p.58) stressed: "Identification and description of spatial patterns is one of the fundamental features of a geomorphological approach and so it is desirable that spatial analysis of fluvial landforms and processes, and eventually all fluvial form-process assemblages, is attempted".

To obtain an ideal comparison of bank erosion rates, calculations of averages for several years are required.   In the present work, 14 months' observations covering parts of two winters are available.   The results have therefore been presented both for the full 14 month period and for the year from March 1985 to April 1986.   As will be discussed, the 1985-86 winter was probably more severe than most and may have accelerated bank erosion.

Erosion at individual pins tends to follow a pattern similar to others at the site.   For example, at Site 1, most individual pins follow the general trend of two distinct seasonal erosion peaks in late winter, with negligible activity taking place at other times of the year (Fig. 5.1.1.2).   Typically, the 1985-86 winter period saw greater erosion than the first, although this tendency appears more marked for the upper sections of bank where pins 1-8 are installed (Fig. 5.1.1.1).

During times of maximum activity, variability follows some pattern, vertically and/or along the stream. With pins extending from base-flow level to bank-top, it was possible to examine how the intensity of erosion varied vertically within each site, and whether any variation present was consistent from one measurement time to another. For instance, the very first reading of the pins at Site C/1 on 31st March 1985 demonstrated that some order could be discerned in the variability, with a clearly defined upper limit to erosion about half-way up the bank around one metre temporary bank mark.

Conclusions

The rate of lateral corrasion exhibited wide variations both in time and space, due to the complex interactions between hydrometeorological factors and bank resistance. Temporal variations in recession rate are mainly influenced by the magnitude of discharge. The mean soil loss by bank scour in the study period amounted to 13.0 kg per metre of bank length.

5.1.2 Subsoil fall

One of the most conspicuous phenomena of stream bank erosion is the subsoil fall process by which the stream bank may be undercut by up to 70 cm. This process plays a major role in widening channel incisions in forested areas.

One of the main features of the subsoil fall process is the dis-integration of the normally very dense subsoil into an incoherent mass of angular blocky soil aggregates upon exposure to the air. At the stream banks these aggregates drop away easily, so that the sides of the incision recede below the rootmat (developed at the interface between topsoil ('A' horizon) and subsoil ('B' horizon)), resulting in an under-cut (Fig. 5.1.2.1). In contrast to other stream bank erosional pro-cesses, it is only indirectly related to rainfall amount and discharge volume.

In general, undercutting by subsoil fall occurs at two distinct locations: one at the top of the channel bank at the edge of the valley incision, and one at a lower elevation directly along the river channel,
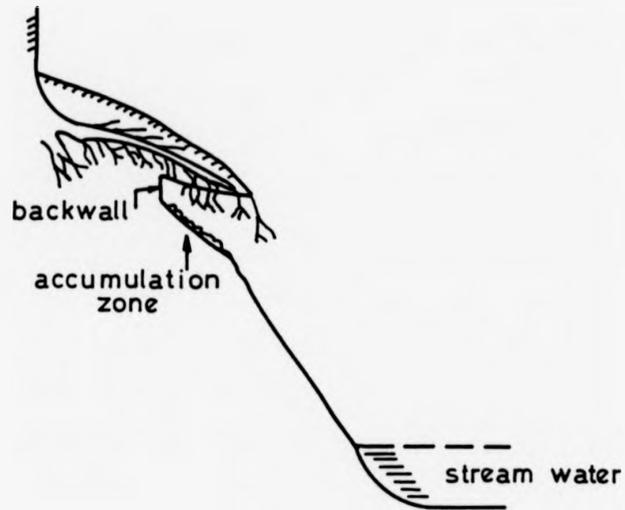
FIGURE 5.1.2.1

Cross-section of stream bank at site of active subsoil fall
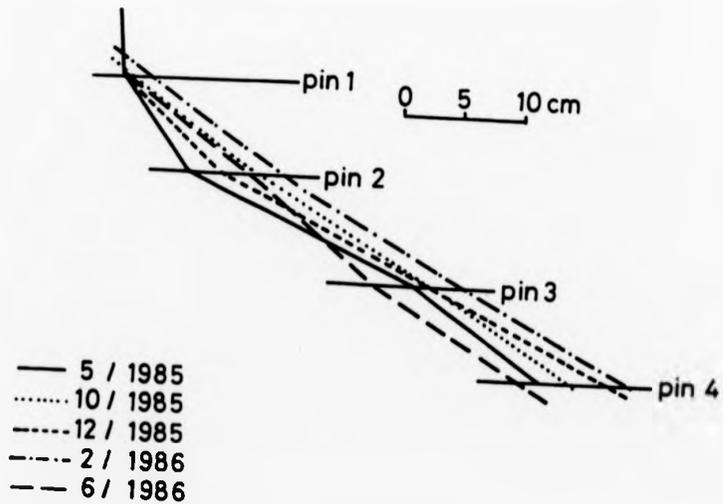
FIGURE 5.1.2.3

Temporal changes in cross-section through the aggregate accumulation zone at soil fall (Site 7A)

i.e. at the level of river side-bars. The higher undercuts mainly occur along arc-shaped embayments where the subsoil is exposed by mass failure. Two factors are of major importance in determining the occurrence of subsoil fall and its spatial variations (Imeson and Jungerius, 1977):

1.   The exposure of the subsoil to the air which only occurs in valley incisions by erosional activity. The rate and pattern of the process depends on the rate of removal of the loosened aggregates as this influences the exposure of the subsoil.

2.   The presence of a dense rootmat between surface soil and subsoil. Such a rootmat is formed where the roots have difficulty in penetrating the subsoil. Some of the reasons are:

   - a clayey texture of the subsoil resulting in low permeabilities;

   - temporary waterlogging;

   - the presence of swelling clay.

As in the case of splash erosion, two phases may be distinguished in the subsoil fall process: a detachment and a transport phase. Detachment takes place mainly at the backwall of the undercut, but also at its roof. The detached aggregates may be transported out of the undercut immediately or may pass through several phases of accumulation and transport in the undercut before they reach the channel bed.

Temporal variations in subsoil fall depend on the interactions between and relative importance of these detachment and transport phases. Detachment at the backwall occurs by disintegration of the subsoil which is caused by several processes:

In winter: during periods of frost, water is drawn from around the clay particles to the ice crystals in the pores, creating a dehydration effect. The combination of ice-crystal pressure and dehydration causes aggregation (Baver et al., 1972). The impact of freezing and thawing varies depending on the amount of excess water in the frozen

layer, the duration of thawing and the water stability of the aggregates formed.

In summer: alternate wetting and drying results in expansion and contraction of the backwall. Under such conditions a friable layer is formed which is highly susceptible to removal. The aggregates produced during alternate wetting and drying are similar to those formed by freezing and thawing. At least two processes operate to cause disruption of the soil into smaller units when the dry soil is wetted. The rapid intake of water causes unequal swelling throughout the subsoil which produces fracturation and fragmentation along planes. Moreover, the sorption of water into the capillaries compresses the included air and results in a virtual explosion of the aggregates when the pressure of the entrapped air exceeds the cohesion of the particles. The intake of water also increases the weight of the aggregates and makes them more susceptible to detachment under the influence of gravity. It is clear that the aggregates in the accumulation zone in the undercut undergo the same effects of alternate wetting/drying and freezing/thawing as those in the backwall. But the effects are in general less because of the lower moisture content.

Small mudflows at the backwall during periods with very wet soil conditions, e.g. prolonged rainfall or snowmelt: This often occurs after heavy rain on exposed undercut banks in the Coombs Brook catchment.

Detached aggregates reach the accumulation zone mainly by gravity. Of prime importance in determining the rate of transport are the slope angle of the accumulation zone, and the size and stability of the aggregates. During periods with prolonged rainfall or snowmelt, emerging throughflow from the B horizon at the roof of the undercut may also entrain the accumulated aggregates. In addition, aggregates accumulated further down the bank may be detached and transported by the impact of raindrops.

Measurement of subsoil fall and relevant parameters

The intensity of the subsoil fall process was measured in two ways:

- By installing small traps (30 cm width) in the undercut which collected all of the detached and transported aggregates (Plate

PLATE 5.1.2.1 (a)

Subsoil fall trap installed at a stream bank.
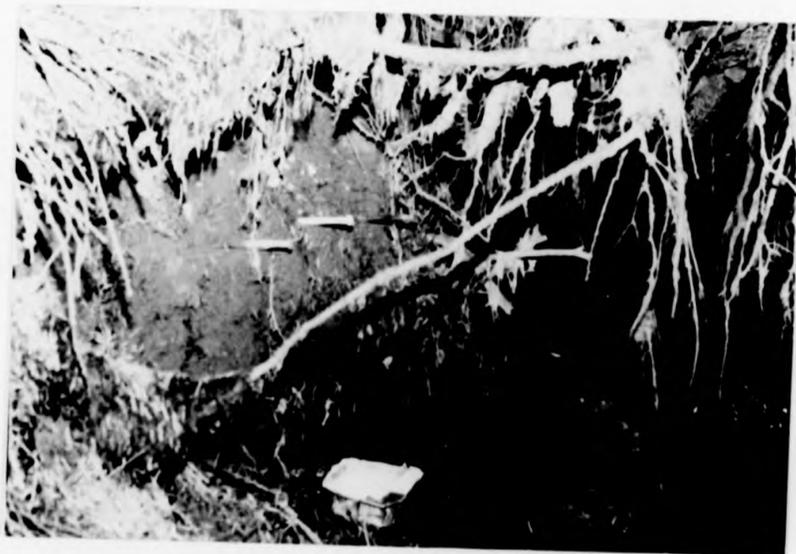
PLATE 5.1.2.1 (b)

Subsoil fall pins installed at a stream bank.

5.1.2.1 (a) and (b)). These traps were installed at 15 sites
and were emptied every month. At several of these sites a
plastic bag was hung under the roof in order to distinguish the
soil material detached from the backwall from that of the roof.

- By measuring the rate of growth of the undercut with erosion pins
  (Plate 5.1.2.1(b)). About 50 of these 30 cm long pins were placed
  at several sites in the backwall and the roof of the undercut and
  were measured every month. Although sometimes measurement was
  difficult due to the irregular surfaces of the undercut or the
  freezing out of some pins, the results give additional information
  about the relative importance of accumulation and transport during
  a certain period.

Air temperature was recorded continuously at the catchment, as the
occurrence of frost and freeze/thaw cycles is one of the major factors
governing subsoil fall.

Particle size distributions were determined for the soil material
from 15 sites where measurements were carried out as soil properties
influence the initiation and continuation of the soil fall process.
To express the volume of the undercuts and their geomorphological
activity, the height of the backwall and length and slope angle of the
zone of aggregate accumulation were measured.

Spatial and temporal variation in subsoil fall

The results from the 15 sediment traps (Table 5.1.2.1 and Fig.
5.1.2.2) show considerable variations in sediment supply by subsoil
fall. Differences of up to 7000 grams of soil loss exist between the
several sites and between seasons at each individual site.

The primary goal of explaining the spatial variation in subsoil
fall is to relate the sediment supply by this process to various site
parameters pertaining to the size of the undercut or to soil properties.
As soil properties determine the occurrence of subsoil fall and there-
fore also the size and form of the undercut, these properties (Table
5.1.2.1) can best be used to describe the susceptibility of a site to
soil fall.

TABLE 5.1.2.1   GENERAL CHARACTERISTICS OF THE INSTRUMENTED SOIL FALL SITES

Site	A	B	C	Slope angle	Sand %	Silt %	Clay %
1-A	20	70	82	32°	53.0	36.0	11.0
1-B	40	41	10	33°	45.1	41.9	15.0
2-A	16	55	39	34°	39.0	43.2	17.8
2-B	19	79	64	23°	40.0	44.0	16.0
3-A	49	29	18	44°	42.6	44.2	13.2
3-B	29	64	67	40°	41.4	43.7	14.9
4-A	7	28	26	50°	23.0	59.2	17.8
4-B	78	56	17	35°	42.6	39.2	18.2
5-A	117	47	28	38°	42.9	40.1	17.0
5-B	25	32	30	40°	25.0	58.3	16.7
5-C	18	21	19	41°	14.7	35.2	50.1
6-A	20	64	28	25°	10.5	50.8	32.7
6-B	40	56	18	38°	19.0	48.0	33.0
7-A	17	26	13	39°	10.5	57.2	32.5
7-B	25	41	16	28°	15.4	48.4	36.2

A = height of backwall in cm;   B = depth of undercut in cm;   C = length of accumulation zone in cm;
Slope angle = slope angle of accumulation zone.
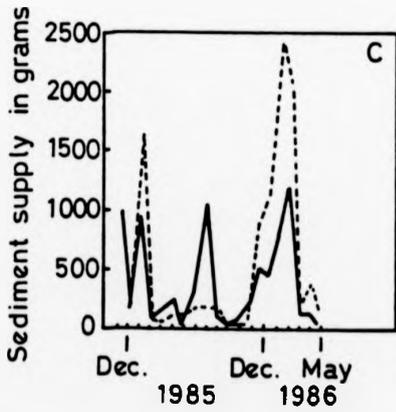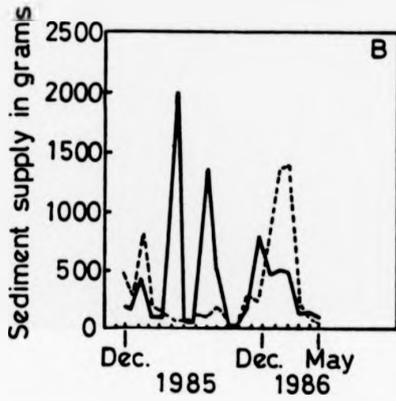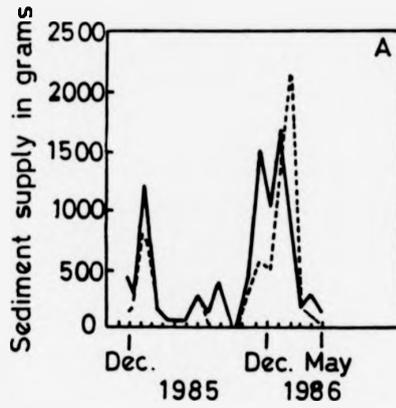
FIGURE 5.1.2.2

Monthly variation in the sediment supply by
subsoil fall

———— Section 1

– – – Section 2

The significant differences in the soil characteristics between the sites were examined. The results of the test (Table 5.1.2.1) showed significant differences in the values of clay, silt and sand percentages, resulting in significant differences in the aggregate stability for the soil in the sites examined.

The difference in the susceptibility to subsoil fall of all the 15 sites is expressed more in the different processes active in the retreat of the backwall and transport of the detached aggregates than in the amount of sediment supply from the undercuts (Table 5.1.2.2). The data also show a distinct seasonal trend with winter maxima and summer minima.

Sediment supply appears to be related to size and form and consequently to the age of the undercut. The higher soil loss in winter is predominantly caused by frost, as is shown by the rather high values of the correlation coefficients between soil loss and various climatological parameters (Table 5.1.2.3).

The intense disintegration of the subsoil due to the influence of frost action agrees with the results from the freeze/thaw experiments carried out by many workers. Poor correlations were found between climatological parameters and summer soil losses at the various sites. Probably this lack of correlation is caused by the combination of the effects of the erosion processes which operate in the undercuts with varying frequencies and intensities. Detachment and/or transport may be caused by throughflow, falling drops, wetting/drying and mass failures of the backwall. It must be noted that these processes are also active in winter, but then their effects are subordinate to the effects of frost action.

The differences in mean backwall retreat between the two winters, respectively (by estimation) 1.2 cm and 2.5 cm in 1984-85 and 1985-86, can be fully ascribed to the severe frost conditions during the second winter (1985-86), respectively 30 versus 65 freeze/thaw cycles and 9% versus 23% of the time with temperatures below $0^{o}C$.

In the foregoing paragraphs the seasonality of the rate of backwall erosion in the undercuts has been stressed. However, other changes occur in the aggregate accumulation and transport zone. Pin

TABLE 5.1.2.2   SOIL LOSS (GRAMS) AT THE 15 INSTRUMENTED SUBSOIL FALL SITES

	Date	Site 1A	Site 1B	Site 2A	Site 2B	Site 3A	Site 3B	Site 4A	Site 4B	Site 5A	Site 5B	Site 5C	Site 6A	Site 6B	Site 7A	Site 7B
Summer 1	31/5/85	51	84	10	17	20	73	25	22	60	41	4	6	61	117	106
	4/7/85	301	200	35	60	275	411	189	35	260	109			214	299	310
	7/8/85	940	120	32	140	432	211	68	1400	245	80			29	285	955
	2/9/85	81	24	26	23	35	212	36	312	150	167	2	4	212	115	112
	1/10/85	18	22	24	16	20	23	11	2	42	41	4	7	32	119	14
	31/10/85	79	36	9	11	145	46	18	8	178	40	150	17	23	140	65
Winter 1	29/11/85	185	41	317	50	185	289	70	189	917	189	989	79	402	315	416
	30/12/85	416	812	75	204	980	749	212	832	1120	224	1654	506	1551	576	2690
	30/1/86	415	1102	128	85	1831	586	584	464	910	845	473	140	973	504	285
	28/2/86	800	1716	177	220	1845	2115	754	439	5215	1340	1385	412	1700	1206	286
	30/3/86	1313	2191	216	316	5440	1890	540	480	7215	1385	1416	612	805	2212	989
	5/5/86	134	154	142	35	312	130	180	129	1120	245	250	125	149	156	251
Summer 2	4/6/86	41	132	59	18	310	130	110	55	123	47	129	45	129	115	475
	Total	4774	6334	1250	1195	11830	6995	2797	4367	17552	4753	6456	1953	6280	6159	6954
	Total summer	1470	486	136	267	927	976	347	1779	935	478	160	34	571	1075	1562
	Total winter	3263	5716	1055	910	10593	5889	2340	2533	16494	4228	6167	1874	5580	4969	4917

TABLE 5.1.2.3   PEARSON CORRELATION COEFFICIENTS BETWEEN SOIL LOSS IN WINTER
                  AND METEOROLOGICAL PARAMETERS

Site	% Frost	Cycles	Minimum temperature
7	0.79	0.64	0.75
6	0.81	0.83	0.78
5	0.85	0.73	0.63

% frost = percentage of time with temperatures below $0^{o}C$;

Cycles = amount of freeze/thaw cycles;

Number of observations n = 18;

All coefficients are significant at p = 0.05 (95% confidence level)

measurements revealed that cyclic fluctuations in the thickness of
this zone take place.   Whereas in the winter a net accumulation occurs,
a net loss predominates in summer (Fig. 5.1.2.3).

Although a large number of studies have described measurements
of the effects of frost action on bedrock and regolith, only limited
quantitative information is available on the effects of frost and
freeze/thaw cycles on cohesive soils in humid temperate climates.
Wolman (1959), Harrison (1970) and Knighton (1973) mention the impor-
tance of frost action in the disintegration of cohesive sediments with
respect to the erosion of stream banks, but present no data concerning
the effect of solely this process.   The results from the present study
indicate that about 70% of the sediment supplied by subsoil fall was
transferred during periods with frost.

Conclusions

Subsoil fall plays a distinct role in stream bank erosion, as is
manifest by the development of undercuts up to 70 cm deep, and a con-
tinuous supply of sediment.   The rate of soil loss from these under-
cuts is largely dependent upon the characteristics of the subsoil,
especially with respect to its structure and stability, and on the
severity of frost conditions.   The average soil loss amounted to
about 10 kg per two years per 30 cm width in the period of investiga-
tion (or about 15 kg $m^{-1} y^{-1}$).

5.1.3 Surface soil downslope movement by creep related processes

Creep in soil has been defined as any movement caused by the re-
working of the surface soil layers as soil moisture and temperature
vary, by random movements due to organisms and by the steady applica-
tion of downhill shear stress (Carson and Kirkby, 1972).   According
to Terzaghi (1950), in a temperate environment the first two elements
of soil creep - frost creep and biological activity - may be described
as seasonal soil creep, because they are triggered by seasonal varia-
tions in the soil micro-climate.

Measurement of soil creep

The major point of interest was to determine the amount of surface

Measurement of movement of surface soil material

PLATE 5.1.3.1 (a)

PLATE 5.1.3.1 (b)

The frame is covered with a 1.5 mm nylon mesh to diminish the
erosive power of falling raindrops and to prevent splash erosion
of the plot.

soil material transported by creep related processes on the valley
floor immediately above channel banks.   Therefore the rate of
these processes was determined by measuring the amount of soil loss
rather than the displacement of discrete particles.

Field observations revealed that the top 1 or 2 cm of the soil
was set in motion by freeze-thaw processes.   Consequently, a method
to measure the movements in this upper 1 to 2 cm layer was chosen.
A simple wooden frame (0.3 x 0.3m) was installed with the four edge
posts fixed in the soil (Plate 5.1.3.1(a) and (b)).   Twenty centi-
metres above the ground surface the frame was covered with a 1.5 mm
nylon mesh to diminish the erosive power of falling raindrops and
prevent splash erosion of the plot.   The mesh size was large enough
for air and rainfall water to pass through, so that the moisture and
temperature regimes of the soil below were not affected.   At the
downslope end of the plot a small tray was dug into the soil with the
upper rim level with the soil surface to collect the material loosened
upslope.   The tray was fixed in the soil with metal rods to prevent
its upheaval by frost action.   The litter cover protecting the soil
was removed from the plots to obtain a maximum rate of surface soil
movement towards the channel banks.   The traps were emptied monthly.
The biological activity in the topsoil was determined indirectly from
monthly estimates of the percentage of bare soil in five $1m^2$ plots.

Results and discussion

Frost heave and biological activity are the main causes of sur-
face soil downslope movement.   Needle ice was observed at many sites
in winter, with needle lengths in general varying from 1-3 cm but at
very moist sites even reaching lengths of about 10 cm.   The maximum
depth of frost penetration was probably 20 cm.

Surface soil downslope movement was only measured above relatively
stable channel banks, as on the unstable banks situated in the outer
bends of the meanders no effects of frost heave and biological activity
were noticed.   The main reason for this might be the shallow soil
depth at these sites, which prevents the rate of migration of water
necessary for the growth of needle ice and ice lenses.   The unfavour-
able conditions for biological activity will be mainly determined by

the very dynamic character of these banks (continuous supply of soil material by subsoil fall and regular removal by mass movements) and the resulting absence of an A-horizon.

To determine the relative importance of both frost heave and biological activity the creep rate will be compared with the variations in frost occurrence (Fig. 5.1.3.1(c)) and bare soil percentage (Fig. 5.1.3.1(b) and Table 5.1.3.1).

Temporal variation in soil creep

For both study years a distinct peak in creep rate occurs at two different times each year, between February and the end of March, and between September and October. However, this trend follows the time of yearly cycles in frost occurrence (which peak in January-February) and soil exposure (which peak in January-March and September-October). This may imply that soil creep is influenced by the effects of the processes of both frost activity and biological activity (Fig. 5.1.3.1(a)). The following course of events may then be postulated: at the end of summer and in early autumn earthworm activity will slow down because of decreasing temperatures, and consequently loosening of the soil surface will occur. These loose conditions of the topsoil will favour the development of needle ice and consequently the down-slope transport of material during the frost heave cycles. In the course of winter the soil surface will be subjected to a larger number of frost heave cycles and, as most of the loosened soil material occurs in late winter (mid-January to the end of March), their net effect will be higher.

The complementary action of both processes (biological activity will be zero when temperatures are below $0^{\circ}C$ and frost heave occurs) makes it possible to determine their relative importance. The mean amount of material transported during periods of frost is 20 g/30 cm width per year, while the soil loss in the remaining (longer) period is 10 g/30 cm width per year (Table 5.1.3.1). These data clearly reflect the importance of frost activity and soil creep on channel banks, although the peak in mean soil creep rate in September-October 1985 may reflect to a lesser extent the importance of biological activity of soil creep in higher temperatures.

TABLE 5.1.3.1   SURFACE SOIL DOWNSLOPE MOVEMENT AND PERCENTAGE OF BARE SURFACE ABOVE STREAM BANKS AT SITES 5, 6, 7*

	Date	Measured soil loss for each observation date (grams collected from 30 cm wide tray)			Mean loss	Bare surface			Mean bare soil	Cause of surface soil downslope movement
		5	6	7		5	6	7		
Winter 1	12.01.85	1.6	2.5	1.2	1.7	6	4	12	7.3	F (Forest activity)
	17.02.85	0.5	0.2	0.2	0.3	5	3	4	4.0	F " "
	20.03.85	4.5	1.2	1.8	2.5	8	4	7	6.3	F " "
Summer 1	20.05.85	2.0	3.0	1.0	2.0	4	5	3	4.0	B (Biological activity)
	27.06.85	0.2	0.1	0	0.1	2	4	5	3.6	B " "
	29.07.85	0.1	0	0	0.03	4	0	1	1.6	B " "
	24.08.85	1.0	0.1	0.3	0.46	5	2	4	3.6	B " "
	30.09.85	4.1	3.3	3.2	3.5	13	4	3	6.6	B " "
	26.10.85	3.0	2.0	3.1	2.7	7	0	8	5.0	B " "
	29.11.85	1.5	1.4	0.9	1.26	1	0	3	1.3	B " "
Winter 2	28.12.85	3.2	1.5	1.2	1.96	0	0	0	0	F (Frost activity)
	31.01.86	0.8	0	0	0.26	0	0	0	0	F " "
	24.03.86	20.9	14.7	11.4	16.0	2	3	5	3.3	F " "
	06.05.86	1.8	2.3	1.7	1.9	4	0	8	4.0	F " "
	Total	45.2	32.3	26	35					
	% of total	44%	31%	25%	-					

Total mean in Summer 1 = 10;   Total mean in Winter 2 = 20;   Mean loss for 1 year = 30

Study period 1985-86

*The data refer to the amount collected on the date stated; collections were made at approximately monthly intervals.

A

Mean soil creep sites (5, 6 and 7)

(See Table 5.1.3.1)

B

Temporal variation in bare soil percentage

C

Occurrence of frost
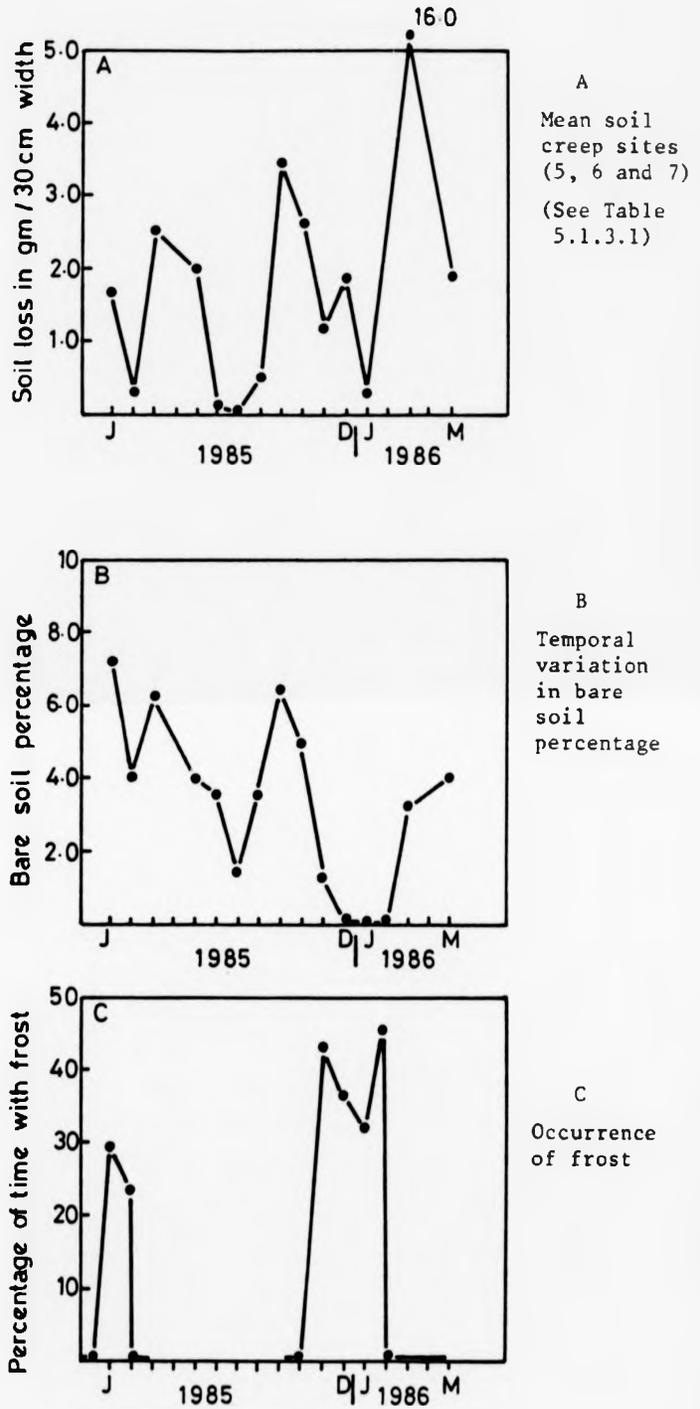
FIGURE 5.1.3.1

Spatial variation in soil creep

The data of Table 5.1.3.1 show a large discrepancy in creep rate between the three plots, with most soil loss (44% of the total) occurring at Site 5 and only slight losses (31% of the total) at Site 6 and (25% of the total) at Site 7.

The main factor governing these differences is probably soil texture. As the soil at Plot 5 contains more silt than at the other sites (Table 5.1.3.2), it is much more susceptible to frost heave. Several determinations of moisture content at the three plots consistently revealed the highest values at Site 5, thereby meeting the second requirement determining the occurrence and magnitude of frost heave: the availability of water. Also, the highest frost susceptibility at Site 5 exhibits the highest soil loss due to biological activity (Table 5.1.3.1). When regarding the seasonal variation in soil cover at the three plots (Table 5.1.3.1), it appears that soil cover conditions at Sites 5 and 7 show rather the same trend (continuous increase of litter-free surface from spring to autumn up to a value of 14%), although soil loss at Site 7 is considerably lower than at Site 5. However, the amount of bioturbation was always less at Site 7, suggesting soil loss at this site resulted from lower organic matter activity. Consequently, the removal of the litter layer may be due to another process, possibly wind action in view of the proximity of Site 7 to the edge of the forest.

The limited data on surface soil creep reviewed by Carson and Kirkby (1972) suggest that creep rate varies in general between 1 and 10 cm^3 cm^{-1} y^{-1}. Soil creep due to frost heave and biological activity in the Coombs Brook catchment approximates 15g 30 cm^{-1} y^{-1}, or about 0.5 cm^3 cm^{-1} y^{-1}, or at the lower limit of previously published data, although site and soil conditions may favour such movement less than those at other sites elsewhere. The short record from the Coombs Brook sites makes comparison with the large number of controlling variables (Anderson and Cox, 1984) impossible. Consequently, a crude generalisation has been made and the value of 15g per 30 cm width per year is used to obtain estimates of loss above unmeasured banks.

TABLE 5.1.3.2   SITE CHARACTERISTICS OF SOIL CREEP PLOTS

	Site Number		
	5	6	7
Slope angle $^\circ$	30	38	42
% Clay and silt	45	24	31
% Fine sand	28	30	15
% Coarse sand	27	46	54

Conclusions

Superficial soil creep on the channel banks was mainly determined by earthworm activity and, to a lesser extent, by frost heave. The occurrence of these processes was restricted to the stable banks, possible due to the presence of an A horizon and sufficient soil depth. Both processes exhibited a maximum intensity on the fine-textured soils of the banks of the catchment formation. The mean rate of sediment supply to the river by soil creep was 15g per 30 cm width per year, which is very low when compared with the soil loss by splash erosion at these sites: about 350g per 30 cm width per year. (Both values are valid for completely litter-free surfaces.)

5.1.4 Overland Flow on Stream Banks

The generation of overland flow and attendant erosion is a sub-ject which is usually considered for valley slopes, and in general little attention has been paid to causes and quantitative effects of overland flow on stream or gully banks. The rare occurrence of such runoff events, the small dimensions of stream banks in comparison to valley slopes, and the occurrence of more intensive processes and spectacular phenomena of bank erosion might probably be causes of this lack of attention.

When considering the generation of overland flow on stream banks in general, four conditions may be distinguished:

1. Rainfall intensity exceeding infiltration capacity.

2. Saturation of the bank material by rainfall followed by saturation overland flow.

3. Surface runoff from valley slopes spilling over the banks.

4. Subsurface flow (seepage) which may result from either a high (perched) water table in the contributing area, or the outflow of water which has infiltrated into the banks during high water stages.

The first two of these conditions are predominantly related to the intrinsic characteristics of the banks, while the latter two

conditions are, to a large extent, dependent upon the hydrological characteristics of the valley slope subsystem.

The occurrence of overland flow on stream banks may have a direct or an indirect effect in terms of erosion:

Direct: erosion by sheetflow, in general caused by conditions 1 and/or 2;

erosion by concentrated overland flow resulting in the development of rills, and in general caused by conditions 3 and/or 4.

Indirect: erosion resulting from an increase in moisture content of the bank material, thereby enhancing the occurrence of mass movements.

In addition, subsurface flow may cause piping, a phenomenon common where alluvial banks are composed of layers with different water transporting capacities or in banks composed of very dispersive material (Jones, 1971; Crouch, 1976). If the flow through the more permeable layers is capable of dislodging and transporting particles from this layer, the material is slowly removed, undermining portions of the banks and again increasing the chance of occurrence of mass movements (Decoursey, 1981).

From the above, it appears that the rate of soil loss by overland flow is determined by a variety of factors:

A. Factors controlling the erosive power of overland flow:

- flow characteristics: flow velocity, flow depth temperature and indirectly precipitation amount and intensity;

- site characteristics: surface roughness, infiltration capacity, slope angle.

B. Factors controlling bank erodibility: texture, aggregate stability, consistency limits, moisture content, organic carbon content, permeability.

Field observations in the catchment

Clear evidence of overland flow action on the stream banks was

observed at only a few sites in the Coombs Brook catchment where it resulted from overland flow on the valley slopes or from seepage. The first process, overland flow from the valley slopes down the stream banks, was observed at six sites; it was always related to the nearby presence of paths and animal tracks. Part of the over-land flow on the valley slopes became concentrated and ran down such tracks. However, at all sites, water entering the stream carried little sediment, reflecting the small uptake of soil material from the banks (and the valley slopes) and its limited importance in stream bank erosion.

In addition to the above field observations, the measurements at runoff troughs installed in the banks (Fig. 3.6.1) indicate that overland flow also occurs at sites where both overland flow and seep-age are absent, suggesting the activity of other runoff generating processes. It was observed occasionally that additional runoff amounts were derived from stemflow and/or flow beneath the litter layer, especially during snowmelt. Water from these non-channel sources entered the channel incision by flowing along the roots at the soil fall undercuts, thereby causing transport of aggregates from the accumulation zone by wash or splash. At a few sites this even led to rill erosion of the banks.

Measurement of erosion by overland flow

The rate of erosion was measured in two ways based upon the possible effects of overland flows:

1.   Measuring the changes in bank microtopography with the aid of erosion pins (Section 5.1.2). These pins were driven into the bank surface and the protruding length was measured monthly. As few banks showed clear evidence of overland flow having occurred, only 18 pins were installed.

2.   Measuring the mass of sediment collected in three 40 x 35 cm troughs each month.

Results and discussion

The observed trend of soil removal by overland flow into troughs

is confirmed by the erosion pin data. While most of the pins at
Site A (Plot I) indicate accumulation rather than removal due to the
lack of sufficient transport conditions, the reverse holds for pins
B1-B6 in Plot II. The lack of pin data at Plot II for the first
winter is due to the occurrence of a mass failure and the loss of the
pins. Erosion pins B7-B10 installed at Plot III show intermediate
results (Table 5.1.4.1).

Sediment transport by overland flow tends to be greatest on
relatively unstable banks, e.g. at Sites A and B. On the more stable
banks, as at the other measurement sites (Sections 5.1.2 and 5.1.6),
splash losses are lower (Table 5.1.6.2), subsoil fall does not occur
and infiltration capacities will be higher due to a more stable
structure of the surface soil (Table 5.1.2.1). As a consequence,
sediment transport by overland flow will be of no importance at these
sites.

Temporal variation in soil loss by overland flow

The limited data from the plots show that the rate of soil loss
is determined by the detachment of soil material by other processes.
From this point of view most erosion might be expected to occur during
winter and spring when large amounts of sediment are supplied by sub-
soil fall and/or detached by rainfall or frost creep. Maximum soil
loss will accordingly be recorded during periods of snowmelt or pro-
longed rainfall when transport conditions are optimal. The measured
changes in erosion pin length, however, seem to be in contradiction
with the plot data, as almost all pins indicate maximum accumulation
in winter. It must then be concluded that, although erosion of the
bank surface occurs in winter and spring, overland flow is not capable
of transporting all of the aggregates supplied by detachment, so that
a net accumulation of material is present at the end of spring.

In summer and autumn, soil losses at Sites A and B show a con-
trasting trend. While all the pins at Site B clearly indicate erosion,
the pins at Site A denote net accumulation or only slight erosion.
This difference might reflect less transport at Site A or differences
in the rate of detachment. However, the data in Table 5.1.2.2 show
that detachment by subsoil fall is lowest at Site B, which implies

TABLE 5.1.4.1   MEAN SEASONAL CHANGES IN PROTRUDING PIN LENGTH ON OVERLAND FLOW SITES

(+ = erosion;   - = accumulation;   data in mm)

	Pin	Winter 1 mm removed	Summer 1 mm removed	Winter 2 mm removed	Summer 2 mm removed
	A1	- 50	- 6	- 32	- 6
	A2	- 11	0	- 70	- 10
	A3	- 13	- 13	- 6	- 4
Plot	A4	- 6	+ 1	- 22	+ 1
I	A5	- 4	+ 2	- 34	- 24
	A6	- 11	+ 3	+ 1	0
	A7	+ 2	0		
	A8	+ 8	+ 2		
	B1		+ 15	+ 20	0
	B2		+ 12	- 15	+ 22
Plot	B3		+ 34	0	+ 1
II	B4		+ 29	+ 29	
	B5		+ 20	0	
	B6		+ 6	+ 17	
	B7	- 64	+ 11	- 9	
Plot	B8	- 56	+ 15	- 87	
III	B9	- 1	+ 10	- 48	
	B10	- 4	+ 15	- 77	

TABLE 5.1.4.2   SITE AND SOIL PROPERTIES OF OVERLAND FLOW PLOT LOCATIONS

	Plot I A 1-8	Plot II B 1-6	Plot III B 7-10
Mean width (cm)	40 x 35	40 x 35	40 x 35
Slope angle (^{o})	46	36	39
Horizontally projected area (m^2)	1.5	1.6	1.4
Particle size			
% Clay	28.0	19.0	20.0
% Fine sand	7.0	42.0	24.0
% Coarse sand	65.0	39.0	56.0
% Organic matter	3.0	0.5	1.9

that the accumulation at this site results from a lower transport rate.

In addition, differences in aggregate stability (Table 5.1.4.2) may be of importance in explaining the variations in transport rate; the low aggregate stability at Site B easily causes breakdown of the aggregates during rainfall or conditions of overland flow, thereby making them more susceptible to transport. Disintegration of the aggregates may also cause reduction of the infiltration rate (Farrel and Carson, 1972) and an increase in the possible occurrence of over- land flow. In contrast, the higher stability of soil aggregates at Site A results in a lesser breakdown and makes them more difficult to transport.

Conclusions

Field observations and measurements of overland flow on stream banks show that this flow action consists of a rather complex set of processes of which the conditions are often not only bounded to the channel incision. Three distinct types of overland flow could be distinguished, each related to specific site conditions: overflow from valley slopes, seepage, and litter/stemflow. It was shown that overland flow acts primarily as a transport medium for material detached by other processes active on the stream banks and that detach- ment by flow action alone is of very limited importance. Consequently, the rate of sediment transport is a reflection of, on the one hand, the sediment supply by processes such as subsoil fall and rain splash, and on the other hand, runoff volume as determined by hydrological conditions. The indirect effect of overland flow on stream banks - the occurrence of mass failures - may be of much greater magnitude.

5.1.5 Mass movements

Mass movement is potentially an important method of sediment transport in the Coombs Brook catchment. Three main types of mass movement may be recognised: slide, flow and heave, based upon three parameters, namely, rate of movement, type of movement and water con- tent of the mobile material (Fig. 5.1.5.1) (Carson and Kirkby, 1972).
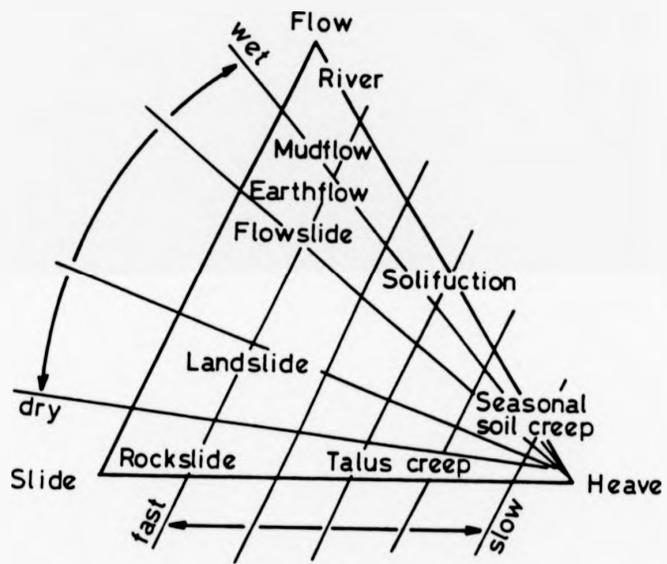
FIGURE 5.1.5.1

Classification of mass movement processes
(after Carson and Kirkby, 1972)

Measurement of soil loss due to mass movement

In general, three types of measurement techniques may be distin-
guished in determining the rate of slope retreat due to rapid mass
movements:

- Indirect measurements: rate of slope retreat measured on
  maps and aerial photographs (Statham, 1981).

- Direct measurements: the direct measurement is a major problem
  because of locating potential landslides before they take
  place.

- Stability analyses of landslides and landslide-controlled
  slopes. Several problems are encountered in this analysis
  (Statham, 1981; Carson and Kirkby, 1972).

In this study an indirect method was chosen (measured on maps
only) in which the banks were examined at regular time intervals. If
a mass failure had occurred, the volume involved was estimated from
the size of scar. At the end of the study period the volume of the
debris still present at the toe of the bank was estimated. By sub-
tracting both volumes the net sediment transfer by mass movements
could be calculated.

Results and discussion

In the catchment area three types of bank failure could be distin-
guished: shallow slides, slumps and flow-slides, of which the first
type was the most common. Only two slumps were recognised, both of
which had already occurred before the author's first visit to the
catchment in 1984. Their volumes were relatively small, about 9 to
12 m^3. Both of the other two modes of failure were active during the
study period. Examination of the stream banks showed that shallow
slides had occurred at four sites. The dominance of shallow sliding
is somewhat counteracted by two facts. First, the internal stability
of the debris transported by flow slides is very low, thereby rendering
it more susceptible to transport by streamflow or other agents than the
more cohesive landslide debris. The second point is that shallow land-
slides stripped off the entire soil mass from the bedrock during one

failure while flow slides occurred repeatedly at the same site,
thereby generating smaller sediment volumes.   The causes of this
difference in intensity of sediment transfer are clearly related to
differences in type of bank material and hydrological conditions
which will be discussed below.

Figure 5.1.5.2 and Table 5.1.5.1 show that the landslides which
occurred during the study period are all in the head water sites 5, 6
and 7, where the soil is exposed.   Although this does not mean that
landslides are absent elsewhere, it implies that shallow sliding is
more frequent in the middle part of the catchment, particularly above
Site 4.   The landsliding sites in Sites A, B and C exhibit a differ-
ence in failure intensity as well as in the degree of basal removal.
While in the C area most of the failed debris is quickly removed by
streamflow, a large part remains behind on the banks in the centre of
the catchment (above Station 7).   This lower rate of basal removal
may be caused by the higher content of stone fragments which retard
lateral corrasion.

Conclusions

During the study period two types of mass failures occurred on the
stream banks: flow-slides and, more often, shallow landslides.   The
occurrence of both types was restricted to periods with much rainfall
or rapid snowmelt.   However, the cause of triggering the failures was
different.   While flow-slide took place due to extra addition of
water by overland flow or seepage, landslides were caused by under-
cutting due to streamflow action.   The total amount of material that
failed and was afterwards transported by streamflow is estimated at
6650 kg in two years.

5.1.6 Splash erosion

A wide range of publications from all parts of the world stress
the importance of splash in soil erosion.   Water droplets can splash
material over distances exceeding 0.5m (Poesen and Savat, 1981a,b).
On a sloping surface the downslope distance of movement of splashed
material exceeds the upslope distance moved, so generating a net down-
slope displacement of material (Poesen and Savat, 1981a,b).   Splash
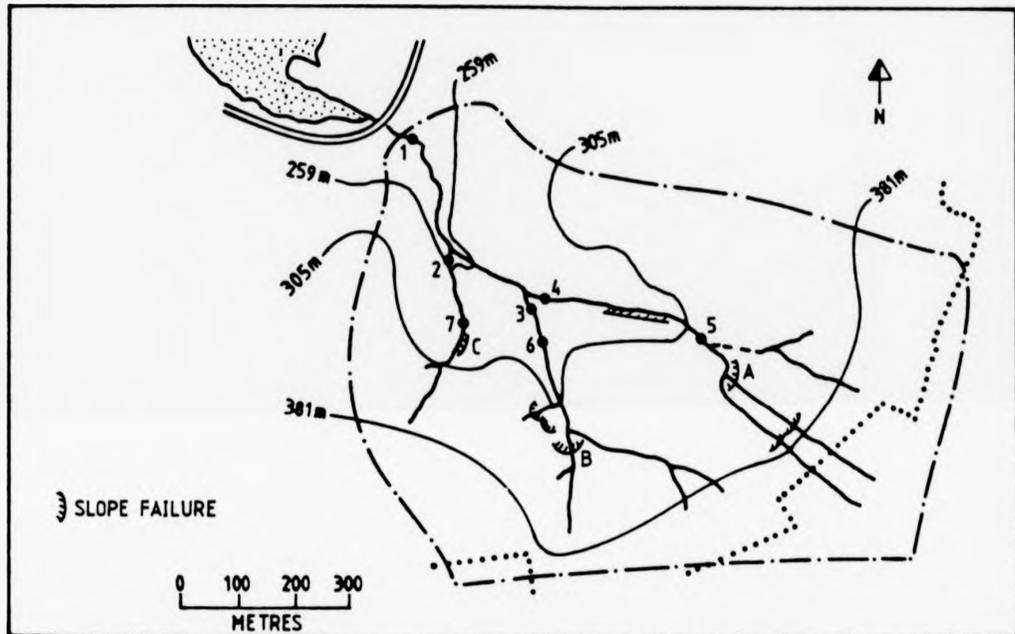
FIGURE 5.1.5.2

Location of bank failures in 1984-86
(Letters refer to Table 5.1.5.1)

TABLE 5.1.5.1   OCCURRENCE OF FAILURES AND ASSOCIATED SEDIMENT
                 TRANSFER, 1984-1986

Site	Location (see map on Fig. 5.1.5.2)	Scar volume m^3	Slide debris m^3	Type of failure
A	4-5	0.9	0.34	shallow
	4-5	0.16	0	"
B	3-6	1.2	0	"
	3-6	1.5	0.15	"
C	2-7	0.22	0.06	"
	2-7	1.4	0	"

erosion is influenced by:

- the physical characteristics of the rain (erosivity);

- the physical characteristics of the soil (erodibility);

- site factors, particularly slope angle and vegetation.

 (Morgan, 1979.)

Measurement of splash erosion

Measurement of erosivity

The erosivity of rainstorms was calculated from rainfall intensity.   Rainfall amounts and intensities vary greatly under the forest canopy, and therefore intensities were derived from the open area recording rain gauge at Station 1.

Measurement of erodibility

The grain size distribution of the soil material smaller than 2 mm (material smaller than 50 μm) was determined by sieving (Chapter 4).   General data concerning slope length, slope angle, texture and organic matter content are given in Table 5.1.6.1.

Measurement of splash

Splash loss on the stream banks was measured by installing three or four simplified Bolline type splash boards (Goudie et al., 1981) at each of the six sample sites along the main channel.

The splash boards used were 52 mm diameter funnels, buried flush with the ground surface to catch splashed soil.   A rot-proof filter is placed into the funnel to catch the sediment.   The funnel is weighed before being placed in the ground and is removed after each rainfall event for re-weighing.   The funnel is cleaned on the outside and dried before re-weighing to obtain the weight of splashed soil.   This apparatus does not separate material splashed downslope from that splashed upslope, nor does it allow soil which has entered the trap from being splashed out again.   Therefore, only cumulative splash is measured and estimation of absolute rates of downslope transport

TABLE 5.1.6.1   GENERAL DATA ON SPLASH SITE CHARACTERISTICS

Splash board	Slope length cm	Slope angle °	Silt & clay %	Fine sand %	Coarse sand %	Organic matter %	Bank Stable	Bank Unstable
A 1	79	30	92.0	7.0	1.0	5.2	X	
2	82	28						
3	80	22						
B 1	132	12	94.0	5.0	1.0	0.9		X
2	130	10						
3	131	8						
4	130	5						
C 1	112	14	62.0	35.0	3.0	3.6	X	
2	112	12						
3	111	2						
D 1	112	12	56.0	37.0	7.0	0.8		X
2	110	10						
3	110	5						
4	110	0						
E 1	140	42	39.0	38.0	23.0	3.0	X	
2	131	33						
3	122	15						
F 1	115	55	70.0	24.0	6.0	1.0		X
2	110	50						
3	105	53						

cannot be made. The funnels can suffer from ingress of overland flow, and therefore may not necessarily give a true measure of splash (Fig. 5.1.6.1).

Results and discussion

Splash erosion in the Coombs Brook catchment yielded a mean of 240 kg y^{-1} over the 1984-86 study period (Table 5.1.6.2). Exposure of soil by tree fall created about 20% of the sites affected by splash erosion. Half of these tree fall sites were within 25m of the stream channel on the steep lower slopes. Lack of stones to provide a protective capping to exposed subsurface soil helped to make splash an important process on the slopes. Highly dispersable clays were quickly removed by storm water.

Direct input of material by splash to the stream channels is probably relatively small, as most splash erosion sites are some distance from the channel on relatively gentle slopes. Along the streams, splash erosion attacks the aggregates released by soil fall, especially on talus slopes at the foot of banks above low water levels. Splash soon generates a surface crust.

Deer tracks across the catchment expose soil to splash erosion, contributing to the considerable spatial variation in the distribution and quantity of splash erosion. Nonetheless, an exponential increase in net amount of material transported with increasing slope angle was detected (Fig. 5.1.6.2).

The translocation of sediment by splash erosion is highly seasonal. In the catchment area maximum rainfall efficiency occurs during the early winter (Table 5.4.2.2), indicating that the canopy increases the erosivity of the rain. Thus, most material is supplied from the lower slopes to the stream when splash erosion is most effective, as shown in Table 5.1.6.2.
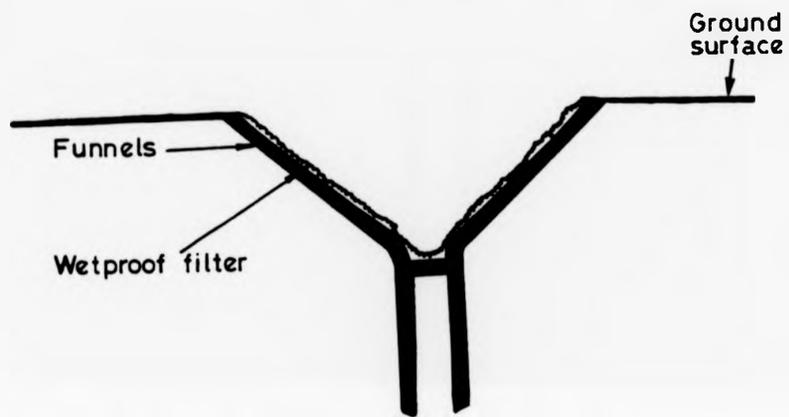
FIGURE 5.1.6.1

Measurement of splash erosion by Bolline type splash, using
52 mm diameter funnels buried flush with the ground surface

TABLE 5.1.6.2   SOIL LOSS AT THE SIX SPLASH SITES (GRAMS)

Date	A 1	A 2	A 3	B 1	B 2	B 3	B 4	C 1	C 2	C 3	D 1	D 2	D 3	D 4	E 1	E 2	E 3	F 1	F 2	F 3	I 30* (see Table 5.4.2.2)
15/05/85	2.4	2.1	0.9	3.4	2.7	4.1	0.9	4.5	3.6	2.6	3.4	3.2	2.6	2.5	4.5	3.7	2.6	3.6	2.7	2.5	2.8
12/06/85	2.6	2.0	0.5	5.1	4.2	3.1	0.1	7.5	6.7	6.1	8.6	7.5	6.4	6.0	8.7	6.5	6.1	7.5	6.1	5.1	6.2
09/07/85	4.3	2.1	0.4	3.6	2.5	2.2	0.1	4.6	3.2	2.3	3.5	3.2	2.1	1.0	3.6	2.1	1.0	3.4	2.1	1.0	2.2
15/07/85	5.2	1.2	0.9	6.5	4.3	5.0	2.1	6.5	5.4	5.2	6.7	5.6	5.3	4.2	7.5	5.3	4.2	6.5	5.3	3.4	5.0
30/07/85	6.2	1.1	1.0	4.3	3.2	3.0	1.0	5.4	4.3	3.2	4.5	3.6	3.2	2.1	4.2	3.1	2.1	4.6	3.2	2.1	3.0
12/08/85	7.5	2.4	0.2	7.5	6.4	6.0	1.4	7.6	6.4	6.2	8.7	6.5	6.2	5.4	7.6	6.2	5.1	7.4	6.2	5.2	6.0
26/08/85	1.2	1.0	0	5.4	4.2	3.4	2.1	5.4	4.3	3.6	5.6	4.5	3.2	2.0	4.5	3.2	2.1	4.7	3.3	1.1	3.4
17/09/85	1.0	0.9	0.01	6.3	5.4	4.0	1.0	6.5	5.4	4.2	5.4	4.6	4.1	2.1	5.4	4.2	3.2	5.6	4.2	2.3	4.0
09/10/85	1.2	0.8	0.02	6.4	4.5	4.2	1.4	5.4	4.4	4.3	6.4	5.3	4.3	1.0	4.6	4.1	3.1	5.1	4.3	2.1	4.2
11/11/85	1.9	0.9	0.09	3.2	2.4	2.3	1.0	4.6	3.2	2.1	3.6	3.2	2.4	1.2	3.5	2.1	1.0	3.4	2.2	1.0	2.3
22/12/85	3.5	1.2	1.4	7.6	6.5	5.3	4.3	6.4	5.4	5.2	7.7	6.5	5.2	4.3	6.5	5.2	4.1	6.4	5.1	3.9	5.3
13/01/86	4.5	1.8	1.0	3.6	2.4	2.4	1.0	4.1	3.2	2.1	4.6	3.5	2.3	2.1	3.4	2.1	1.2	3.5	2.3	1.1	2.4
01/02/86	1.2	1.0	0.9	6.4	5.6	5.4	2.1	7.5	6.4	5.3	6.8	5.7	5.3	4.1	6.3	5.3	4.2	6.7	5.2	3.7	5.4
30/03/86	4.7	1.5	1.0	3.5	2.4	2.3	1.2	4.2	3.1	2.1	3.5	3.4	2.1	1.0	3.4	2.2	1.0	3.5	2.1	2.0	2.3
15/04/86	4.2	2.7	1.2	4.7	3.5	3.0	2.0	5.3	4.2	3.2	5.6	4.5	3.2	2.1	4.2	3.1	2.1	4.5	3.2	2.0	3.0
Total	51.6	22.7	9.52	77.5	60.2	55.7	21.7	85.5	69.2	57.7	84.6	70.8	57.9	41.1	77.9	58.4	43.1	76.4	57.5	38.5	-

*I 30 = maximum 30 minutes intensity in mm hr^{-1}
1117.5 (g) = 1.1 kg y^{-1} (total of soil loss)
Number of observations in the field = approximately 219
Approximate total = 219 x 1.1 kg = 240 kg/y^{-1}
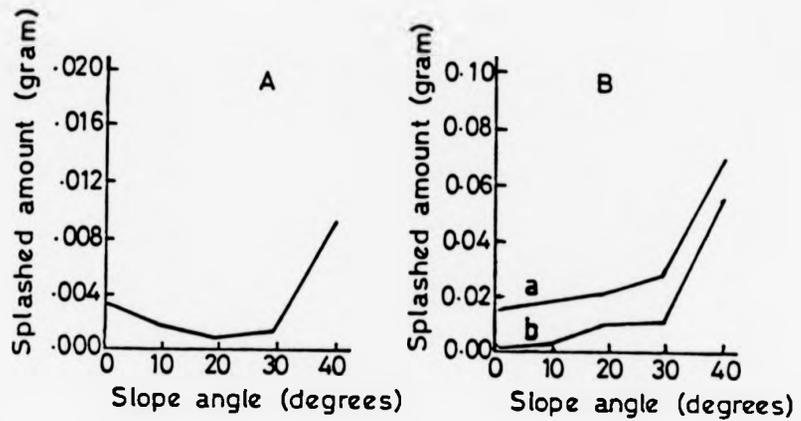
FIGURE 5.1.6.2

A Amount of material splashed in an up-slope direction as a function of slope angle

B (a) Amount of material splashed in a downslope direction as a function of slope angle

(b) Net amount of downslope transported material by splash as a function of slope angle

5.2 EROSION PROCESSES ON VALLEY SLOPES

Soil erosion is defined as: detachment of individual particles from the soil mass and their transport by erosive agents such as running water, wind and raindrop impact. In this definition the two phases of the erosion process are clearly stated: detachment and transport. Although it is often difficult to separate these two phases in the field, it forms the basis of understanding the variation of soil erosion in time and space. The erosive agents active on the slopes of the Coombs Brook catchment (Table 5.1.1) do not include litter fall, as leaves on the forest floor only carry soil material deposited on them when they are moved downslope, and do not detach soil material.

In addition to the contrast between detachment and transport, a contrast in source areas may be recognised, such that between areas of rill erosion and areas of inter-rill erosion, Meyer et al. (1975) showing some rilling to be essential for sediment production from eroding slopes. They further showed that practically all soil from inter-rill areas is detached by raindrop impact and that most of the detached soil is transported by flow. The percentage of total inter-rill derived material splashed directly to rills appeared to be approximately equal to the percentage of the slope surface that is rilled. In fact, the rill system of the catchment (Fig. 5.2.1) is stable, as no new rills developed during the two years of investigation. Only minor extensions occurred due to collapse of the roofs of pipes (Plate 5.2.1(a,b,c,d)). Many of the stable rills are related to drainage lines constructed during afforestation 50 years ago.

According to the above general description of soil erosion, the following processes may be distinguished as being active in the various source areas on the valley slopes:

Inter-rill - gully areas

- Splash detachment and splash transport.
- Splash detachment and overland flow transport.
- Throughflow.
- Activity of burrowing animals.
- Litter transport.
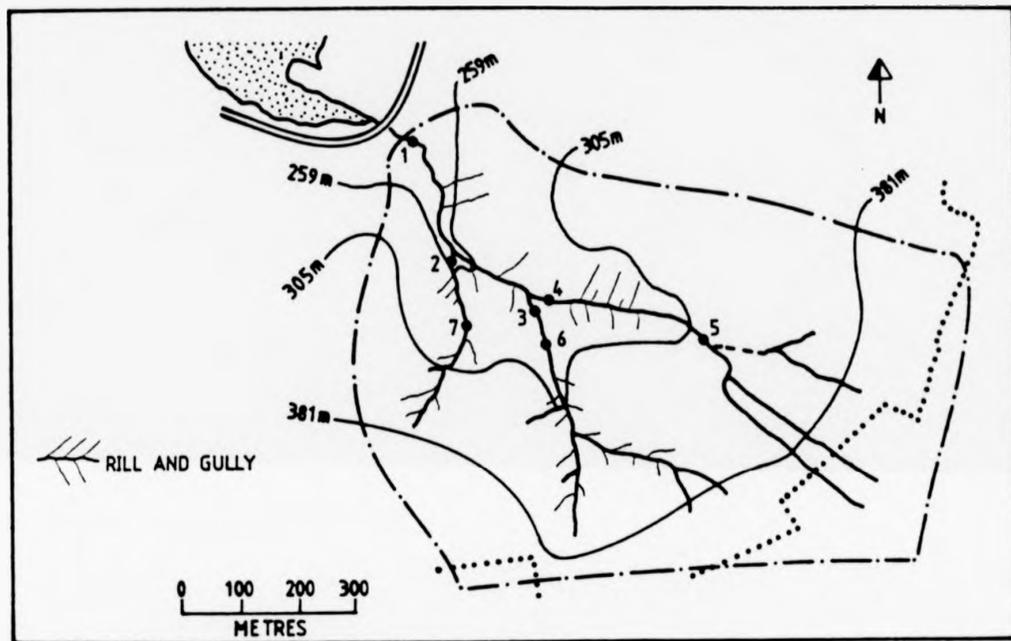
FIGURE 5.2.1

Coombs Brook catchment.   Main rills and gullies system

PLATE 5.2.1 (a)   PLATE 5.2.1 (b)

The rill system of the catchment is quite stable in some sites.

PLATE 5.2.1 (c)

PLATE 5.2.1 (d)
Rill erosion expanding downslope.

Rill areas

- Splash detachment and flow transport.

The following section presents approximate calculations and estimates of the soil losses caused by the various processes and compares these with the sediment output from the sub-catchment.

5.2.1 Erosion of Inter-Rill Areas

Of the various processes active in surface soil detachment - raindrop impact, overland flow and animal activity (which in fact is a process controlling the effect of raindrop impact) (Table 5.1.1) - raindrop impact seems to be the most important. From information on the hydraulic characteristics of overland flow (Section 5.1.4), it appears that overland flow is not able to cause detachment.

Splash erosion

This was measured by installing the six (52 mm diameter) funnels described in Section 5.1.6.

Activity of burrowing animals

The two main effects of animal activity on soil erosion have already been referred to in foregoing sections:

- Removal of the protective litter layer, resulting in a higher susceptibility of the soil surface to splash erosion.

- Deposition of soil material on the forest floor, followed by detachment and transport by raindrop impact and overland flow.

Throughflow

In the catchment area two types of throughflow were distinguished:

- Violent flow through macropores contributing to storm-flow, together with quick return throughflow that produces saturated partial source areas.

- Delayed return flow in the upper soil layers contributing
  to base flow.

The first type of throughflow does not occur independently of
overland flow and thus also transports material detached by raindrop
impact.   As a consequence, sediment transported by sub-surface flow
is indistinguishable from that carried by surface runoff.   Such con-
ditions were described in more detail by Pilgrim and Huff (1983) for
plot experiments in California.   Data on the erosion of macropores in
the Coombs Brook are not available.   However, some sub-surface erosion
may have occurred.

No direct measurements were made of water volumes and sediment
amounts related to the second type of throughflow.   Water samples
taken at the weir during baseflow conditions (smaller than 10 1 s^{-1})
showed a rather constant suspended sediment concentration ranging
from 80 to 120 mg 1^{-1}.   Sediment in all of these samples consisted of
fine dispersed clay, probably originating from the upper part of the
soil layers (15-35 horizon).   The amount of sediment transported by
delayed, slow throughflow could roughly be determined by calculating
baseflow volumes from water level recorded and attributing a mean
suspended sediment concentration of 100 mg 1^{-1} to these.   This
resulted in an estimated value of about 2000 kg in two years.

Leaf transport

Leaf transport provides a mechanism whereby sediment splashed from
soil exposures located anywhere beneath a forest may be relatively
rapidly supplied to the drainage courses.   Heavy rain (310 mm/h)
occasionally displaces litter which becomes re-arranged in concertina-
like forms.   Such movements often occur downslope from trees, and
presumably reflect the occurrence of stemflow on their smooth trunks.
Due to splash erosion, such leaves may have mineral particles adhering
to their surfaces.   Two main types of event can initiate the movement
of such leaves lying loose on the forest floor.   First, leaves may be
dislodged by occasional extreme events, such as localised overland flow,
a severe gale, or trampling by deer.   Such events occur irregularly
in time and may not be concentrated at specific locations.   Secondly,

minor but frequent movements of a more continuous nature are initiated
by wind or rain.   Monthly collections of moving litter and the sedi-
ment adhering to it revealed that leaf transport varies with type of
leaf, slope angle, and with various microclimatic factors (Fig. 5.2.1.1).
The thickness of the transportable leaf cover on the slopes is impor-
tant.   This is a very variable quantity, depending on antecedent con-
ditions.   Inevitably, it is greatest during the autumn period of leaf
fall, when the leaves of the deciduous trees, especially near Station
6, are very susceptible to transport.   They do not, however, necessar-
ily transport much sediment, since they mainly remain close to areas
of bare soil only temporarily.   During a measurement period in 1985,
in autumn, 0.10 grams of sediment was translocated per 10 grams of
transported leaves, compared with 1.6 grams during the late summer
period.   The amount of sediment transported by a given weight of leaves
is dependent on the amount of bare soil from which the sediment is
supplied.   The transport of leaves tends to decrease after the autumn,
but the seasonality is not pronounced.   The amount of sediment trans-
ported by leaves shows a late-summer - early-autumn peak, reflecting
the changes in areas of bare ground and in the erosivity of the rainfall
(Fig. 5.2.1.2).

As mentioned above, litter transport is not an erosion process,
as it is only effective in transporting soil material.   Soil material
is deposited on litter by splash, animal activity and overland flow.
As transported litter is trapped behind the weir or held behind large
cobble fragments in the channel, the soil material may only leave the
catchment if it is washed from the leaves (Plate 5.2.1.1(a) and (b)).

No continuous measurements of the amounts of soil material trans-
ported in this way are available for the catchment.   However, as the
soil material on the litter is mainly derived from raindrop detachment
(or in an indirect way by settlement of sediment entrained in overland
flow), the transported sediment volume is already included in the soil
losses attributed to splash erosion.

5.2.2 Erosion of Gully Areas

So far the loss of material from different sites in the catchment
has been considered without reference to gullying.   The shallow
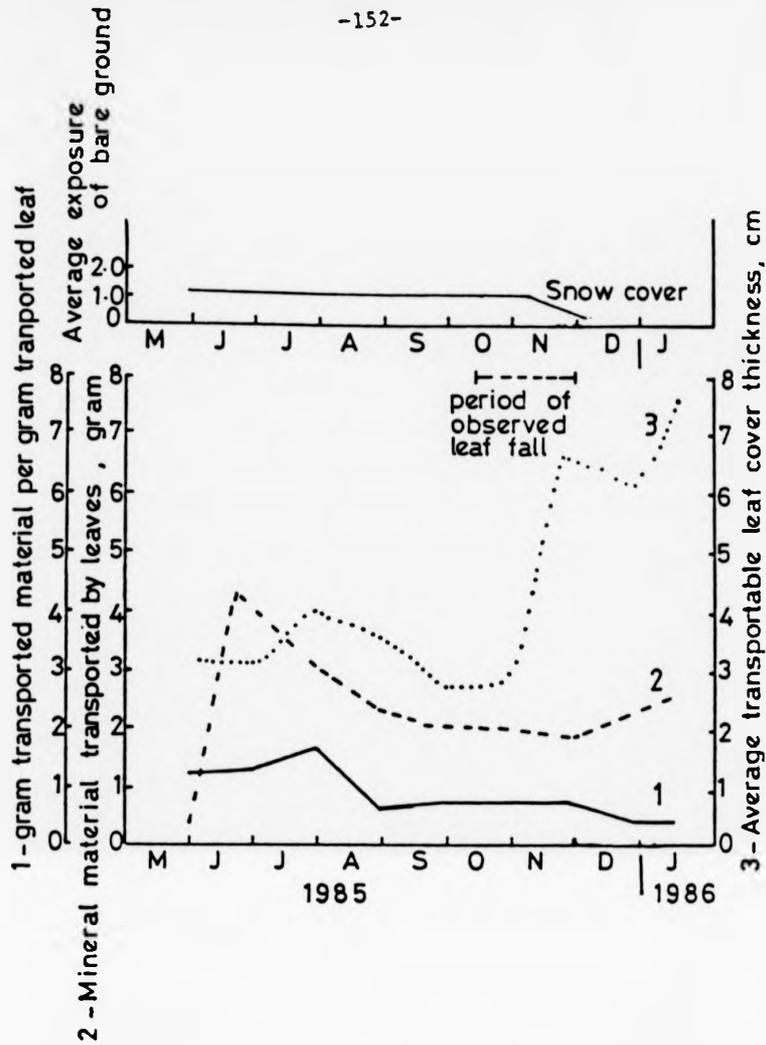
FIGURE 5.2.1.1

Average exposure of bare ground, average transportable
leaf cover thickness, mineral material transported by
leaves and gram transported material per gram transported
leaf, over the period May 1985 - January 1986, at the
catchment area around site 5.
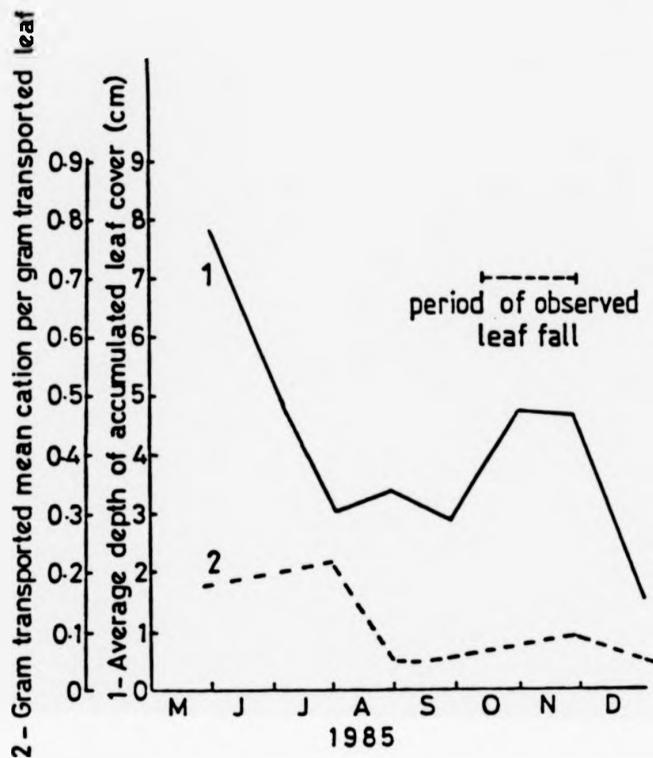
FIGURE 5.2.1.2

Transported leaf in the stream bed over
the period May 1985 - December 1985.
(South-east of the catchment area
around site 6).

Leaf transport

PLATE 5.2.1.1 (a)
Transported litter is trapped behind the weir.
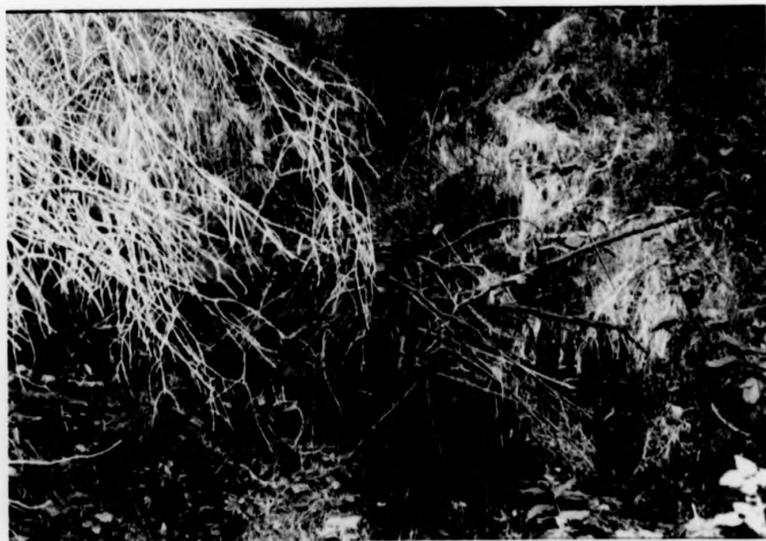
PLATE 5.2.1.1 (b)
Transported litter is held behind large cobble fragments in
the channel.

intermittent channels range in depth from 10-30 cm to 3-4m.   These
gully features are considered separately because they cross the whole
catchment area (Fig. 5.2.1).   During the course of field-work, the
following general observations on hydrology and gully development were
made:

1.   In some places, where the root cover is fully-developed,
       gullies are overgrown and intermittent; elsewhere, parti-
       cularly downslope of heavily eroded burnt ground, gullies
       may be very active (Plate 5.2.2.1(a) and (b)).

2.   The overgrown gullies in areas of thick roots are shallow
       and only rarely carry water.

3.   Most gullies have a humic topsoil which overhangs a sandy
       subsoil. Frequently the gully bed or low gully sides are
       composed of clay.

4.   Where the gully sides are of clay, the gully is wide with
       relatively gentle slopes. This is not what might be expec-
       ted if running water were the main agent of gully enlarge-
       ment.

       To supplement these observations, a detailed survey of gullying
was made between Stations 4 and 5, on an area which was heavily burnt
in early 1984 and was subsequently subjected to severe erosion and
gullying.   The nature of gullying in this area is considered below,
in a downslope direction, because it indicates the processes by which
gullies enlarge and the conditions which favour their development.

       The gentle slope was broken by two or three large and several
small step-like seepage faces, running across the slope.   These pre-
sented vertical faces of sand, up to 60 cm high, which passed down-
wards into a clay soil at their base.   The clay extended from the
base of the face, downslope, to form a bare surface which appeared to
be subject to surface wash.

       At 10-15m, downslope from the zone of seepage faces, small gully-
heads began abruptly as steep-sided concentric depressions, 50-150 cm
wide and 13-15 cm deep.   Some gully-heads were overgrown, but others

PLATE 5.2.2.1 (a)

Coombs Brook catchment. In some places, where the root cover is fully developed, gullies are overgrown.

PLATE 5.2.2.1 (b)

In heavily eroded burned ground, gullies may be very active.

appeared to be extending by basal sapping, under-mining and slumping. The area where the gully-heads originated had more gentle slopes (10°-25°) than the land above or below, and a surface cover of 70% plant, 10% grass and 20% bare ground. Downslope, the gullies, extending from the gully-heads, became wider and deeper, although a few subsequently petered out after 50m, in a bare washed sandy area. At this point, the hillside was strewn with angular gravels resting directly on the surface and coinciding with the outcrop.

Those gullies that survived this area, increasing in size downslope, passed into an area supporting a thick cover of grass. The gullies, by now about 3m wide and 1.5m deep, were completely overgrown. The main surface drainage of the lower slopes was along shallow marshy channels.

Gullies up to 2m deep were present on steeper slopes, notably in the fine sand and silt deposits of hillslope chutes. In places, gully development is associated with the enlargement of drainage ditches, but this is not universal; elsewhere tile drains have been uncovered by down-cutting.

Soil material in rills may be detached by concentrated runoff, raindrop impact and, to a lesser extent, frost activity (needle ice). The peak instantaneous discharge measured in one of the rills was 45 l s^{-1} in October 1985. This value is only slightly higher than the threshold value of 44 l s^{-1} as given by Hjulstrom (1935) for detachment of particles from the rill floor. This implies that rill erosion by flow will be of minor importance, agreeing with Meyer et al. (1975). They state that: "The transport capacity of rill flow is much greater than the rate at which flow can detach soil". Rill bottom and sides are almost bare throughout the year, which is favourable for detachment by raindrop impact if water depth in the rill is not too high (Palmer, 1964). If runoff occurs in the rill, by far the largest part of the detached material is carried off, since only minor amounts of bedload (soil aggregates) were observed in the rills after runoff events.

Measurement of gully growth

Generalisation from erosion pin measurements is difficult. Fewer

measurements of gully erosion were made than was anticipated, because many pins were lost through a larger scale of erosion than envisaged; running water or slumping swept away a considerable number of pins.

Measurements of erosion from small overgrown gullies in regions of fully developed plant were relatively low.   For example, some gully clay sides lost material at the average rate of 32 mm/year from the banks and 10 mm/year from the bed.   In one area, a gully 15 cm deep was not deepened at all in about two years, and the side only lost 10 mm of material during this period.   Most other high losses were recorded in different parts of the catchment from wide gullies cut in silt and clay.   The average loss of 50 mm/year reflects the importance of running water.   In other gullies documented in areas very close to the mean tributary, slumping was so severe that most measurements were lost.

Similar gullies cut in sand in the interfluve showed similar rates of enlargement, the gully sides retreating at an average of 20-50 mm/year, respectively.   Measurements of gully deepening were not successful, owing to scouring by flowing water around the erosion pins distorting the true rate of erosion, and to pins being buried by slumping.   The highest rates of gully enlargement were measured in the centre of the catchment, beneath the actively eroding area near the gully heads between Stations 4 and 5 (Fig. 5.2.1), where gully sides were eroded back an average of 80 mm in a year.   It is interesting to note that a similar gully to the south, above Site 6, deposited an average depth of 30 mm y^{-1} of sand over an area of about $30m^2$, just below its termination.

The average rates of gully widening, described above, reflect the general range of existing conditions.   In any one gully the measure-ments of soil loss are exceedingly variable.   These losses show just how rapid gully development may be and suggest that gullies form an important source of sediment in the catchment area.

5.3   NEEDLE ICE, FROST ACTION AND BANK EROSION

5.3.1   Introduction

The accessibility and size of the Coombs Brook catchment permitted a reasonably detailed study of bank erosion processes.   Most observations were made in the centre of the catchment area around erosion pin sites C1, C4 and C5 (Fig. 3.6.1).   Effort and resources were concentrated here in order to achieve as much detail as possible.   While this may raise problems of representativeness, in view of the lengthy periods of observation and measurement required, this approach was thought preferable to the alternative of allotting small amounts of time to a large number of sites.

This section deals with the statistical analysis of the results of observations of erosion processes and quantities made at different field sites.   Many of the observations are applicable to other sites. Regular and frequent visits to these sites commenced just before installation of the erosion pins in March 1985 and were continued until late May 1986.   Infrequent visits were made thereafter.   The seasonal nature of bank retreat, as revealed by the pin network, periodic photography and qualitative impressions, soon became apparent, and field observations were intensified during the winter months (November-April) when most erosion seemed to be occurring (Plate 5.3.1(a) and (b)).

5.3.2   Frost Action at Sites

January 1985 marked the beginning of detailed work on the significance of frost action in the erosional regime at the catchment.   During a period of low temperatures from December 1984, the stream banks were subject to intense frost action.   This was the first time that the bank material had been observed to freeze, and it coincided with a period of marked diurnal temperature fluctuation: air temperature dropped to $-6.8^{\circ}C$ at the catchment area and $-10.0^{\circ}C$ on the ground. The pattern of frost activity at some sites exhibited strong spatial variation, particularly in the vertical sense, with increased ice growth on the lower bank slope (Plate 5.3.2.1(a) and (b)).   Closer inspection revealed a clear vertical zonation in the nature and intensity of frost activity (Fig. 5.3.2.1).

PLATE 5.3.1 (a)

Coombs Brook catchment pins network: field
observations were intensified during frost action.

PLATE 5.3.1 (b)

Pins network: field observations were made in the study period.

PLATE 5.3.2.1 (a)

PLATE 5.3.2.1 (b)

Coombs Brook catchment with increased ice
growth on the lower bank slope.

Typical bank temperature profile at 20mm depth during freezing conditions

Silt & clay content

1.5

frost action zonation

ice crystals / frost disrupted face

small ice needles

aggregate debris

1.0

Height (m)

Cheshire materials

well developed ice needles

0.5

limited activity

stream

0.0

0.5   1.0

Distance (m)

0   1.0   2.0

°C

0 5 10 15 20 25

%
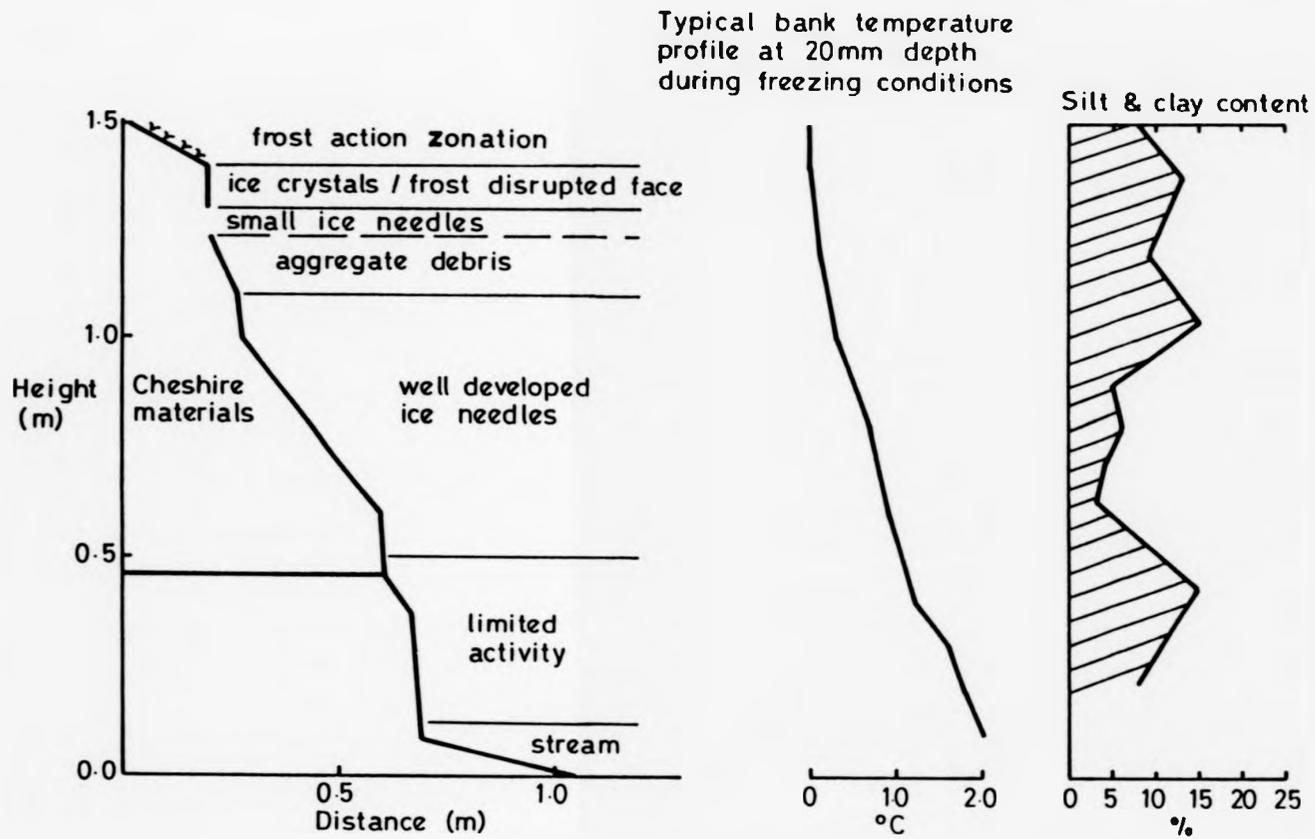
FIGURE 5.3.2.1   Vertical zonation of frost action and needle ice development at Site C/5 – typical temperature profile and silt and clay content of bank material given for comparison

Generally, most subsequent frost periods complied with this scheme (Plate 5.3.2.1(a,b)). The characteristics of the individual zones are described below.

The upper, near-vertical, parts of the bank showed severe disruption of the material and a scattered distribution of small ice crystals (Plate 5.3.2.2).   Numerous indentations of the bank surface could be seen.   These indentations took the form of conical depressions about 6 mm in depth and 8 mm in diameter (Plate 5.3.2.3).   The intensity of disruption was greater at the base of the vegetation root-mat zone, where many grass roots had become exposed, and to which only a few soil crumbs had remained adhered (Plate 5.3.2.4(a,b,c)).   The material appeared dry and fragile, with many aggregates crumbling easily upon slight pressure.

Often these upper parts were frozen, sometimes to a depth of 20 mm. Below this, a narrow zone of short ice needles was found (<10 mm in length), many having a cap of sediment (Fig. 5.3.2.1).   Interestingly, at the break of bank slope, about 0.8m from mean bed level, aggregate debris had collected as a wedge-shaped zone (Plate 5.3.2.5(a)&(b)).   The orange colour of the aggregates matched that of the face immediately above, and it was assumed that they had been detached and heaved from the upper parts of the bank.   In the downstream half of Site C1, no clear break of slope exists, and here the aggregate debris lay as a coarse, discontinuous dusting on the bank.

The main concentration of frost activity, however, occurred on the more gently-angled lower slopes where, repeatedly, needle ice growth was found to be extensive (Fig. 5.3.2.1).   It is this lower zone that stands out so clearly as the white area on Plate 5.3.2.1(a).

A detailed view of the needle ice can be seen in Plate 5.3.2.4(a,b,c). The base coarse layer was generally a zone of limited activity.   There are interesting similarities between the vertical distribution of frost action at Site C1 and the pattern observed by Beskow (1935) in a road cutting, the base of which was in contact with ditch water.   Beskow's (1935) diagram is reproduced here for comparison with Fig. 5.3.2.2. Some of the zones identified are examined in more detail below.

PLATE 5.3.2.2
Coombs Brook catchment. Distribution of
material and scattered distribution of small
ice-crystals.

PLATE 5.3.2.3

Some needle ice which took the form of conical depressions.

Scale: 10 x 5.5 cm

PLATE 5.3.2.4 (a)

Needle ice showing vegetation roots, soil and sediment, indicating the vital role of needle ice as an agent of erosion.

Scale: 16 x 12 cm

PLATE 5.3.2.4 (b)

Scale: 10 x 5.5 cm

PLATE 5.3.2.4 (c)

Needle ice showing vegetation roots, soil and sediment, indicating the vital role of needle ice as an agent of erosion.

Scale: 6.5 x 6.5 cm
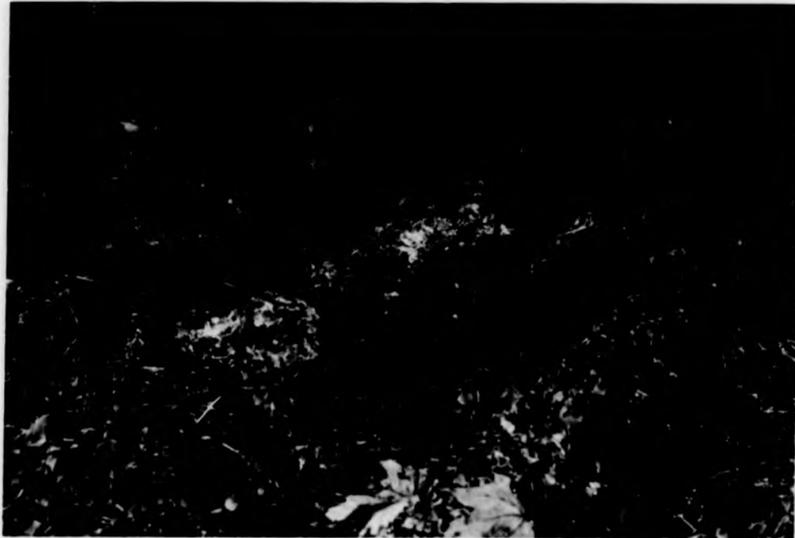
PLATE 5.3.2.5 (a)

PLATE 5.3.2.5 (b)

At the break of bank slope about 0.8m from mean bed level aggregate debris appears as a wedge-shaped zone.
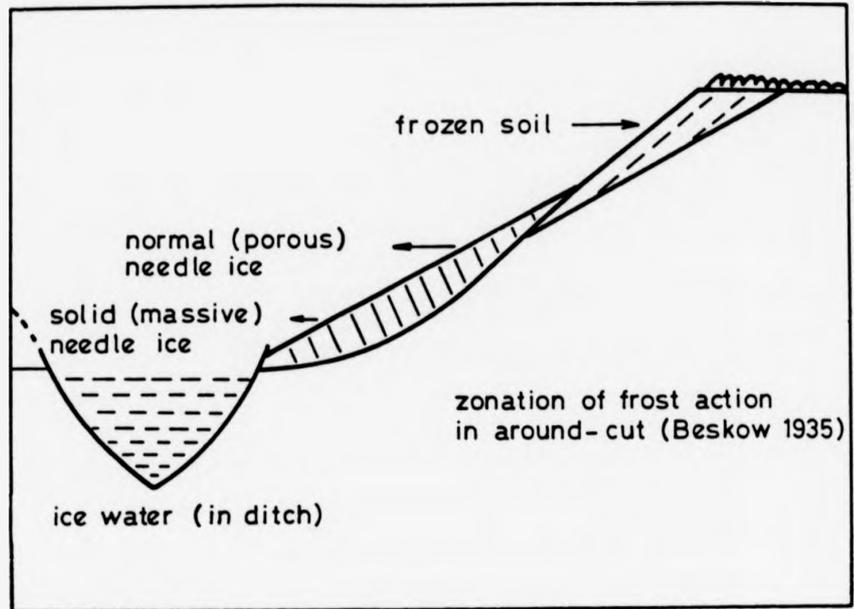
FIGURE 5.3.2.2

Vertical zonation of frost action in a road-cut
(Beskow, 1935; Lawler, 1984)
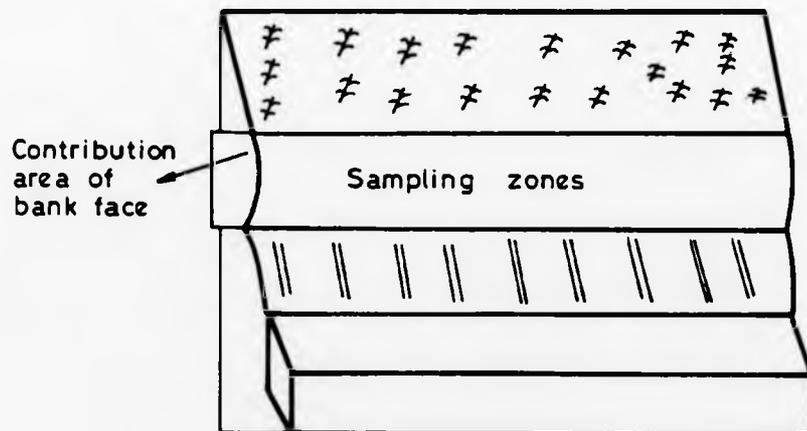
FIGURE 5.3.3.1

Sampling zones

5.3.3 Aggregate-debris Zone

The aggregate-debris zone is important because it represents the temporary accumulation of material directly eroded by the action on the sedimentary units above.   Zones of accumulating soil crumbs have been noticed by other workers (e.g. Thornes, 1978), particularly after nights of frost.   The zone appeared on slightly more occasions than needle ice and became the only erosive agent on the site at times when the lower slopes were covered with snow.   The debris was noticed in January 1985 and February 1986.   On 24th February 1986, four samples were taken, which involved the complete removal of the debris at four 10 cm wide sampling zones (Fig. 5.3.3.1).

From the combined dry weight of these samples it was possible to estimate a linear retreat rate for the upper portions, after making the following assumptions.   First, it was assumed that all eroded material was stored in the debris slope and none travelled further downslope.   Second, it seemed reasonable to suppose that all debris had accumulated as a result of the period of low temperatures immediately preceding sample collection (10 frost events), because the storm at the end of January 1986 had almost completely submerged the bank at all sites and is assumed to have washed off any loose debris that may have collected in association with earlier freezing conditions.

By obtaining the combined dry weight of the sampled aggregates and by scaling this value up, the assumed dry weight of the whole debris accumulation was calculated as below:

Samples	(1)	(2)	(3)	(4)
A - Weight of ice and sediment per gram	562.3	211.1	35.1	48.5
B - Measured volume of melt-water per cm^3	494.0	166.4	27.7	43.0
C - Measured volume of residual sediment/cm^3	52.0	29.2	3.54	3.3
D - Grams of sediment per cm^3 of total dry weight g/cm^3	0.09	0.14	0.10	0.07

This value represents an average retreat for the upper portions of bank by grams/cm^3, but as the field measurement the value represents an average retreat for the upper portions of bank of 10-15 mm per frost

event.   The upper portion of the ground, 2-5 cm depth, has a differ-
ent amount of removal material during each individual frost event.

5.3.4 Needle Ice as an Agent of Bank Erosion: A Simple Model

The previous discussion has concentrated on needle ice as a
meteorological phenomenon and has examined its temporal and spatial
distribution at Site C5 in relation to temperature, moisture availab-
ility and bank sedimentology.   This section examines the role of
needle ice as an agent of bank erosion by focussing on those aspects
which relate to the disruption, transfer and eventual entrainment of
material.

Needle ice was observed to have both direct and indirect effects
on bank erosion in this study.   These concepts may usefully be
embraced within a tentative and simple model of needle ice as a bank
erosion agent presented in Fig. 5.3.4.1 described by Lawler (1984).
Some interesting linkages which connect system variables are postulated
and are explored further in the discussion below.   Some of these links
are based on theoretical considerations, while others are included on
the basis of empirical observations.   Briefly, needle ice extrudes
bank sediment in many forms.   Some of this disrupted sediment may
settle back into the bank face as a loose skin of prepared material,
as Lawler (1984, 1986), McGreal and Gardiner (1977), amongst others,
have noted.   This prepared material, of lowered bulk density and
reduced inter-particle contact, may be sticky (McGreal and Gardiner,
1977), or dehydrated, puffy and friable (Soons and Greenland, 1970).
In either form, it is relatively easily entrained by subsequent stage
rises, even if of quite moderate magnitude (Wolman, 1959).   This
illustrates the indirect effects of needle ice development.   Direct
bank erosion may result if the extruded sediment is transferred to the
stream by mechanisms related to the ice growth itself, without the
need for fluvial entrainment.   However, it is reasonable to assume
that there is a relationship between catchment antecedent wetness and
subsequent runoff response.   It is also suggested that a weak inverse
relationship exists between needle ice extent and stage at the time of
formation, all other factors being equal.   Low river levels, by
definition, mean that large areas of bank face may be exposed to atmos-
pheric cooling, and hence more areally widespread needle ice development
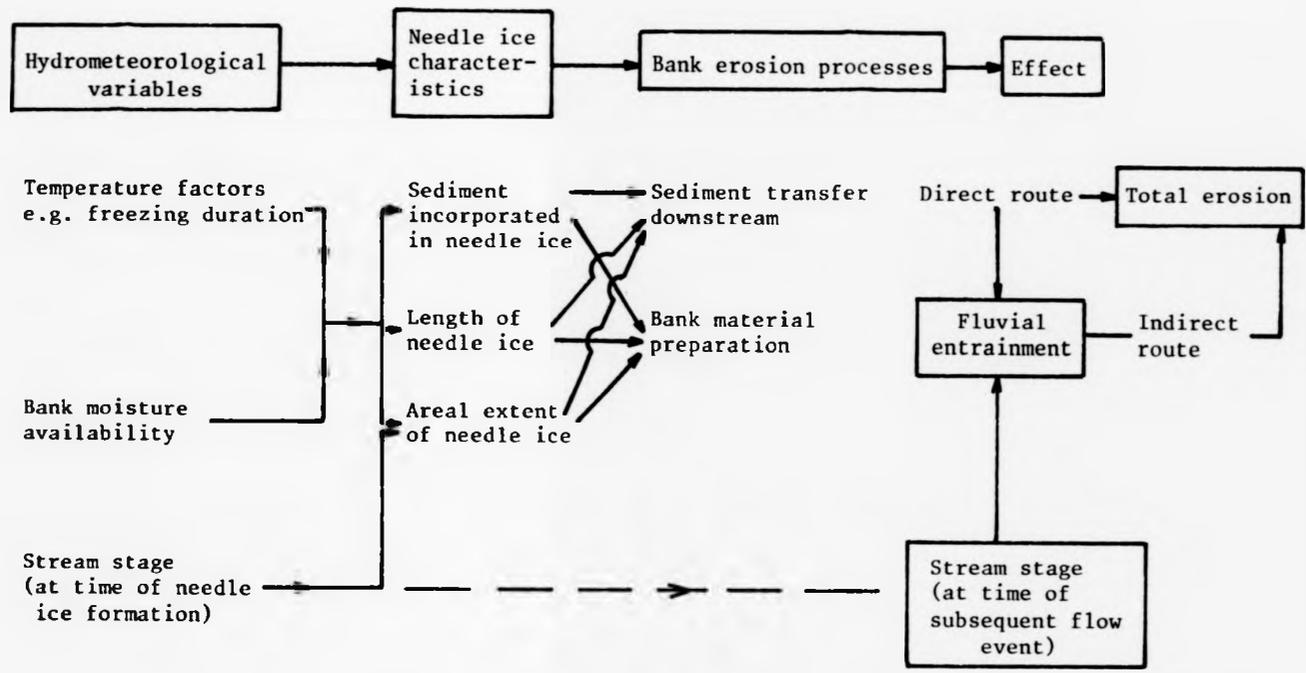
FIGURE 5.3.4.1   A SIMPLE MODEL OF NEEDLE ICE AS AN AGENT OF RIVER BANK EROSION

(after Lawler, 1984)

may result (Lawler, 1984, 1986).

Conversely, higher river levels may be associated with substantial bank storage of relatively warm flood water which could inhibit bank freezing despite appropriately low air temperatures.   Commonly, the area subjected to the most intensive development was clearly demarcated at Site C5 with a sharp upper limit and a rather more blurred lower limit, a few centimetres above stream level.   Generally, the upstream half of Site C1 was characterised by greater needle ice development than the downstream half.

5.3.5 Length of Needle Ice

The erosive effect of needle ice was also anticipated to be influenced by the intensity of development, as measured by ice-filament length.   It was through this variable that a link could be sought between meteorological conditions and subaerial geomorphological processes on river banks, because needle length should vary with temperature conditions and moisture supply in a temporal, as well as spatial, manner (Fig. 5.3.4.1).

5.3.6 Amounts of Extruded Sediment

The first stage in an attempt to quantify the significance of needle ice in causing direct erosion of river banks should be the calculation of the amount of sediment extruded.   This was achieved by removing samples of needle ice from Sites C1, 2, 4 and 5 during selected events for subsequent melting.   After all the water had been driven off by oven-drying at 105°C, the residues could be weighed. The sampled areas were determined by tracing round each needle ice sample on a sheet of paper or, occasionally, by measuring the resultant bare area on the bank face itself (Fig. 5.3.6.1(a) and (b)). The positive relationship between size and sediment content is less clearly defined, partly because of the limited range of needle ice lengths encountered, and that there is a positive linear relationship between the sample size and sediment weight extruded, which helps to define the appropriate linkage of the simple model presented in Fig. 5.3.4.1.
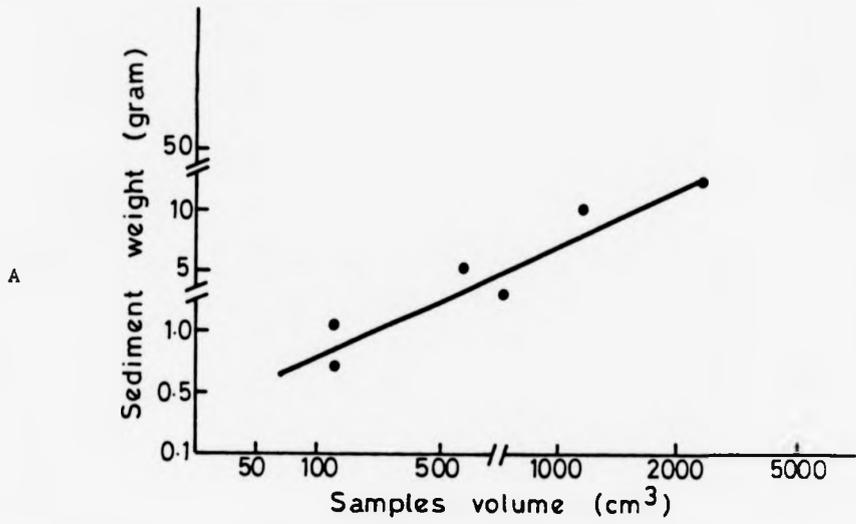
FIGURE 5.3.6.1 (A)   The relationship between sample volume of
needle ice and sediment weight
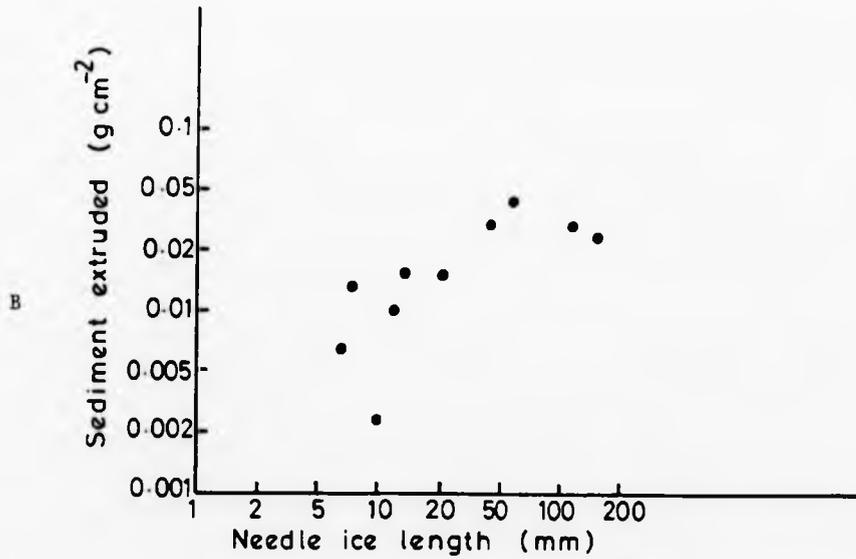
FIGURE 5.3.6.1 (B)   The relationship between needle ice length (mm)
and sediment extruded (gram/cm^2)

The fact that size or intensity of needle development alone does not completely explain sediment content suggests that the mechanism by which material becomes incorporated into growing ice needles may operate intermittently. This conclusion, in fact, was reached by Fukuda (1936), and Lawler (1984).

5.3.7 Mechanisms of Sediment Transfer

For needle ice to be directly effective in producing bank erosion (the direct route of Fig. 5.3.4.1), mechanisms must exist which transfer the sediment, once extruded, to the stream. It was not possible to quantify all the mechanisms noted, and qualitative field observations only are presented. Four principal routes were identified by which sediment encapsulated within needle ice was introduced to the stream (Fig. 5.3.7.1).

First, the direct approximately vertical dropping of particles from the sediment cap on the outer face of a sheet of needle ice was observed (Fig. 5.3.7.1(a)). Much of this sediment appeared dry and its detachment may have been wind-assisted.

Second, the mechanism occasionally observed to transfer material downslope and, ultimately, to the stream, was by sediment-laden rivulets of meltwater (Fig. 5.3.7.1(b)). These flowed across the outer surface of the needle ice sheet as well as along the interface between the bank surface and the base of the ice needles.

Third, sliding of the needle ice clusters was seen to occur. If melting occurred at the base of the ice needles during the return soil heat flow of the late-morning and afternoon, gaps developed between the ice cover and bank surface. This allowed sections of needle ice to become detached from the main sheet and slide slowly down the steep river bank slopes, transporting the incorporated sediment (Fig. 5.3.7.1(c)).

The last needle ice mechanism observed involved the toppling of small bunches of ice needles as lateral support weakened (Fig. 5.3.7.1(d)). Once melting begins at the base, then the weight of a sediment cap may create additional instability and, on a number of
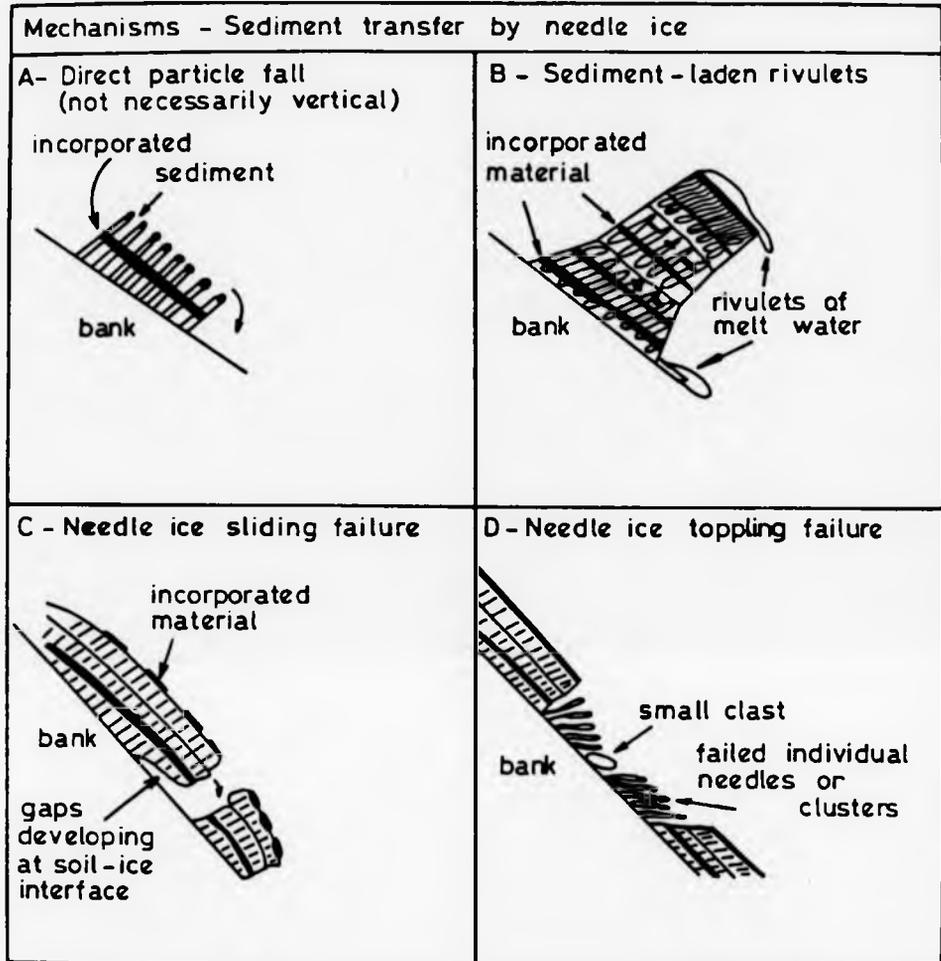
FIGURE 5.3.7.1

Schematic portrayal of four identified mechanisms of sediment transfer
by needle ice on river banks
(after Lawler, 1984)

occasions, small areas of needles had collapsed downslope almost completely, domino-style, to lie at various angles along the bank face. The latter mechanism is briefly alluded to by Gradwell (1957), although the previous two forms of sediment transfer (Fig. 5.3.7.1(b) and (c)) were first identified by Lawler (1984, 1986).

5.3.8 Indirect Effects: Needle Ice Preparation of Bank Material

If one makes the unlikely assumption that all sediment incorporated into needle ice is eventually delivered to the stream by one or more of the mechanisms discussed above, and also take the highest estimates of needle ice sediment content, then this process could be directly responsible for bank erosion of the lower slopes of about 0.8 mm for every ice growth of 20 mm. Assuming 15-20 needle ice events of this average magnitude in a year, this represents an annual retreat rate of $0.012 - 0.016m\ y^{-1}$. These annual retreat rates are remarkably close to those calculated from the weight of aggregate debris produced from the direct erosion of the upper layers by frost action; this represents approximately one-quarter to one-fifth of the observed retreat rate at Site C1, of $0.067m\ y^{-1}$. This appears to demonstrate that the direct effects of needle ice and other frost processes may be relatively small; indirect effects, plus the operation of entirely different agents, may perhaps account for the greater part of the erosion. The supposition that needle ice can act in an indirect, preparatory way, rests on a series of observations of the interrelationships between frost action on river banks and subsequent stage rises at Site C1 and elsewhere.

It was noticed that, after periods of freeze-thaw activity, all the sediment extruded was not immediately transferred downslope, with most settling back into the river bank.

This phenomenon of a prepared skin of material existing after frost action on a river bank has been noted by other workers, for example Lawler (1984, 1986). Hill (1973) describes the process on the Clady River banks in Northern Ireland:

> "When the ice melted during thaw phases not all the till
> fragments fell to the base of the bank. Instead, many
> settled back onto the face to form a loose layer of till

approximately 0.5 cm thick which covered the bank after
a series of night frosts. Periods of rain converted this
loosened layer of till into a sticky mud which flowed
slowly down the bank face in places."

These characteristic layers of prepared material were observed
to be highly suitable for fluvial entrainment during the subsequent
rise in stage and a few observations of this are presented below.

A more prominent notch became evident on 5th March 1986, a few
days after a series of snow-melt events in the early part of March
1986.   This time, the height of the notch (approximately half-way up
the bank) reflected the upper limit of needle ice activity.   This
observation lends further weight to the argument that most bank erosion
here seems to be produced by a combination of freeze-thaw processes
and fluvial activity.

Only a little erosion takes place without rises in stream level
which are able to remove a prepared layer of sediment - although the
extent of removal is severely reduced above the upper limit of inten-
sive needle ice activity.

These considerations, if generally applicable, weaken slightly
the theoretical basis of channel sediment production models which
assign equal weight to discharge increments (because of the submergence
of new parts of bank surface), regardless of where they take place on
the hydrograph (e.g. Carson et al., 1973).

Early February 1986 saw a period of needle ice activity, and in
mid-February, incipient peeling of the surface layer of bank material
at bank stream.   By 19th February, the skin of prepared material had
begun to exfoliate, without the assistance of fluvial activity, as
the stream level had remained virtually static for the 10 previous
days.

The thickness of the active skin was around 12 cm and covered most
parts of the bank surface, even the upper sedimentary units.   With
the material in this susceptible condition, the moderate stage increment
of only 0.40m on 5th March succeeded in trimming off a complete layer
of sediment, to create a spectacular erosional notch.   It was developed
more fully in a downstream direction, although it could be traced up-

stream as well.   This is a good example of how the height of a notch
reflects the maximum stage reached when a readily available frost-
prepared skin of material covers the complete vertical profile.   It
is stressed that the model of bank retreat reported here is different
from the bank erosion caused by the development of thermo-erosional
niche in regions of permafrost, observed by a number of workers (e.g.
Czudek and Demek, 1970;   Gill, 1972;   Klimek, 1975;   McCloy, 1970;
Scott, 1978).   The latter, as the name suggests, is caused by the
melting of inter-particle ice bonds in bank materials by the relatively
warm river water followed by fluvial entrainment sediments.   As such,
a niche may develop at river level and subsequently be exposed by a
drop in stage.   At the Coombs Brook sites, the notch is caused by the
removal of material which has been weakened by previous freeze-thaw
activity (principally needle ice) but which is not in a frozen state
at the time of river-level rise.   The resultant forms may be similar
then, but the precise causal mechanisms are slightly different.
However, the depth of thermo-erosional niches, because of "the increased
strength provided by permafrost in the banks, permits greater amounts
of undercutting" (K.M. Scott, 1978, p.10) may be much greater than the
observed range of 10-50 mm for the Coombs Brook sites.   Czudek and
Demek (1970) cite examples in excess of 10m depth for the Deputatko
River in N.E. Siberia, while Gill (1972) observed a niche 5m deep on the
Mackenzie River delta in Canada.

5.4   CALCULATION OF TOTAL SEDIMENT SUPPLY AND THE BUDGET

In the succeeding section the total two-year sediment supply by both stream bank and valley slope processes is calculated on the basis of the survey data of 1986 (Table 5.4.1).

5.4.1   Calculation of Total Sediment Supply

1.   Lateral corrasion

Sediment supply by lateral corrasion was calculated for those sites which showed clear evidence of erosional activity: ' bare bank faces'.   Based on the above criteria, 1200m of stream bank or 24% of the total channel length was subject to lateral corrasion, supplying a total amount of 33240 kg in two years (Table 5.4.1).   It must be remembered that in both processes frost-thaw and wetting-drying cycles were the most important causes of detachment of the bank material.

2.   Subsoil fall

Subsoil fall was observed to be active at 224 sites, affecting $5000m^2$ of channel bank and gully wall throughout the catchment.   The total supply of bank material by this process is about 17000 kg y^{-2}. This amount is about 13 times greater than the sediment amounts supplied by splash action on the banks, although the sediment producing area (total width x height of the backwall from the undercut) is considerably smaller.

3.   Soil creep

No relationships were developed to relate sediment supply by soil creep (surface creep) to site-factors, as there were wide discrepancies between the three measurement sites.   For these reasons, sediment loss by soil creep could only be estimated.   It was assumed that the mean measured rate of 34g per 30 cm width in two years was typical for banks of the study area.   As soil creep was observed on the bank of the 'stable' type (sample sites 5,6 and 7), which take up 80% of the total stream length (3300m), it may be estimated that about:

TABLE 5.4.1   SEDIMENT BUDGET FOR THE COOMBS BROOK CATCHMENT (0.8 km^2) MAY 1984 – APRIL 1986

		Process	Sediment supply during the study period (kg)	%
Input	Stream banks (8% of the catchment area (64 ha)	Lateral corrasion	33240	36.5
		Subsoil fall	17000	18.7
		Soil creep	598	0.6
		Mass movement	6650	7.3
		Splash erosion	1250	1.3
		Stream bank total	58738	65
	Valley slopes 92% of the catchment area (736 ha)	Overland flow and splash detachment	30100	33.1
		Throughflow	2000	2.2
		Slopes total	32100	35
Output		Total sediment input	90838	
		Suspended load	84038	92
		Bedload	6800	8
		Total sediment output	90838	

0.80 x 3300 x 0.034/0.3 x 2 (left and right bank)
= 598 kg sediment is supplied by surface soil creep
in two years. This results in a specific erosion
factor of about 0.03 kg m^2 y^{-1}.

4. Overland flow

Observations and measurements of overland flow occurring on stream
banks show that it merely acts as a transport medium for material
detached by other processes; detachment by flow action is of very
limited importance. Consequently, the soil material supplied by over-
land flow is already included in the measurements of these other pro-
cesses and its direct contribution to stream bank recession may be
neglected.

On the other hand, overland flow is very effective in transporting
soil material. To calculate the total sediment transport by overland
flow, however, some assumptions on the extent of overland flow con-
ditions have to be made:

- Widespread conditions of overland flow occur at least once
  a year when all of the detached material is transported.
  This assumption is based on the fact that in the study period
  these conditions were observed several times.

- Hydrograph analyses of two major storms in the study area
  showed that at least 60%-75% of the area of the sub-catchment
  contributed to the storm hydrograph as quickflow. It was then
  assumed that overland flow transports splash-detached material
  from 70% of the sub-catchment area.

- Net differences in storage of splash-detached material between
  the start and end of the period of investigation are neglected.

If the above assumptions are valid, then, taking the area of the
catchment upstream of the lined channel reach as 50 ha (sub-catchment
area) x 0.70 (overland flow contribution) x 0.086 (splash loss in
kg m^2) = 30100 kg of soil material has been transported by overland
flow in two years.

5.   Mass movements

The total amount of material that failed and was afterwards trans-
ported by streamflow was already estimated at 6650 kg per two years.
Figure 5.1.5.2 and Table 5.1.5.1 show that the major contribution
occurred in the main branch of the channel incision in the centre and
headwater.

6.   Splash erosion

The sediment supply by splash erosion was determined by measuring
width, length and slope gradient of the bare bank surface subject to
rainsplash activity.   Also the type of bank (stable/unstable) and
percentage bareness of the bank surface were noted.   In total, 250
sites were distinguished with a total bank area of 940 m^2, providing
1250 kg of sediment (Table 5.4.1).   The relative importance of splash
erosion on the stream banks may be better characterised by the specific
erosion factor which is expressed as kg supplied material per m^2 of
eroded surface per year.   Although this factor is time-dependent
because of yearly variations in amounts of rainfall, freeze-thaw
cycle, etc., it may be used as a relative criterion for typifying
the erosional intensity of the various processes.   In the case of
splash erosion this factor amounts to about 1.2 kg m^2 y^{-1}.

7.   Bedload

Bedload is the material that moves by sliding, rolling or saltating
on or very near the bed of the river;   the material includes the sizes
of material found in the bed.

> "The problems involved in the direct measurement of bedload
> transport include the alteration of the pattern of flow
> and transport by the presence of the sampling device, the
> difficulties of positioning the measuring apparatus on an
> uneven and variable channel floor, sampling efficiency
> and the irregular movement of the bed material. In view
> of these practical difficulties, much attention has been
> paid to the derivation of theoretical formulae for the
> estimation of bedload transport. These vary in complexity
> from pure empirical approaches to attempts at more theoretical
> modelling of the physical processes involved."
>
> (Gregory and Walling, 1973.)

No apparatus for direct measurements was available, and consequently a figure for the total amount of transported bedload could only be obtained by weighing the volume of bed material trapped in a small pool directly behind the weir (Table 5.4.1). At irregular intervals, bed material was removed from this reservoir to ensure reliable registration of discharge, and was subsequently deposited on both sides of the channel. The total volume of trapped material was measured at 6800 kg in two years .

When compared with a suspended load of 84038 kg, bedload yield contributes only 8% to total sediment output from the catchment. This value fits well in the range of 1% to 15% as given by Gregory and Walling (1973).

Grain size analysis of the 56 bedload samples showed that the coarse material content was about 82%, fine sand 16%, and silt and clay 2% (Table 5.4.1.1).

Considerable errors in estimations of bedload transport may occur due to the possible inclusion of suspended load during sampling or to the catching of suspended material in a reservoir or behind the weir. The grain size frequency curves of both suspended and bedload material (Fig. 5.4.1.1), however, show that this potential error is minimal: maximum particle size of suspended material is about 0.25 mm, while the proportion of particles smaller than 0.25 mm in bedload amounts to only 5-6%.

The proportion of silt/clay materials in all of the samples is apparently small, reflecting the fact that most of the fine material is transported as suspended load. The main reason for this is the nature of the bed configuration and the supply of materials available for transportation.

The frequency distributions (Fig. 5.4.1.1) denote that material transported as bedload is mainly delivered by lateral corrasion. Landslides will also form a distinct source of bed material, but as the grain size distribution of the material involved is strongly dependent upon type, volume and site of the mass movement, no data are available.

TABLE 5.4.1.1   AVERAGE GRAIN SIZE FOR BEDLOAD SAMPLES DURING THE STUDY PERIOD

Date	Coarse sand, gravel	Fine sand	Silt and clay
24/07/85	82.0%	16.0%	2.0%
04/09/85	84.3%	14.1%	1.3%
12/12/85	76.8%	20.3%	3.0%
10/02/86	83.0%	15.0%	1.6%
Mean of grain size for the study period	82.0% > 0.21 mm	16.0% 0.063-0.21 mm	2.0% <0.05 mm <0.002 mm
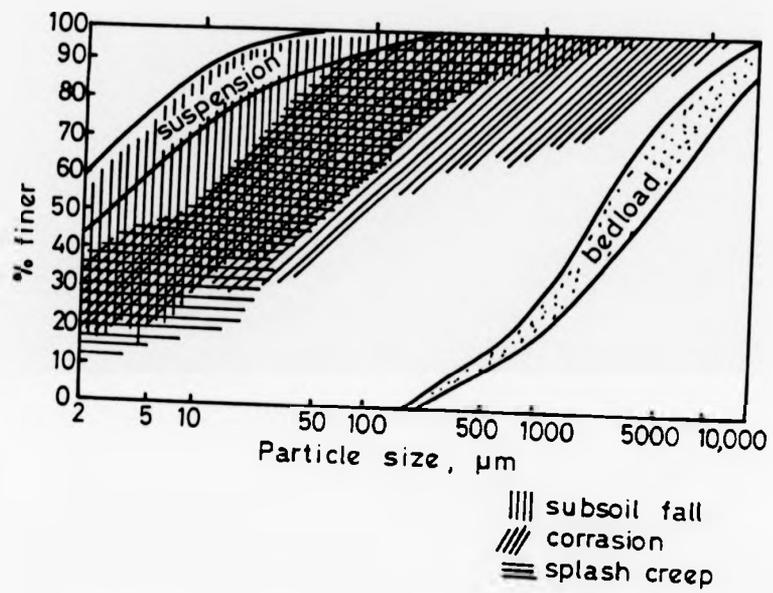
FIGURE 5.4.1.1

Cumulative grain size frequency 'zones' for
the different modes of sediment supply and
sediment transport

5.4.2 Temporal Variation in Gross Stream Bank Erosion

The temporal variation in gross stream bank erosion is considered in order to relate specific rates of sediment supply to sets of meteorological and hydrological conditions. The establishment of such relationships was undertaken by distinguishing four classes of monthly sediment yield: <1000, 1000-2500, 2500-5000 and >5000 kg per month. The number of boundaries of these classes were based upon the range in values of the existing dataset (Harvey, 1974). For each of the available 24 months, the data on amount of precipitation, erosivity and discharge were used (Table 5.4.2.1) and revealed the following results:

- Very high soil loss (>5000 kg per month) from the stream banks results during major floods in association with high rainfall and a very high erosivity.

- High sediment yields (2500-5000 kg per month) occur in periods with medium peak flow in combination with frost action.

- Medium sediment yields (1000-2500 kg per month) result when medium peak flows occur in association with high rainfall and negligible frost action.

- Low sediment yields (<1000 kg per month) occur during periods with low flow, little rainfall and negligible frost action.

The above ranking of sets of erosion conditions is in remarkable agreement with the findings of Wolman (1959). However, the complex interactions between the various sediment supplying processes and environmental conditions permit no such approach without generalisation of data (Harvey, 1974). The results undoubtedly stress the importance of shear stress (peak flow) and frost action in determining the rate of soil loss from the catchment.

Sediment supply data are obtained on a monthly instead of an event basis. For example, high active erosion occurred during a 30-minute intense storm event on 21st December 1985. On the same day, a rainfall amount of 21 mm was recorded. Table 5.4.2.2 shows rainfall events in maximum daily amounts during the study period. It appeared that the rainfall amount of 21 mm had only been exceeded three times

TABLE 5.4.2.1   MEAN VALUES FOR DISCHARGE AND RAIN INTENSITY FOR FOUR SEDIMENT YIELD
CLASSES AND THEIR RELATIVE CONTRIBUTION TO TOTAL SEDIMENT YIELD

Class sediment yield kg per month	1 <1000	2 1000-2500	3 2500-5000	4 >5000
Number of periods (24 months)	10 – 12	6 – 8	4 – 6	2 – 3
Q max. 1 s^{-1} (from discharge data)	50	50 – 70	70 – 100	100 – 120
Peak 30 min. intensity in mm/hr (Table 5.4.2.2)	2.0	3.0	4.0	6.0
% contribution to total sediment supply (approx.) (From Table 5.4.1 and sediment and discharge data)	10%	30%	45%	15%

TABLE 5.4.2.2   COOMBS BROOK CATCHMENT: STORM EVENT RAINFALL
DATA AND INTENSITY INFORMATION

Month & Year	Monthly rainfall mm	Storm event <10 mm	Rain intensity information			
			Date	Total rain intensity mm	Storm duration	Peak 30 minute intensity in mm/hr
May 1984	51.4	2.0	22.05.84	8.8	2 hr	4.4
June 1984	76.1	3.0	03.06.84	8.8	2 hr	4.4
July 1984	33.9	1.0	13.07.84	5.6	2 hr	2.6
Aug. 1984	61.8	3.0	01.08.84	4.0	1 hr	3.0
			02.08.84	6.8	1 hr	4.2
			06.08.84	4.0	1 hr	3.0
Sept. 1984	170.2	9.0	03.09.84	7.2	1½ hr	3.2
			17.09.84	10.4	2 hr	4.4
			22.09.84	10.4	1½ hr	4.6
Oct. 1984	96.7	5.0	17.10.84	11.0	2 hr	4.7
			24.10.84	7.4	2 hr	3.2
Nov. 1984	160.1	4.0	02.11.84	21.5	1 hr	6.2
			08.11.84	7.2	1 hr	4.2
Dec. 1984	62.3	-	-	-	-	-
Jan. 1985	63.5	1.0	29.01.85	6.0	1½ hr	4.2
Feb. 1985	8.4	-	-	-	-	-
March 1985	71.6	1.0	-	-	-	-
April 1985	110.7	6.0	07.04.85	8.0	2 hr	4.4
			08.04.85	8.0	2 hr	3.4
			10.04.85	8.6	1 hr	2.8
May 1985	63.9	1.0	14.05.85	6.0	2 hr	2.8
June 1985	94.6	1.0	08.06.85	4.0	1 hr	2.0
			10.06.85	4.0	1 hr	2.2
			11.06.85	16.0	1 hr	6.2
July 1985	73.5	2.0	08.07.85	4.0	1 hr	2.2
			13.07.85	8.0	1 hr	4.9
			28.07.85	5.0	1 hr	2.9
Aug. 1985	92.8	2.0	11.08.85	14.0	2 hr	5.2
			23.08.85	4.5	2 hr	2.8
			25.08.85	4.0	1 hr	2.4

TABLE 5.4.2.2 (Continued)

Month & Year	Monthly rainfall mm	Storm event <10 mm	Rain intensity information			
			Date	Total rain intensity mm	Storm duration	Peak 30 minute intensity in mm/hr
Sept. 1985	48.0	1.0	02.09.85	4.0	1 hr	1.8
			07.09.85	4.5	1 hr	2.6
			16.09.85	6.0	1 hr	4.0
Oct. 1985	72.8	2.0	03.10.85	4.0	1 hr	2.8
			06.10.85	11.7	2 hr	3.6
			08.10.85	8.5	2 hr	4.2
Nov. 1985	91.0	3.0	07.11.85	6.3	2 hr	2.4
			08.11.85	4.0	1 hr	2.4
			09.11.85	4.0	1 hr	2.3
Dec. 1985	130.2	3.0	21.12.85	21.0	2 hr	5.3
Jan. 1986	140.1	3.0	01.01.86	4.0	1 hr	2.2
			12.01.86	4.5	1 hr	2.4
			28.01.86	22.0	2 hr	5.4
Feb. 1986	56.0	-	-	-	-	-
March 1986	102.2	1.0	16.03.86	4.0	1 hr	2.2
			22.03.86	4.0	1 hr	2.2
			26.03.86	4.0	1 hr	2.4
			29.03.86	4.0	1 hr	2.2
			30.03.86	4.0	1 hr	2.3
April 1986	111.5	4.0	14.04.86	13.0	3 hr	3.2
			15.04.86	10.0	2 hr	2.4
			16.04.86	16.0	4 hr	3.4
			19.04.86	12.5	1 hr	4.2
			21.04.86	4.0	1 hr	2.2
			28.04.86	3.0	1 hr	1.9

TABLE 5.4.2.3   CONTRIBUTION OF BANK PROCESSES TO TOTAL SEDIMENT
SUPPLY FOR FIVE (SPATIAL) SEDIMENT YIELD CLASSES
(SEE TABLE 5.4.3.1 AND FIGURE 5.4.3.1)

Class	kg m^{-1}	n	Splash %	Soil fall %	Corrasion %	Failures %
1	5	12	22.2	67.5	10.3	-
2	5-25	20	6.3	59.5	34.1	-
3	25-50	5	3.9	28.3	67.7	-
4	50-100	2	2.6	56.7	40.7	-
5	100-200	3	0.7	27.0	40.5	31.8

in the period 1984-86 with the following values: 21.5 mm (November 1984), 22 mm (January 1986). It may then be concluded that the high erosive conditions as exhibited in December 1985 might possibly have been exceeded 7-9 times during the study period (Table 5.4.2.2).

The data on the relative contributions of the various sediment yeild classes to total sediment supply (Table 5.4.2.1) show maximum contributions of class 2 and 3 periods because of the combination of intermediate sediment supply and intermediate frequency of occurrence. The magnitude and frequency concepts expounded by Wolman and Miller (1960) have proved to be very valuable in geomorphological thinking. They were originally related only to sediment discharge by rivers; in these contexts they emphasised the importance of gradual and con-tinuous processes. Similar results are reported by Hooke (1980) and Andrews (1982).

5.4.3 Spatial Variation in Gross Stream Bank Erosion

The spatial variation in stream bank erosion is mainly determined by variations in channel morphology, hydraulics of flow in the channel, and mechanical properties of the bank material. In general, such variations have been studied by examining measured erosion rates from selected bank reaches spread discontinuously along the stream (Hooke, 1979, 1980; Lyons and Beschta, 1983), and/or by considering data from a large number of cross-sections (Mosley, 1981; Hannam, 1983). However, in this study, spatial variation is considered from data from 42 adjacent channel sections (Table 5.4.3.1 and Fig. 5.4.3.1). This approach has both advantages and disadvantages compared to the above procedures. The main advantage of studying data from continuous reaches is the possibility of relating sediment supply not only to static variables describing morphology, etc., of the section in question, but also to more dynamic variables. The latter describe relative changes of the relevant parameters with respect to the nearest upstream and downstream section, e.g. an increase or decrease in bed gradient relative to the upstream section which may lead respectively to erosion and deposition (Tuckfield, 1980). The inclusion of such 'dynamic' variables may increase the level of explained variance of stream bank erosion rates (Beschta, 1981). A major disadvantage of

TABLE 5.4.3.1   SEDIMENT SUPPLY BY STREAM BANK PROCESSES
FOR 42 CHANNEL REACH SECTIONS

(For location of Sections, see Fig. 5.4.3.1)

Section Number	Sediment supply in kg per metre of valley length			
	Splash	Subsoil fall	Corrasion	Failures
1	0.7	1.3	0.2	-
2	0.8	1.2	0.1	-
3	0.6	1.1	0.1	-
4	0.5	1.0	0.1	-
5	0.3	7.8	1.3	-
6	0.6	2.5	13.5	-
7	0.2	4.8	0.3	-
8	0.9	6.9	2.5	-
9	1.5	4.3	0.2	-
10	1.0	14.3	0.6	-
11	0.5	4.2	1.2	-
12	1.3	8.7	30.5	-
13	1.4	7.6	28.4	-
14	0.6	2.4	0.1	-
15	0.4	1.8	0.3	-
16	0.9	31.5	56.0	-
17	0.9	5.0	19.0	-
18	0.3	3.9	1.0	-
19	0.4	4.1	0.9	-
20	0.7	1.2	0.1	-
21	0.6	4.1	0.1	-
22	0.5	3.9	0.1	-
23	0.7	4.4	0.3	-
24	0.8	4.0	16.0	-
25	0.2	1.2	0.2	-
26	0.3	1.3	0.1	-
27	0.5	4.2	0.2	-
28	0.45	4.0	0.2	-
29	0.3	21.0	49.6	11.2
30	0.7	1.2	0.2	-
31	0.3	1.2	0.1	-
32	1.6	40.5	5.8	86.8
33	0.5	29.3	80.0	8.3
34	3.9	67.0	19.0	-
35	0.9	25.6	40.0	-
36	0.6	2.5	12.0	-
37	1.6	17.8	9.1	-
38	0.6	5.9	8.3	-
39	0.1	4.5	14.0	-
40	0.5	15.1	1.6	-
41	0.2	1.2	0.1	-
42	0.1	0.9	0.1	-

CLASS (1) a <5 Kg/m
CLASS (2) b 5-25 Kg/m
CLASS (3) c 25-50 Kg/m
CLASS (4) d 50-100 Kg/m
CLASS (5) e 100-200 Kg/m
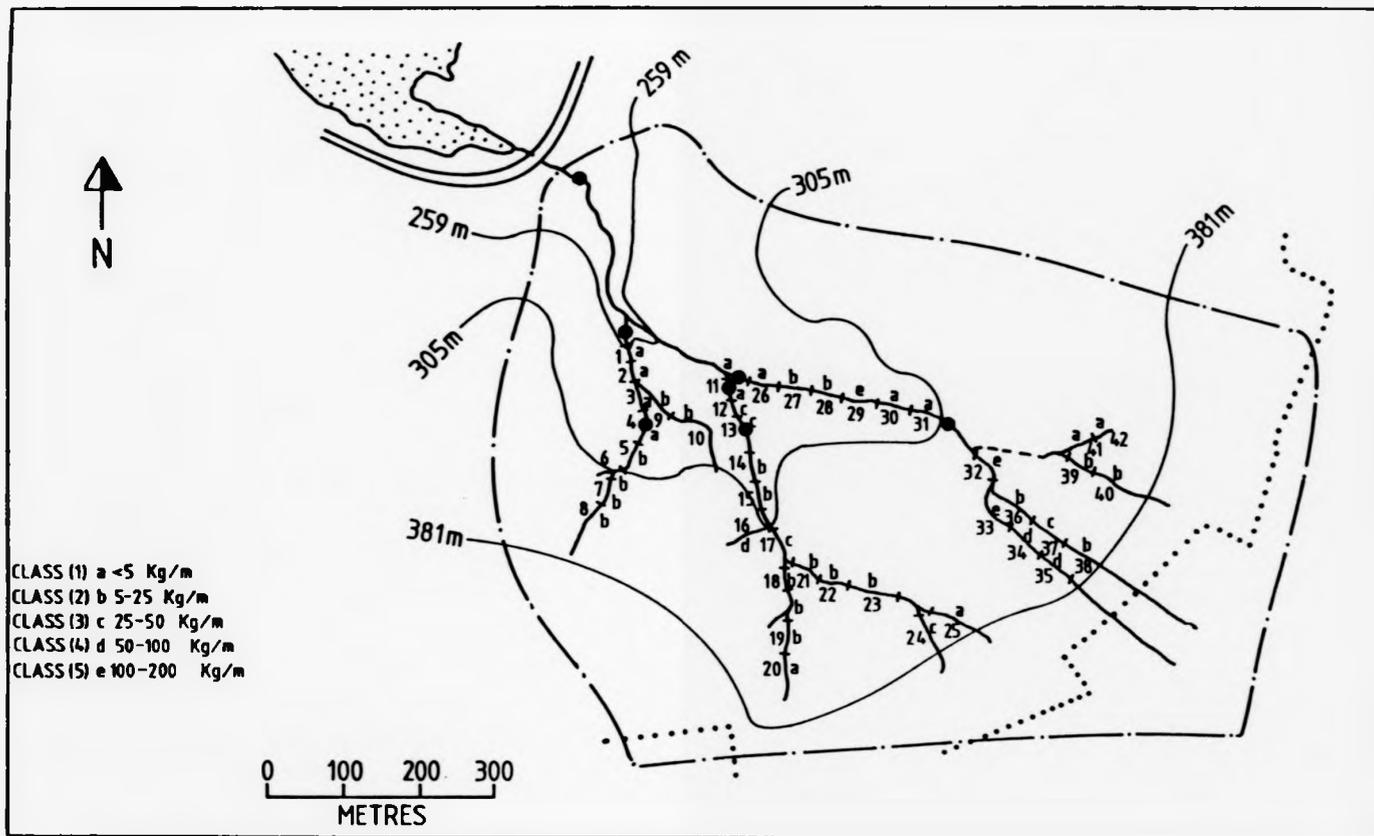
FIGURE 5.4.3.1   Spatial variation in sediment supply from banks

this procedure is that parameters generally used for describing site characteristics, such as bank erodibility, cannot be used, as they vary widely along a 50m channel section.

Attention is primarily paid to the development of quantitative relationships between sediment supply from the banks and channel mor-phology in order to increase insight into the morphological controls/ effects of stream bank erosion. To meet this aim, data on sediment supply were obtained for each of the 42 sections in which the stream network was divided (Table 5.4.3.1), and these were expressed in kg per metre of valley length in order to account for differences in section length. Thereupon total sediment supply from each section (splash + subsoil fall + corrasion + mass failures) was determined and sub-divided into five sediment supply classes: <5, 5-25, 25-50, 50-100 and 100-200 kg per metre of valley length (Fig. 5.4.3.1). In addition, morphological characteristics were derived from field mapping for each section. These included: cross-sectional area, incision depth, incision width (at the base), bed slope, sinuosity and contributory catchment area (Hooke, 1980). Also the relative increase or decrease in cross-section, sinuosity and bedslope with respect to the nearest up- and downstream section were added. It was then attempted to relate each of the supply classes to more specific mor-phological conditions.

Sediment supply appears to be highly variable, especially along the main river where the major sediment source areas are located (Fig. 5.4.3.1). Supply in both the side branches is less variable and always less than 25 kg m^{-1}, reflecting the smaller contributory area with consequently smaller cross sections. The relative contri-butions of the various bank processes to each yield class are shown in Table 5.4.2.3. Considering the channel network in its totality, a general trend of increasing sediment yield with increasing contri-butory area may be observed with class 1 yields in the shallow stream sections and class 3 yields in upstream sections. In fact, channel sections with a depth of less than 1m always exhibited sediment yields of less than 5 kg m^{-1}. The section containing classes 4 and 5 yields a greater quantity of sediment which may contribute to the relatively high sediment yield of the following sections.

In the following paragraphs attention will be paid to channel processes controlling these anomalies in the sediment supply pattern, with special reference to the five class 4 and 5 sections, as these contribute 64.4% of the total sediment supply.

The data in Table 5.4.2.3 and Table 5.4.3.1 show that in three of the three class 5 sections (29, 32 and 33), the high sediment supply resulted from the occurrence of mass failures accompanied by an increased rate of scour, subsoil fall and splash with respect to the class 1 to 3 reaches. The occurrence of these failures was ascribed to bank seepage (inducing flowslides in section 32) and severe bank under-cutting (inducing shallow landslides in other sections). Surveys showed that the severe bank scour in the latter sections was attributed to the effects of various processes:

(a) A large increase in catchment area due to the confluence of the main channel with a tributary draining (sections 29 and 30).

(b) Accumulation of inorganic debris behind logs, causing considerable aggradation and resulting in both the development of a plunge pool with associated bank, and in an increase in eroding force of the stream flow due to a decrease in sediment load. Such steps were observed in sections 5, 15, 17, 28 and 34; they caused high scour rates in reaches 4, 14, 15, 27 and 33. These observations agree with the findings of Mosley (1981), who reports on the association of major changes in bed and bank morphology with the occurrence of in-stream organic debris.

The above discussion shows that channel sections with a rather similar rate of sediment supply may owe this supply to the effects of various processes, indicating again that bank erosion is controlled by a complex combination of factors (Hooke, 1980).

Summarising, it may be stated that a general trend of increasing sediment supply per metre of valley length with increasing catchment area exists in the Coombs Brook catchment. Extremes (high and low) in sediment supply with respect to this general trend mainly occur in the centre and upstream part of the main stream, due to various indirect

effects of distinct breaks in the longitudinal profile. These con-
clusions support the inclusion of channel morphological characteris-
tics in studying stream bank erosion and stress the low level of
information retrieval when exclusively site measurement data are used
for such complex channel systems, in contrast to data obtained for
channel reaches.

5.4.4 The Sediment Budget and its Geomorphological Implications

In the preceding sections the calculation and interpretation of
sediment supply and transport by the various transfer processes has
been considered in detail. In this section, the results are summar-
ised in the form of a sediment budget. Attention is given to the
representativeness of the budget and to the implications of the budget
for the geomorphological evolution of the valley incision.

5.4.4.1 Compilation of the sediment budget

In Fig. 5.4.4.1, sediment supply from stream banks as a con-
tribution to the sediment budget (Table 5.4.1) is distinguished
from that from the valley slopes. Stream bank erosion contribu-
tes about 65% of the total sediment supply, with lateral corrasion
and subsoil fall being the main sediment-producing bank processes.
The data of Table 5.4.1 and Fig. 5.4.4.1 denote the importance of
stream bank erosion in a zone above the maximum high water level,
thereby stressing the direct effects of meteorological factors
(rainfall amount and intensity, wet/dry and freeze/thaw cycles)
in determining the rate of bank erosion. The figure of 65% is
just above the range of values generally reported: 25% to 60%
(Anderson, 1954, 1975; Robinson, 1977; Smith and Hicks, 1982).
As the latter studies only estimated stream bank erosion as the
difference between sediment transfer to the channel and sediment
discharge from the drainage basin, the measured quantity from
Coombs Brook may be more realistic for an area of incision of
unstable glacial deposits. Despite the small area, 8% of the
catchment, supplying bank erosion material, the remaining 35% of
the sediment load has to be explained. The catchment in its
entirety needs to be considered. As the contribution of sediment
from the valley slopes is mainly determined by the extent of
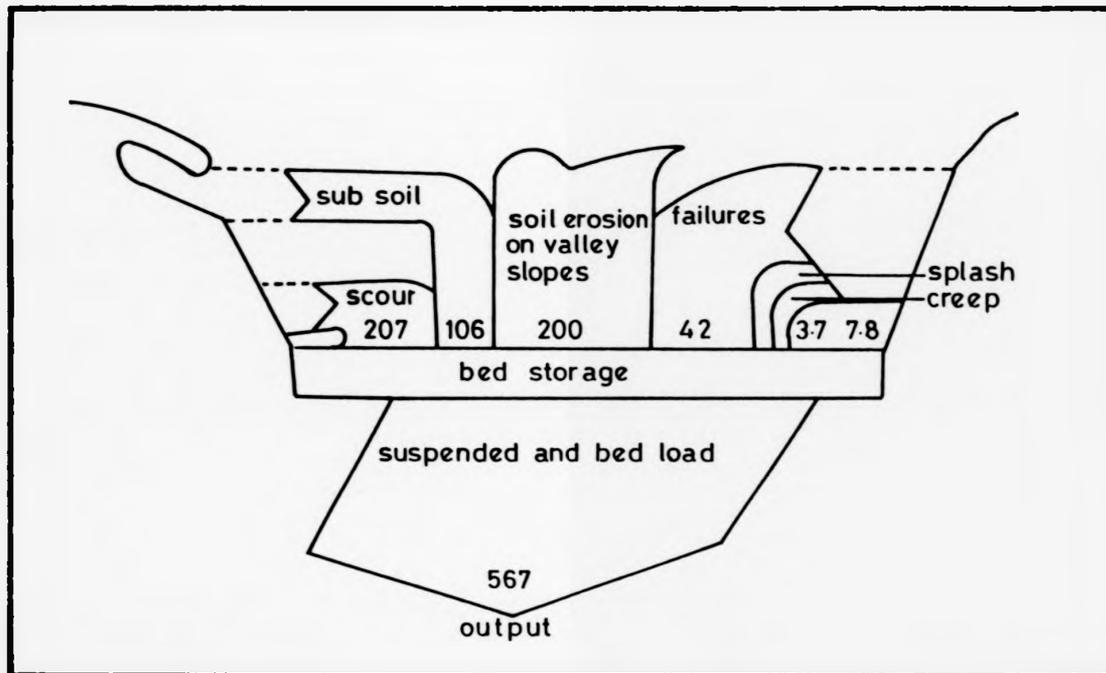
FIGURE 5.4.4.1   Sediment budget for the Coombs Brook catchment 1984-1986
(Numbers are in kg ha^{-1} y^{-1})

saturated overland flow, it is clearly the soil system which plays the central role in the sediment budget of the catchment, because of its repercussions on erodibility, drainage and consequent streamflow generation and bank erosion.

The greatest uncertainty in this study is the amount of sediment that either entered or was removed from bed storage by aggradation or degradation of the channel. As the total inputs and outputs of sediment were more or less in balance during the two years of measurement (Table 5.4.1), the net effect of changes in channel storage (the non-measured residual term in the budget) was of only limited importance. With regard to the residence time of the supplied material in the channel incision, it may be assumed that only the part of the supplied sediment larger than 0.25 mm in size might have been stored in the stream bed, while the correspondingly smaller particle size left the catchment during the study period as suspended load. Consequently, suspended load may be estimated to account for 100% of the sediment supply from valley slopes, 95% of the amount supplied by rain-splash and creep (Fig. 5.4.1.1), 90% of the subsoil fall, about 80% of the scour, and an estimated 75% of the sediment contributed by bank failures, resulting in a total amount of about 84000 kg. This estimate implies that only about 7000 kg (in two years) or 8% of the supplied sediment may have been stored in the channel incision, which agrees very well with measured bedload output (Table 5.4.1).

5.4.4.2 Accuracy and limitations of the sediment budget

It is impossible to calculate an estimate of the accuracy of Table 5.4.1 objectively, owing to the lack of data to quantify some of the key assumptions used to make the erosion rate calculations. When possible, they have been referred to in the sections in question. Accuracy of calculations is a particular problem in the cases of bank failures and bedload transport which generally occur during infrequent heavy storms.

The lowest degree of accuracy is expected for the rates of creep and throughflow supply, as these were estimated from a

limited number of data.   The consequences for the sediment
budget, however, are small because of the low transfer rates.
The other more frequent and relatively continuous processes are
better characterised by the available data.   Rates of soil ero-
sion on hillslopes and suspended sediment transport are distinctly
related to annual water yield.

5.4.4.3 Geomorphological implications

In his well-known discussion of geomorphic concepts, Schumm
(1977) states: "In actuality the fluvial system is a physical
system with a history. Hence the objective of the geomorphologist
is to understand not only the physics and chemistry of the land-
scape, but its alteration and evolution through time".   Though
more research is needed for fully understanding landscape develop-
ment, the results from the present sediment budget study have
general implications concerning the geomorphological development
of the channel incision.

The high degree of conformity between sediment production
from stream banks and valley slopes on the one hand, and sediment
output on the other, might denote a steady state situation concern-
ing sediment transfer from and through the channel.   Although
data have only been collected for two years, it has been shown
that such conditions of stream equilibrium may exist for a longer
time span than the measured one.   Consequently, the channel system
may be assumed to be in a state of dynamic equilibirum.   Chorley
and Kennedy (1971) define this state as:

>   "... balanced fluctuations about a constantly changing
>   system condition which has a trajectory of unrepeated
>   'average' states through time.
>
>   "The rate of change of the fluctuations is so much greater
>   than that of the average system that, when observed instan-
>   taneously or on a short time scale, the former masks the
>   latter to give the appearance of a steady state equilibrium."

As such an equilibrium state is defined for the entire stream
system, this does not preclude the existence of unstable conditions
on the more local scale of discrete channel reaches.

Cycle of stream bank evolution

The mechanisms of the processes described in previous sections and the results from the channel surveys and budget calculation may be summarised in a descriptive model for the widening of the valley incisions in the study area which is schematically depicted in Fig. 5.4.4.3.

This figure shows a stable stream bank only slightly affected at its base by stream scour, e.g. along a straight part of the channel, and subject to splash erosion and soil creep. Large runoff events or the development of organic debris dams indirectly lead to increased bank and bed scour, resulting in intense undercutting of the bank (Fig. 5.4.4.3(b)). Bank stability gradually decreases until failure occurs, generally by shallow sliding or flow sliding during periods with prolonged rainfall or snowmelt, eventually influenced by effects of seepage. These failures cause the more erodible subsoil to be exposed to the atmosphere (Fig. 5.4.4.3(c)), resulting in an increased splash loss. Moreover, subsoil fall starts to take place and the development of a small overhang may be observed (Fig. 5.4.4.3(d)). Continuing soil fall activity leads to a net enlarging of the undercut while detached aggregates are transported over the bank surface under the influence of gravity, rainsplash or overland flow (Fig. 5.4.4.3(e)). With increasing lateral depth (and fairly constant height) of the undercut, however, the transport rate of the detached aggregates decreases and sediment supply gradually slows down. The stability of the overhang decreases too and irregularities on its top denote its gradual collapse (Fig. 5.4.4.3(f)). A consequence of the decreasing distance between roof and bottom of the undercut is that the detached aggregates are trapped behind roots hanging down from the roof. This leads to gradual disappearance of the niche (Fig. 5.4.4.3(g)). As the supply of aggregates from the undercut stops, material transported over the bank surface by splash action and overland flow decreases due to both a lower availability of easily transportable material and to an increasing stability of the bank surface. This bank type is in general observed in older, abandoned parts of the meandering channel system, where no attack by scour occurs. In the research catchment, all stages in the
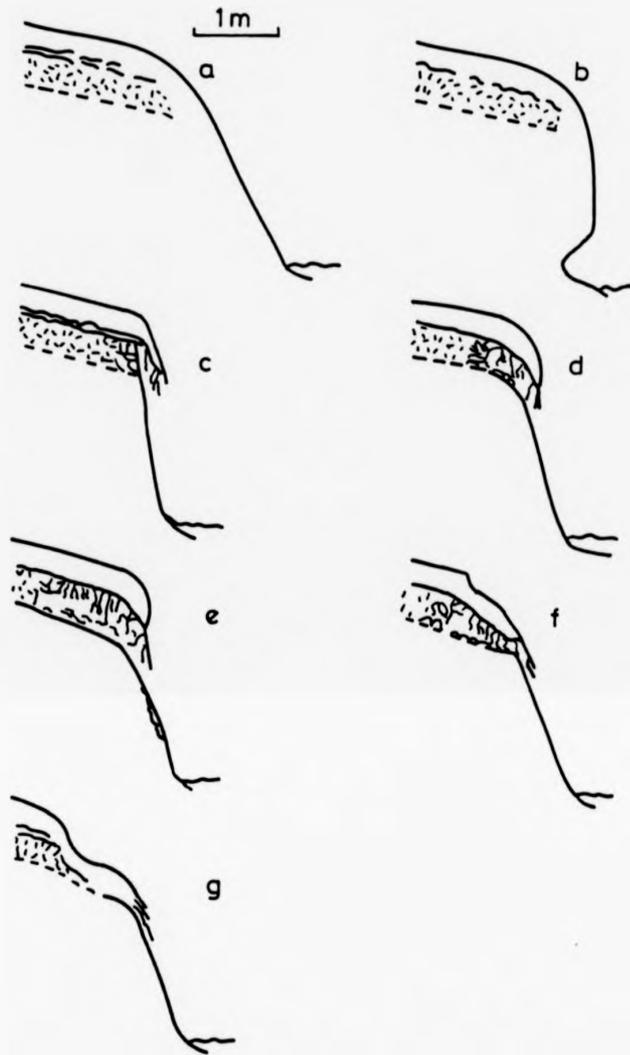
FIGURE 5.4.4.3 (a-g)

General model for the widening of valley incisions
in the study area (see text)

stream bank evolutionary cycle were observed.

The cycle described above may, however, be interrupted at any time by renewed occurrence of bank failures (related to channel planform changes or bed scour) which may cause rejuvenation of the cycle.

Role of scour

The above model clearly stresses the dominant effect of lateral and vertical scour in triggering bank failures and consequent initiation or acceleration of the other bank processes.

Keller and Swanson (1979); Mosley (1981); Megahan (1982); and Gurnell and Gregory (1984) highlight the influence of the forest vegetation on sediment transfer through the channel, as this supplies the logs, branches and litter for the development of such dams. This relationship between forest vegetation and channel erosion might explain the large cross-section of stream channels under forest conditions in contrast to the much smaller cross-sections under agricultural land use conditions. Recently, Murgatroyd and Ternan (1983) reported more active bank erosion along forested than along non-forested channel reaches for a Dartmoor catchment. Their measurements revealed that active bank erosion was largely caused by the suppression by the forest of thick grass turf and its associated dense network of fine roots, and secondly by the river's attempting to bypass log jams and debris dams in the channel reaches. Besides determining the rate of sediment transfer from the banks in an indirect way, the dams play a prominent role in the catchment's sediment budget through their effect on bed storage (Mosley, 1981). Grain size analysis of material supplied to the channel bed of the Coombs Brook revealed that the coarse bedload was delivered by the channel incision (Section 5.4).

As supply of coarse material generally (though not in the study period) exceeds transport, channel erosion leads to increasing bed storage and eventually to bed armouring. To a lesser extent, however, the supply of fine material may be out of phase with transport during selected time spans. The subsequent time

lag between supply and transport might explain part of the variance not accounted for by streamflow (Vansickle and Beschta, 1983). These results point to the importance of the development of dynamic models of sediment yield - e.g. Moore (1984) - in which not only the various source areas are identified, but also temporal and spatial variations in supply availability and entrainability of sediment are included.

Effect of drainage operations

The sediment budget and the model for channel widening also denote that subsoil fall plays a distinct role in channel widening, thereby confirming the results of measurements during the study period. For a certain type of bank material, the depth of the undercut is assumed to be positively related to its age. Comparing maximum observed depth of the undercuts of 80-100 cm with measured backwall recession of 3 cm y^{-1} indicates that the maximum age of the undercut will be in the order of 40-50 years. Although the rather wide difference in measured and extrapolated time span induces that such a comparison must be treated with some caution, the resulting age agrees remarkably well with the time which has elapsed since forest drainage operations were carried out, during 1930-1935. A major point of concern in this context, however, is the fact that the maximum depth of the undercuts of 80-100 cm might denote the maximum possible depth in relation to the stability of the overhang. Nevertheless, the construction of a system of narrow, shallow ditches will probably have resulted in higher peak flows and an increased discharge frequency; such discharge parameters have been shown to condition overall channel size, slope and planform properties. Consequently, the rate of channel erosion-scour and subsequently bank failures and subsoil fall would probably have increased shortly after the execution of the drainage operations.

Summary

The primary aim of this section is the construction of a sediment budget for a small forested catchment, special emphasis being given to the contribution of stream bank erosion. The lower part of the drainage

basin is characterised by gentle slopes, but the streams are deeply
incised valleys with meandering streams. The sediment budget of the
catchment was divided into three main parts: sediment transfer from
the stream bank (Section 5.1), sediment transfer from valley slopes
(Section 5.2) and sediment output from the drainage basin (Section 5.4).

The stream banks contributed 65% to the total supply of sediment,
with lateral corrasion and subsoil fall being the main bank processes
contributing 36% and 18% respectively. Bank failures, rainsplash
erosion and soil creep transferred 7.3%, 1.3% and 0.6% respectively.
The sediment transfer by overland flow was left out of the budget, as
it was observed that overland flow predominantly acted as a transport
medium for material detached by other processes. Consequently, the
transferred amount was already included in the results for these pro-
cesses.

The activity of each of these processes was restricted to a parti-
cular part of the bank and to specific hydro-meteorological conditions.
Maximum rates of lateral corrasion and splash erosion were generally
encountered during wet periods, while the highest rates of subsoil fall
were measured during frost periods. High rates of soil creep could
largely be attributed to the effect of biological activity (in summer)
and to a lesser extent to the effect of frost action. The spatial
trend in sediment supply from the stream banks showed a general increase
with increasing catchment area. However, the highest rates of bank
recession were encountered in the upstream part of the main channel.
These were due to various indirect effects of distinct breaks in the
longitudinal profile, especially related to the presence of organic
debris dams.

Splash detachment and subsequent transport of detached material
by overland flow appeared to be the dominant mechanism of soil erosion
on the valley slopes, contributing 35% to total sediment supply. Both
the rate of splash detachment and storm runoff generation were influenced
to a large degree by the forest ecology: apart from the canopy effects
on the erosivity of rainfall, the rate of splash detachment was related
to the spatial and temporal variations in the occurrence of exposed
soil. In addition, the combination of clayey soils and a rich soil
fauna led to a high content of biopores and pipes above the seasonally

saturated subsoil, causing rapid drainage of the topsoil. Widespread conditions of overland flow on the valley slopes occurred at least once a year during which up to 75% of the catchment contributed to the stream hydrograph. Throughflow through biopores and pipes supplied sediment originated from the subsoil. This sediment transfer dominantly occurred during baseflow conditions and contributed 2.2% to the total sediment supply.

Sediment transfer out of the drainage basin dominantly occurred as suspended load (92%), while bedload contributed only 8% approximately. Both transport modes showed highest output rates during wet periods. Grain size analysis of the sediment supplied by the various stream bank and valley slope processes revealed that bedload was largely made available by lateral corrasion, subsoil fall and bank failures. On the other hand, hillslope processes were the main contributor to suspended load.

The results from the sediment budget showed that during the study period sediment production from stream banks and valley slopes was about equal to sediment output from the drainage basin, implying a present state of dynamic equilibrium in sediment transfer. When viewing the results from the 1984-1986 period within a wider time scale (about 50 years), the present-day activity of the erosion processes reflects adjustment to channel changes indirectly caused by the drainage operations carried out between 1930-1935. Insufficient data were available for further extrapolation in time to calculate the real age of the channel incision.

The results of the channel surveys and observations of bank processes are summarised in a descriptive model for the widening of valley incisions in the study area.

CHAPTER SIX

VARIATION IN THE SEDIMENT LOAD

Introduction

6.1   Temporal Variations in the Suspended Sediment Load

6.2   Sediment Variations with Time

6.3   Parameters used to Measure the Factors in the Suspended Sediment
       Concentration

6.4   Variation in Suspended Sediment Concentration and Load as a
       Function of Catchment Hydrometeorological Conditions

       6.4.1 Introduction

       6.4.2 Hydrometeorological results

       6.4.3 Suspended sediment results

              I - Short-term variation in suspended sediment
                  concentration

              II - Single rise storm events

              III - Multiple rise events

Discussion

Conclusion

CHAPTER   SIX

VARIATION   IN   THE   SEDIMENT   LOAD

INTRODUCTION

Since, ultimately, one main geomorphological concern is with the amount of material being lost by erosion of channels, valley floors or slopes, the sediment discharge of streams is important.

Throughout this chapter the distinction is made between suspended sediment concentration and discharge.   The former refers to the weight of solid particles in a given volume of water sampled from the stream and expressed in mg l^{-1}.   The latter refers to the weight, or volume, of sediment carried past a given point by a stream in a given time. This distinction is made because, by its definition, the suspended sediment discharge will always correlate with the water discharge. A series of samples having the same sediment concentration, but occurring over a wide range of discharge, will give a perfect correlation between sediment discharge and water discharge.

The sediment discharge is so closely related to the water discharge that the relationships between the sediment load of a stream and changing catchment conditions are obscured if the sediment discharge is used as the sediment variable.

6.1   TEMPORAL VARIATIONS IN THE SUSPENDED SEDIMENT LOAD

Most work concerned with sediment production from catchment areas has implicitly differentiated between sediment load variations in time and sediment variation in space.

The influence of contrasts in the catchment conditions on the variations of the sediment yields in the catchment has been studied at seven sampling stations.   Although this section is concerned with temporal variations in the suspended sediment concentration, spatial variations

in sediment discharge are worth considering. Such variations enable
an assessment to be made of the importance of particular sub-catchment
characteristics, such as the nature of the geology and soil types
influencing the nature and quantity of sediment supplied to the streams.

If factors that vary little over short periods of time are exclu-
ded, a spatial sediment production would see sediment concentrations
as a function of:

1.   Geology - particularly lithology.

2.   Geomorphological and topographical characteristics.

3.   Soil type.

4.   Vegetation cover.

5.   The influence of man, such as the presence or absence of channel
     protection works.

6.   Climatic characteristics, such as rainfall intensity, etc.

The operation of the above factors is, in reality, complex even
in a small catchment area, and a spatially orientated investigation of
sediment yield requires hydrometeorological detail.

The relative importance of a particular factor in influencing
variations in the sediment concentration within a given area depends
upon the scale of investigation. On a world scale, when the widest
possible range of variations is being considered, climatic variables
have been shown to explain most of the long term differences in sedi-
ment production. Climatic factors do not explain variations in sedi-
ment production in small catchments of less than 1 km^2.

For example, Douglas (1970) related sediment production, on a
world scale, to rainfall and relief parameters, while Langbein and
Schumm (1958) found that throughout the United States sediment produc-
tion could be expressed as a function of the effective precipitation.
These relationships occur partly because sediment and stream discharge
are closely related. If the scale of study is reduced so that clima-
tic factors become constant expressions, geomorphological differences

then explain most of the spatial variations in sediment yield.   Thus, in the study area, sediment yields could be related hydrometeorological paramaters (Chapter 3).   Finally, reducing the scale still further, to an area of similar geology and lithology, sediment production differences could be related to vegetation, soil characteristics and channel characteristics differences (Appendix 1).   Variation in sediment yield at the seven sites is largely dependent on the location of erosion activity and variation discharge per unit area.

6.2   SEDIMENT VARIATIONS WITH TIME

The length of time over which temporal variations are being considered is important.   While, over several million years, changing slope and soil conditions are likely to be important, over the 24 months covered by this thesis, seasonal changes in temperature and vegetation cover from winter are likely to be as important (Fig. 6.2.1).

The model set up to describe suspended sediment concentrations during such a short time span only needs to incorporate hydrometeorological and land cover and use factors (Table 6.2.1).   If the source of suspended sediment is the land surface, as opposed to the stream channel, then the availability of material depends upon such factors as the amount of bare land, the type and nature of the vegetation cover, and the condition of the soil.   These factors are modified by antecedent hydrometeorological conditions which, within the context of the above factors, influence infiltration, soil aggregation and the way in which runoff will occur, thereby affecting the removal of soil material.   If the climate and soil factors are held constant, then the effect of any rainfall depends upon its intensity, duration and energy.

If the suspended sediment in the stream is derived from channel erosion, then a similar set of factors operates, except that runoff is an important agent of bank erosion.   Vegetation was shown to play a vital role in protecting the soil from the impact of rain, preserving the soil structure, and keeping infiltration at a maximum.

Input

(Climate: precipitation

radiation and wind, human

activity)

Land surface

catchment

system

Output

(Evaporation

Runoff

Input

Modified

catchment

Sediment

Dissolved load)

Input

Landscape

evolution

Modified

output

N. output
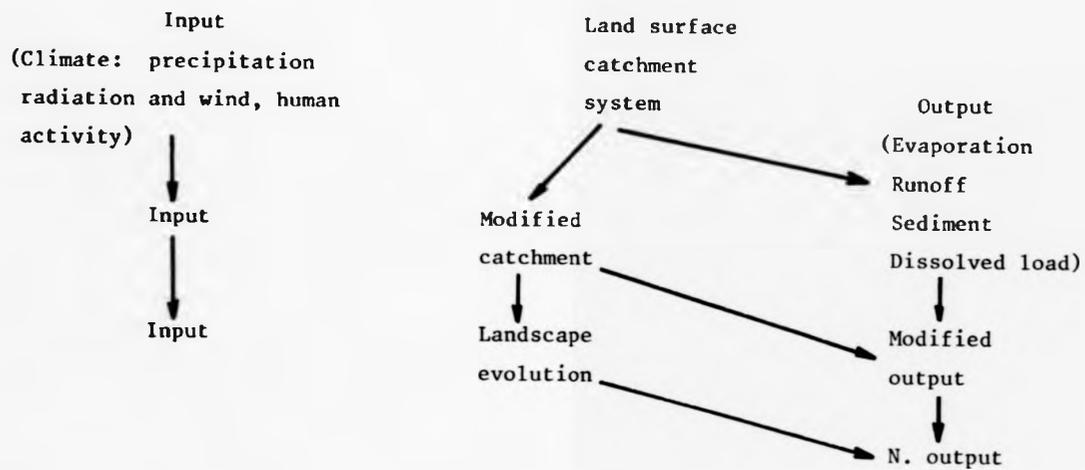
FIGURE 6.2.1   IDEALIZED SEDIMENT PRODUCTION MODEL

TABLE 6.2.1   FACTORS INVOLVED IN THE SEDIMENT TIME MODEL

Major Factor	Elements	Influence of elements on soil erosion
1. Climate	Rainfall	Raindrop, soil splash, rainsplash erosion, throughflow, overland flow, breaks down aggregates and disperses soil, thereby sealing the surface and increasing precipitation excess (Sections 5.2.1 and 5.2.2).
	Runoff	Entrainment of debris - physical force due to pressure differences and impact of water dislodges, disperses and transports. Rain intensity and duration affect rate of runoff after infiltration capacity reached (Sections 5.2.1 and 5.2.2).
	Temperature	Alternate freezing and thawing - expands soil, increases moisture content and decreases cohesion, thus facilitating dislodgement, dispersion and transport.
2. Soil	Properties of soil consti-tuents	Frost susceptibility
		Grain size, shape and specific gravity
	Topography	Slope angle, degree and slope length
	Vegetation	Protection against splash, seasonal variations in ground cover, role in soil processes, litter fall, fallen trees.
	People	Human influences on vegetation Human influences on hydrology (presence or absence of channel protection works).
3. Time	Antecedent conditions	Antecedent - runoff, influences affect of subsequent rainfall

6.3 PARAMETERS USED TO MEASURE THE FACTORS IN THE SUSPENDED SEDIMENT CONCENTRATION

To establish the relationships between the sediment concentration and the various factors operating in the sediment concentration model, discussed above, it is necessary to select parameters that measure these factors. The parameters chosen to do this usually measure more than one factor owing to the inter-relationships between the different factors. Therefore, when considering the results presented later, it is necessary to understand exactly what each parameter is measuring. For example, the discharge of a stream is an important parameter, which reflects the amount, intensity and duration of rainfall and the antecedent hydrometeorological conditions and catchment wetness. The parameters used in this section are defined below.

1. Rainfall

Total precipitation in the five days before sampling was used to indicate antecedent conditions in terms of catchment wetness (Table 6.4.2.1). The disadvantages of using rainfall measurements are that effective rainfall is not measured and that rainfall often has not occurred during the period immediately preceding sampling.

2. Stream discharge

The discharge of a stream reflects the intensity and magnitude of precipitation events, so that almost all workers have obtained good correlations between sediment concentration and stream discharge.

3. Rising and falling stage

A series of parameters, describing the rate at which the catchment streams were rising or falling, was obtained by subtracting the discharge, at the time of sampling, from the discharge at various times before and after sampling.

6.4   VARIATION IN SUSPENDED SEDIMENT CONCENTRATION AND LOAD AS A
       FUNCTION OF CATCHMENT HYDROMETEOROLOGICAL CONDITIONS

6.4.1 Introduction

Variations in suspended sediment concentration-discharge rela-
tionship reflect differences in hydrometeorological conditions at
different sampling times and different times of the year (Figs. 6.4.1.1
and 6.4.1.2 and Table 6.4.1.1).   The suspended sediment concentration-
discharge relationships for Sites 2-7 varied, with weak correlations
and regressions with a broad scatter (Table 6.4.1.1).   Because no con-
tinuous discharge information is available for Sites 2-7, the only
gaugings were the time of sampling, and thus the type of response of
sediment concentration is apparently random.   Greater attention will
be given to Site 1, where the automatic sampler and the water level
recorder were situated.

6.4.2 Hydrometeorological Results

Rainfall totals during the period of the study were about 870 and
1038 mm for the period 1984-1985 and 1985-1986, while the mean annual
rainfall is 954 mm.   Rainfall in the upper part of the catchment is
approximately 50 mm more than downstream, based on the differences
betweeen rain gauges 1 and 2 (Fig. 6.4.2.1).

The magnitude of rainfall events was extremely variable, including
several large storms during the two year study period, the heaviest of
which yielded 33 mm of rain in 10 hours (on 17th October 1984 and 6th
October 1985), representing 34% to 45% of the total for the month
(Tables 5.4.2.2 and 6.4.2.1).

A total of 45 storm events was sampled, with rainfalls ranging
from 10 to 35 mm.   For each rainfall event, maximum 30-minute rain-
fall intensity and an indication of antecedent moisture are shown in
Tables 5.4.2.2 and 6.4.2.1.   The runoff characteristics of some of
the storms have also been shown in these tables.

Relatively high rainfall intensities occur at almost any time of
the year.   The highest rainfall intensity recorded was 21 mm h^{-1} in
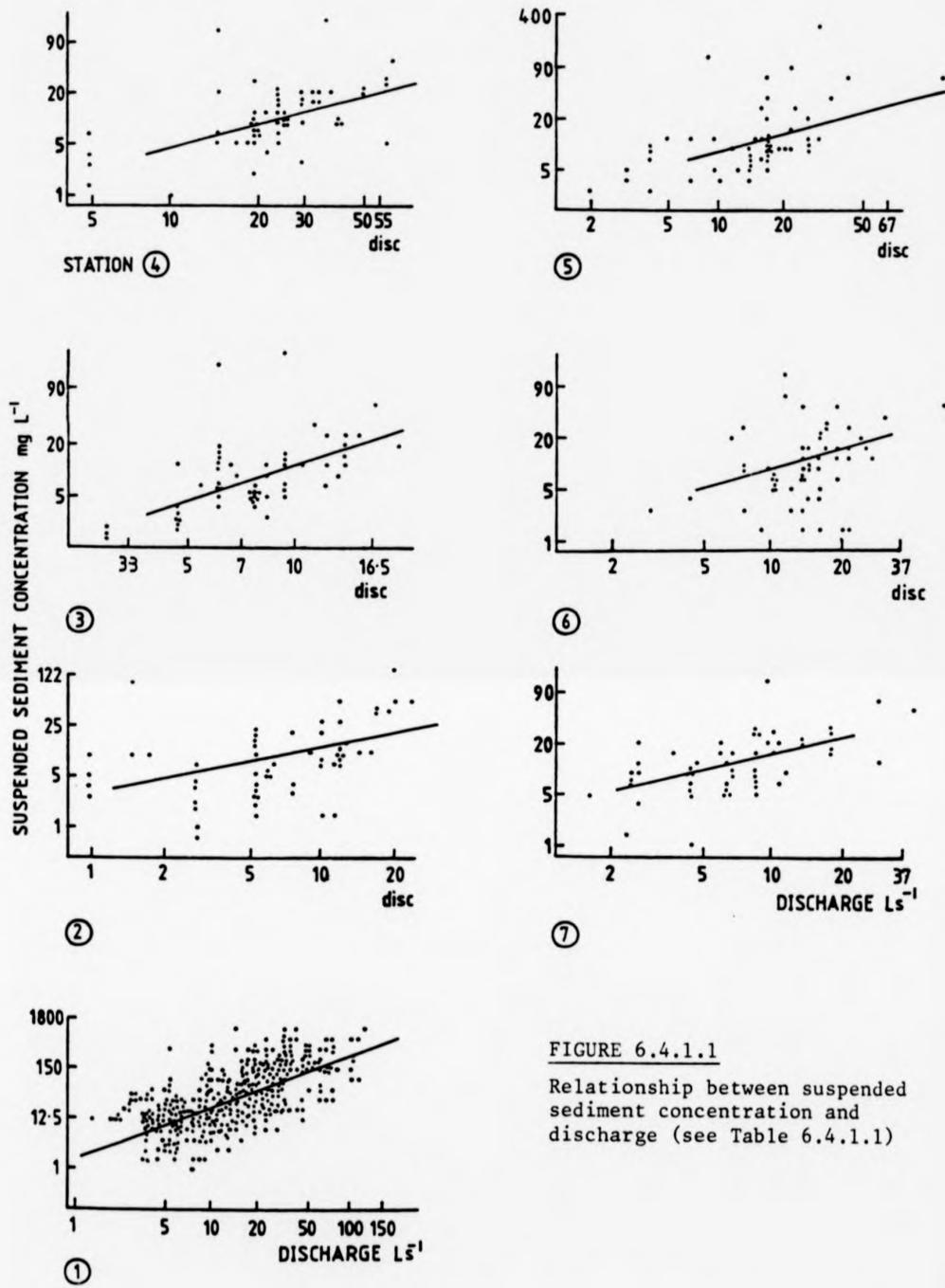
FIGURE 6.4.1.1

Relationship between suspended sediment concentration and discharge (see Table 6.4.1.1)
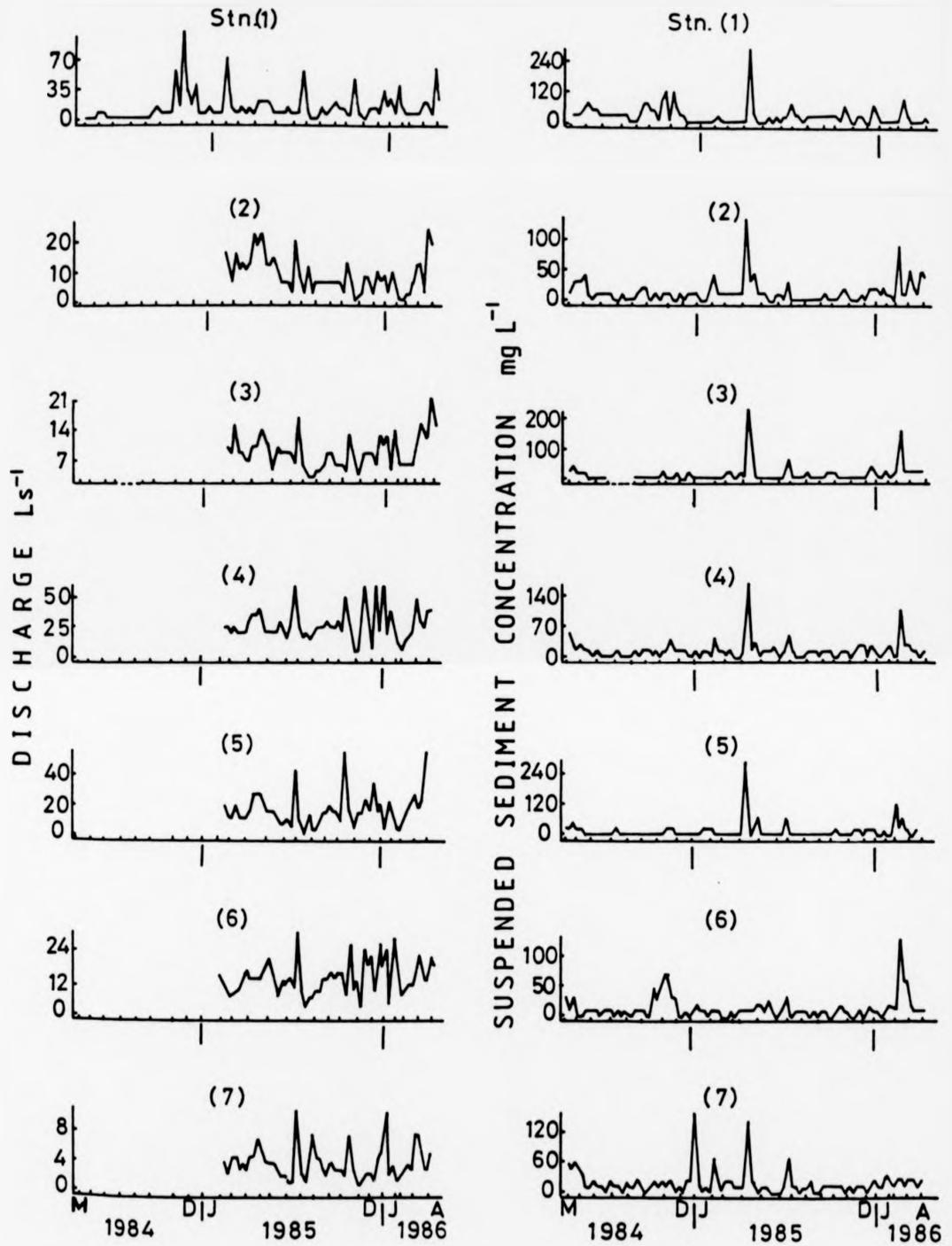
FIGURE 6.4.1.2   Temporal variation in discharge $(1\ s^{-1})$ and
suspended sediment concentration $(mg\ 1^{-1})$
during the study period (1984-1986)

TABLE 6.4.1.1   SUSPENDED SEDIMENT CONCENTRATION-DISCHARGE RELATIONSHIP
FOR THE SEVEN STATIONS

Regression equation and correlation coefficients (see Fig. 6.4.1.1)

Station No.	Regression equation $\log y =$	Correlation $r =$	Significance level
1	0.750 + 1.06 log disc	0.647	>99.9%
2	1.07 + 0.524 log disc	0.394	>99.9%
3	0.80 + 1.39 log disc	0.574	>99.9%
4	0.408 + 0.847 log disc	0.519	>99.9%
5	0.699 + 0.630 log disc	0.479	>99.9%
6	0.799 + 0.517 log disc	0.263	>95.0%
7	1.32 + 0.862 log disc	0.572	>99.9%
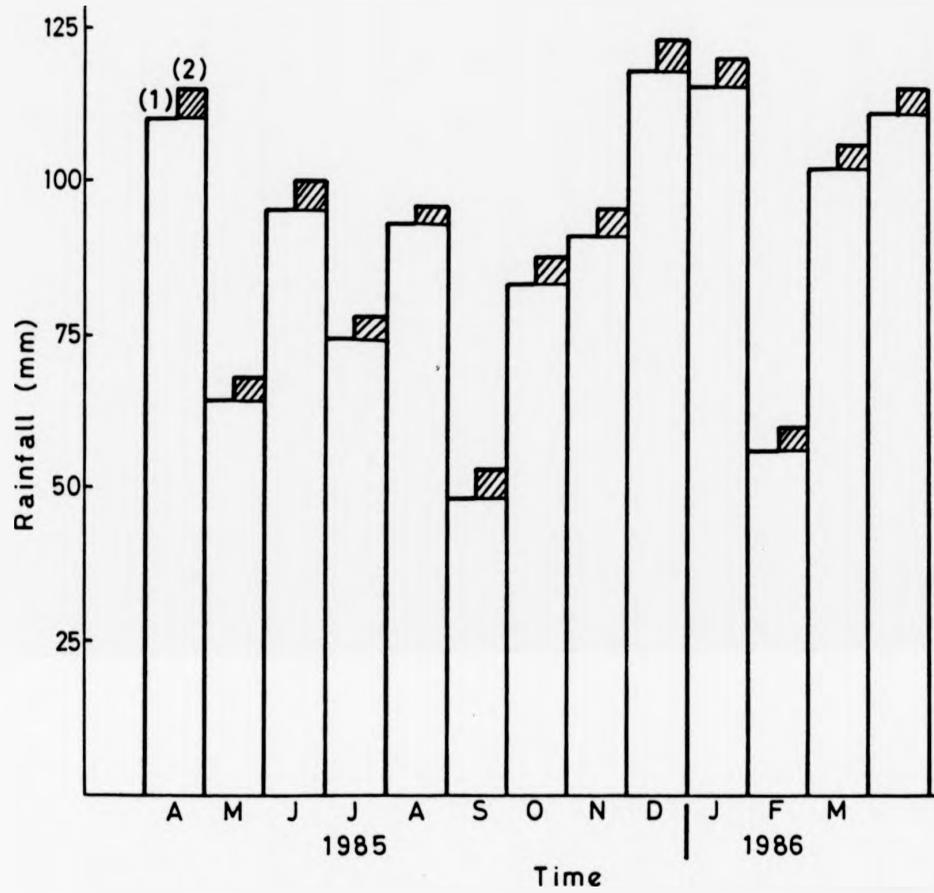
FIGURE 6.4.2.1

Difference of rainfall amount in two rain gauges (1) and (2)
in the catchment area

TABLE 6.4.2.1   HYDROMETEOROLOGICAL DATA FOR INDIVIDUAL RAIN
EVENTS AT STATION 1 IN COOMBS BROOK

No.	Date	Rainfall mm	Discharge Q 1 s^{-1}	Rain in previous 5 days mm	Date	Lag time/hr
1	22.05.84	18.0	62.6	8.0	22.05.84	1.0
2	27.05.84	10.8	22.3	2.4	27.05.84	8.0
3	02.06.84	12.8	49.9	19.6	02.06.84	4.0
4	03.06.84	13.2	52.8	11.6	03.06.84	2.0
5	12.07.84	15.6	24.7	0.8	12.07.84	11.0
6	13.07.84	3.0	47.6	18.0	13.07.84	3.0
7	01.08.84	10.4	7.67	5.3	02.08.84	12.0
8	02.08.84	16.8	43.2	14.9	02.08.84	7.0
9	03.09.84	22.0	86.4	6.8	03.09.84	10.0
10	14.09.84	2.0	15.3	27.4	04.09.84	2.0
	"	4.0	23.2	29.4	"	3.0
	"	3.0	59.9	32.4	"	2.0
	"	4.0	59.9	36.4	"	2.0
11	17.09.84	17.6	93.2	27.0	17.09.84	1.0
12	17.10.84	33.2	76.9	0.3	18.10.84	13.0
13	02.11.84	40.0	140.0	14.0	02.11.84	1.0
14	21.01.85	8.1	25.9	1.5	21.01.85	12.0
15	29.01.85	19.0	142.0	16.4	29.01.85	8.0
16	10.04.85	12.1	141.0	27.3	11.04.85	13.0
17	14.05.85	4.5	17.7	3.9	14.05.85	4.0
	"	6.5	47.2	7.9	15.05.85	4.0
	"	3.5	48.5	10.0	"	4.0
18	27.05.85	10.7	43.2	13.7	27.05.85	5.0
19	06.06.85	9.4	12.1	9.5	06.06.85	2.0
20	07.06.85	6.4	10.3	18.9	07.06.85	2.0
21	09.06.85	8.1	19.8	33.6	09.06.85	1.0
22	10.06.85	8.3	56.8	35.4	10.06.85	3.0
23	11.06.85	19.2	86.4	40.5	11.06.85	1.0
24	29.07.85	9.4	68.1	30.1	30.07.85	5.0
25	11.08.85	18.0	95.9	5.9	11.08.85	4.0
26	16.09.85	10.5	62.5	8.7	17.09.85	5.0
27	06.10.85	33.0	141.4	7.3	06.10.85	5.0
28	05.11.85	8.4	35.4	12.7	05.11.85	2.0
29	06.12.85	11.9	89.1	27.8	06.12.85	4.0
30	13.12.85	18.0	144.1	23.9	13.12.85	3.0
31	21.12.85	25.4	142.3	10.6	21.12.85	2.0
32	01.01.86	7.9	16.4	6.9	01.01.86	3.0
33	12.01.86	10.2	37.9	15.8	13.01.86	7.0
34	29.01.86	8.5	64.2	23.2	30.01.86	8.0
35	22.03.86	9.0	35.0	9.6	23.03.86	10.0
36	23.03.86	15.1	58.3	18.6	24.03.86	11.0
37	24.03.86	4.9	36.9	27.3	25.03.86	12.0
38	14.04.86	23.0	24.7	6.0	15.04.86	4.0
39	15.04.86	13.2	128.9	32.0	15.04.86	1.0
40	19.04.86	18.9	140.0	38.3	19.04.86	3.0

early November 1984, 16 mm h^{-1} on 11th June 1985, 10 mm h^{-1} on 11th August 1985, 13 mm h^{-1} in late December 1985, 14 mm h^{-1} in late January 1986, and 12.5 mm h^{-1} on 19th April 1986.

At other times rainfall intensities are much lower, less than 4.0 mm h^{-1} or 2 mm per 30 minutes. During winter, the runoff responds rapidly to rainfall, almost every period of rainfall being followed by a corresponding rise in the hydrograph between 1 and 13 hours later (Table 6.4.2.1 and Fig. 6.4.2.2).

In late spring and summer, this relationship becomes less pronounced until, in late summer and autumn, heavy rainfalls produce only small amounts of runoff.

The enormous contrast between summer and winter rainfall-runoff relationships is illustrated by comparing the summer peak discharge of 86 1 s^{-1} after 19 mm of rain on 11th June 1985 and 95 1 s^{-1} following 18 mm of rain on 11th August 1985, with the hydrograph peak of 144 1 s^{-1} following 18 mm of rainfall on 13th December 1985 (Table 6.4.2.1). This type of contrast reflects the high water table in winter, when evapotranspirational losses are slight.

6.4.3 Suspended Sediment Results

A plot of adjusted data obtained with the Coombs Brook samples is shown in Fig. 6.4.1.1: some of the considerable scatter can be accounted for by variations in the duration and intensity of the causative precipitation. Figure 6.4.3.1 shows two runoff events, demonstrating the differences in concentration as a result of heavy short-duration rainfall (A), and relatively light rainfall spread over a long period (B). Concentrations on the rising limb of the hydrograph were generally greater than on the falling limb.

Thus suspended sediment-discharge relationships for the catchment show many of the characteristics previously noted: a wide scatter of points on the plot which may in part be related to seasonal, hysteretic and exhaustion effects. Further examination of data also suggests two complementary methods for distinguishing sediment sources, the differential operation of which may explain some of the scatter in the data.
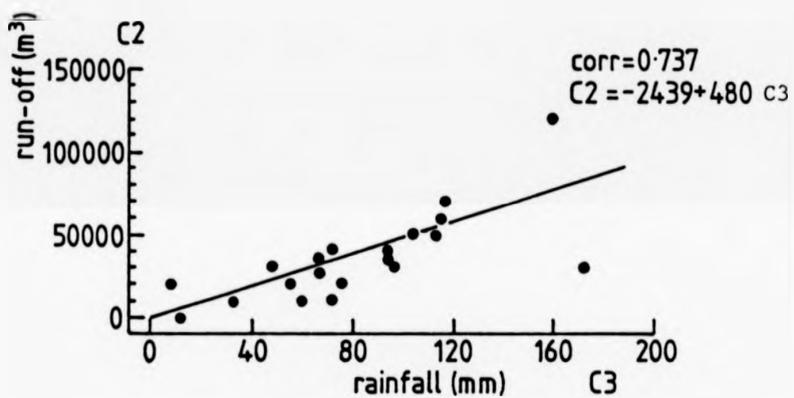
FIGURE 6.4.2.2

Correlation between rainfall and runoff in
the catchment area Site 1, 1984-86
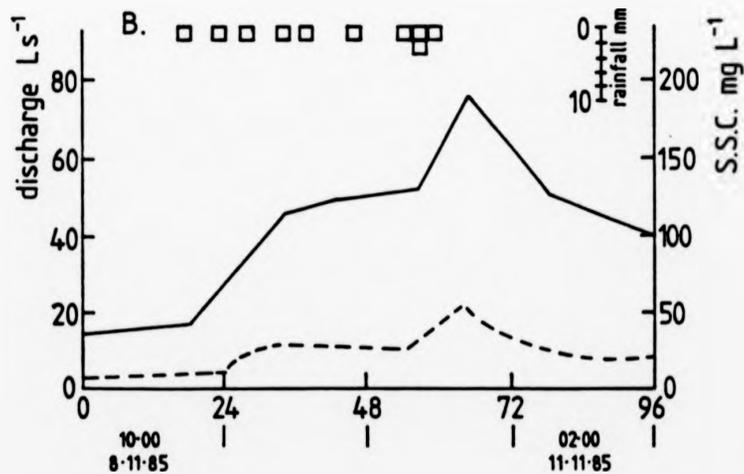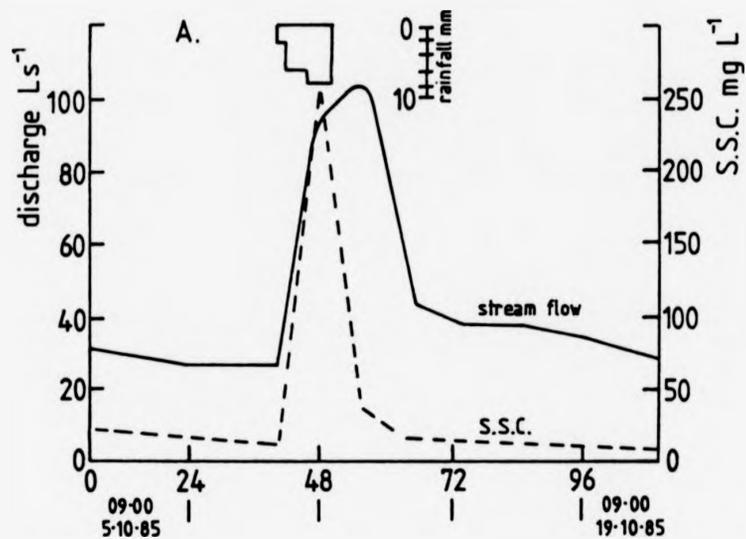
FIGURE 6.4.3.1

Rainfall, runoff and suspended sediment concentration
for two runoff events in October and November 1985

The first may be appreciated from the general plot of concentration against discharge (Fig. 6.4.1.1): for a given discharge there is a minimum sediment concentration such that the data plot on log scales has a linear lower boundary. By contrast, the upper boundary is highly variable. Higher concentration values for a given discharge appear to occur particularly in winter and on occasions when surface slopes were contributing sediment to channels. The existence of a pronounced lower limit may be explained by the fact that the channel and its banks constitute a source of fine sediment which is always available for transport whatever the origins of channel runoff, provided stream power is sufficient to entrain and transport it.

It is possible to distinguish the contributions of two separate sediment sources: channel sources (derived from the bed and banks of streams and gullies) and non-channel sources (from catchment slopes and including bare soil areas susceptible to erosion). The operation of channel sources closely relates to stream discharge, even though affected by all the variations in bank erosion described in Chapter 5. By contrast, sediment from non-channel sources may be highly variable in its supply, since its production and transport into streams depends on a large number of factors which differ for each runoff event (Chapter 5).

I   Short-term variations in suspended sediment concentration

Suspended sediment concentrations were determined during storm events for the catchment area between May 1984 and April 1986. A total of 60 storm responses was analysed, some 15 rejected through sampler malfunction, and both storm hydrographs and hysteresis loops were produced for the other 45. The behaviour of suspended sediment concentration was extremely variable and some different types of response were recognised. The free availability of suspendable material appears to be an important limiting control on sediment concentration, and this appears to be related to different responses, such as soil moisture conditions, the activity of bank erosion, and bank collapse.

The generally accepted model is that of a clockwise hysteresis with a sediment lead where concentration peaks before discharge and then sediment depletion occurs and concentration decreases. Examples of this model are described by Gregory and Walling (1973), who also refer to sediment lags, which result in anti-clockwise loops, and

sediment depletion in events with multiple peaks (Fig. 6.4.3.2). A more complex generalised model has been produced by Wood (1977), who examined 22 storm events in the River Rother in West Sussex. His model provides six different types of response, depending on sediment availability and whether the storm had a single or multiple peak. In the case of events with multiple peaks, sediment depletion was common, with progressively lower sediment concentrations in each subsequent rise. He suggests this is a result of either dilution due to an increasing contribution by groundwater and throughflow, or that fines may be more difficult to entrain while wet.

The dominance of storm events in the transport of suspended sediment was clearly evident, with very low suspended sediment concentrations during low flows and rapid rises associated with storm events. No actual sediment loads have been calculated due to errors associated with traditional techniques, but some indication of the importance of storms has been indicated. The load was between $0.8 - 1000$ mg 1^{-1}, the maximum value was carried in one event on 6th October 1985, while the mean annual value was 80 mg 1^{-1}, and the median was 21 mg 1^{-1}.

Using the plots, seven different types of suspended sediment concentration response have been recognised and behaviour is discussed in terms of these groups. The first three groups involve simple storm events with a single hydrograph rise; groups four to six are multi-rise events, usually larger in size; while the final group covers a range of storm types. In many cases in the storm hydrographs not included there was little or no response of sediment concentration during storms. This was restricted to small isolated storms, such as dry period thunderstorms, and was particularly evident if antecedent rainfall was low.

II Single rise storm events (after Olive and Rieger, 1984)

In this group there is a simple single rise of stream discharge. This type of response is normally associated with smaller, short duration storms where the rainfall distribution pattern is relatively simple.

1. Single rise with sediment lead

This is the conventional or generally expected type of sediment
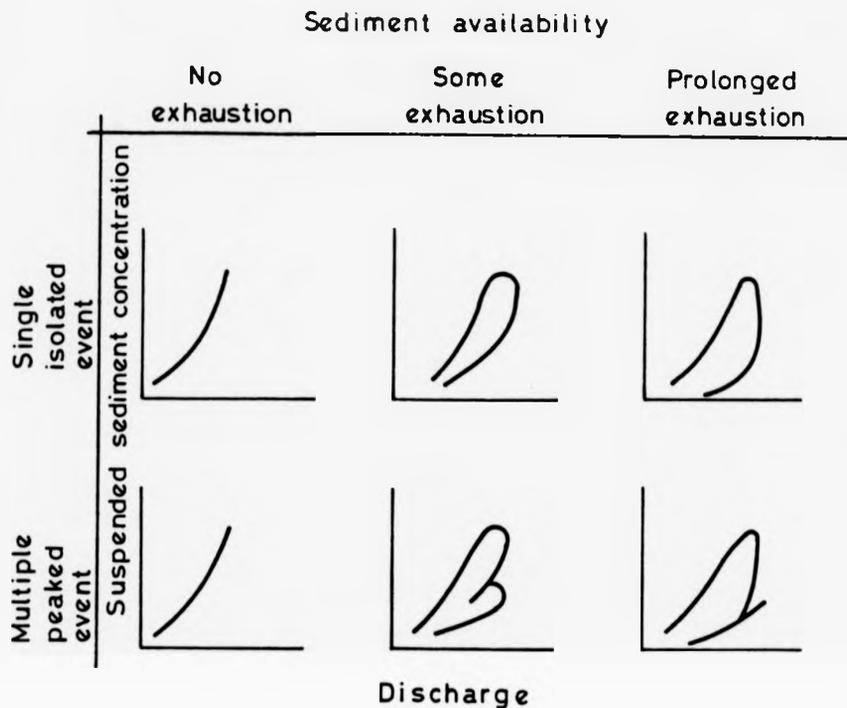
FIGURE 6.4.3.2

Model for suspended sediment concentration and discharge
relationship

after:

(1)   Wood (1977)

(2)   Gregory and Walling (1973)

(3)   Olive and Rieger (1984)

response. A simple single rise discharge response occurs with suspended sediment concentration peaking before discharge and then falling as the storm proceeds, resulting in a simple clockwise hysteresis loop. In the study, a number of plots of this type occurred, and an example of the type of response is shown in Fig. 6.4.3.3. This type was associated with small to moderate sized events, with rainfall ranging from 10 to 40 mm with a wide range of maximum rainfall intensities and antecedent moisture conditions.

2. Single rise with discharge and sediment correlation

A simple single rise of discharge where discharge and suspended sediment concentration are closely related and rise and fall together with the peaks occurring approximately simultaneously (Fig. 6.4.3.4).

3. Single rise with sediment lag

Discharge again shows a simple single rise but suspended sediment concentration lags behind discharge with maximum concentrations occurring on the falling limb of the hydrograph after maximum discharge occurred (Fig. 6.4.3.5).

III Multiple rise events (after Olive and Rieger, 1984)

These events were generally large, associated with rainfall over long periods. The small and relatively steep nature of the catchments, with rapid stream responses, produces multiple stream rises. In virtually all cases some sediment depletion is evident, with the maximum sediment concentration decreasing with each subsequent stream rise.

4. Multiple rise with sediment lead

These events are characterised by multiple stream rises with maximum sediment concentration preceding the stream discharge peak, resulting in a series of clockwise hysteresis loops. Sediment concentration decreases relative to stream discharge with each subsequent stream rise and, in some very large events, virtually no sediment response occurred in the third and subsequent rises. Few examples of this type of response were observed in the catchment;
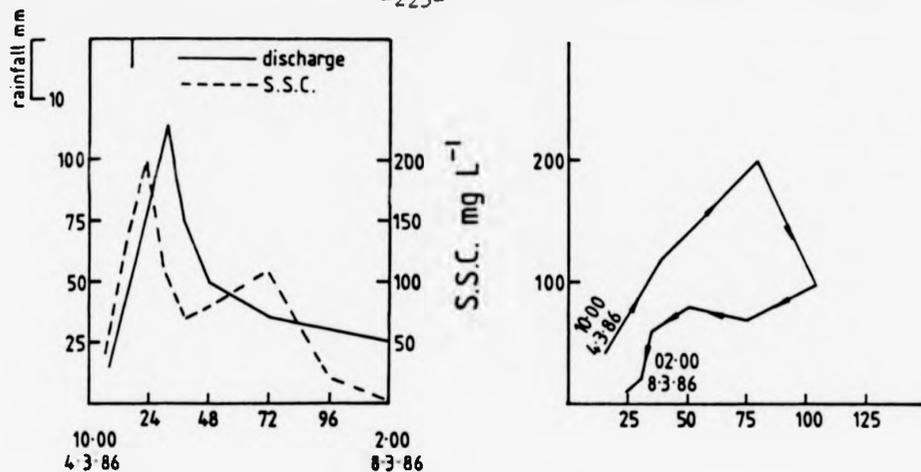
FIGURE 6.4.3.3   Single rise with sediment lead
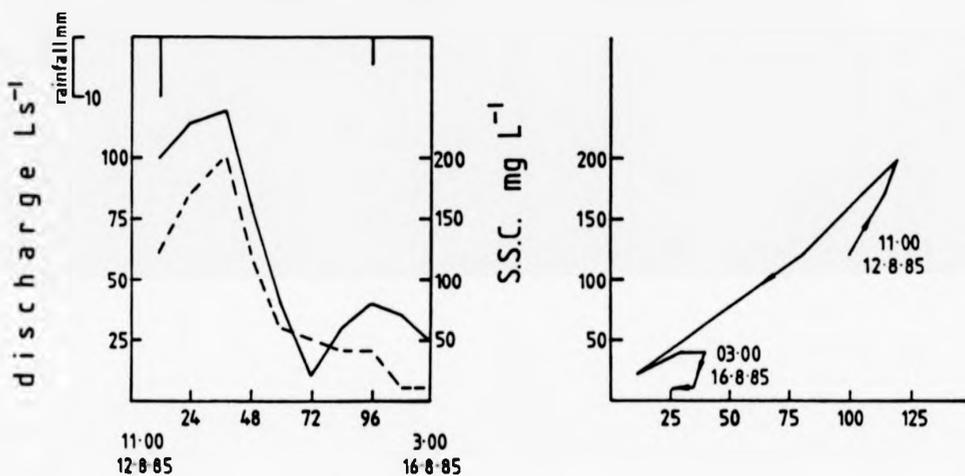
FIGURE 6.4.3.4   Single rise with sediment and discharge
                   correlation
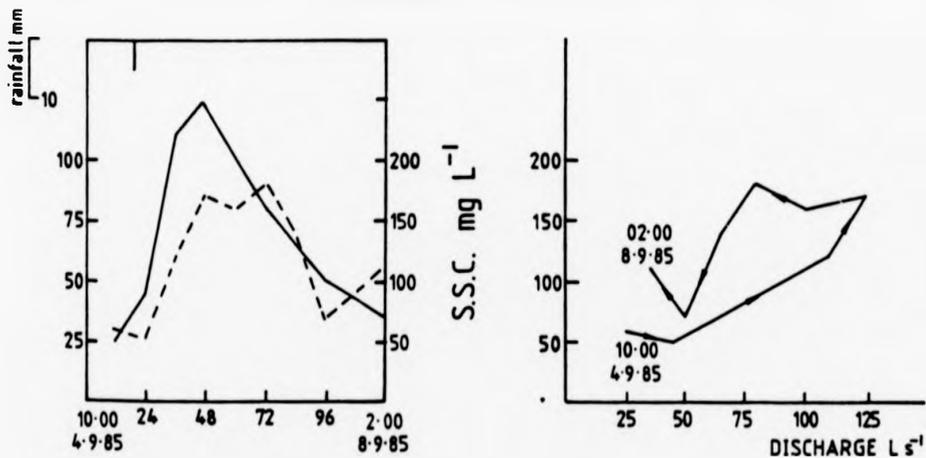
FIGURE 6.4.3.5   Single rise with sediment lag

the example shown in Fig. 6.4.3.6.   Interestingly, this type of
response was identified in the catchment in October-November 1985,
after it had undergone major disturbance by logging when it might
be expected that available sediment was at a maximum.   In this case,
sediment concentrations were much higher in the initial rise, but
still showed characteristic sediment depletion in subsequent rises,
with virtually no sediment response in the third rise (Fig. 6.4.3.7).

This type of general response occurred in large storm events extend-
ing over several days with total rainfalls ranging over 40 mm.
Maximum rainfall intensities varied from 16-20 mm/hr, while antece-
dent moisture conditions were generally relatively dry.

5.   Multiple rise with sediment lag

In this case multiple stream rises are associated with a lag in
sediment response and maximum sediment concentrations occur after
peak discharge, resulting in anti-clockwise hysteresis loops.
Again, subsequent stream rises in the same storm event result in
relatively low rises in sediment concentration.   Few examples of
this type of response were observed; the storm from the catchment
is shown in Fig. 6.4.3.8.   This example occurred during the largest
storm sampled (July 1985), when total rainfall was 75 mm and maxi-
mum rainfall intensity was 12 mm/hr.

6.   Multiple rise with both lead and lag response

This response represents a combination of the previous two where
there is a multiple stream rise storm which results in sediment
exhibiting both a lead and lag response on different rises.   This
results in a hysteresis with clockwise and anti-clockwise loops
often with a figure-of-eight pattern.   This pattern was recognised
in the catchment (the example shown in Fig. 6.4.3.9).   In this
particular example, sediment concentration leads discharge in the
initial rise, corresponds with discharge in the second rise, and
lags it in the subsequent rise.   This pattern was not exhibited
in all examples.   The examples occurred in December 1985, when
total rainfall was 130 mm, maximum rainfall intensity was 10 mm/hr,
and the catchment was relatively moist preceding the rain.
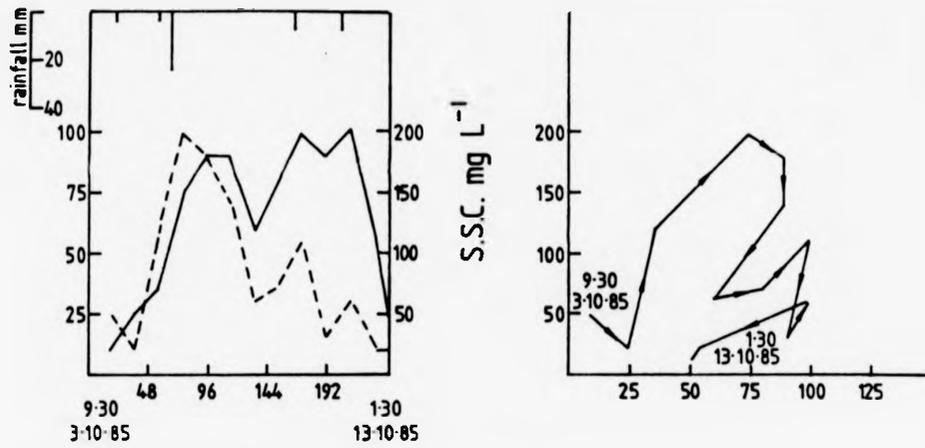
FIGURE 6.4.3.6   Multiple rise with sediment lead
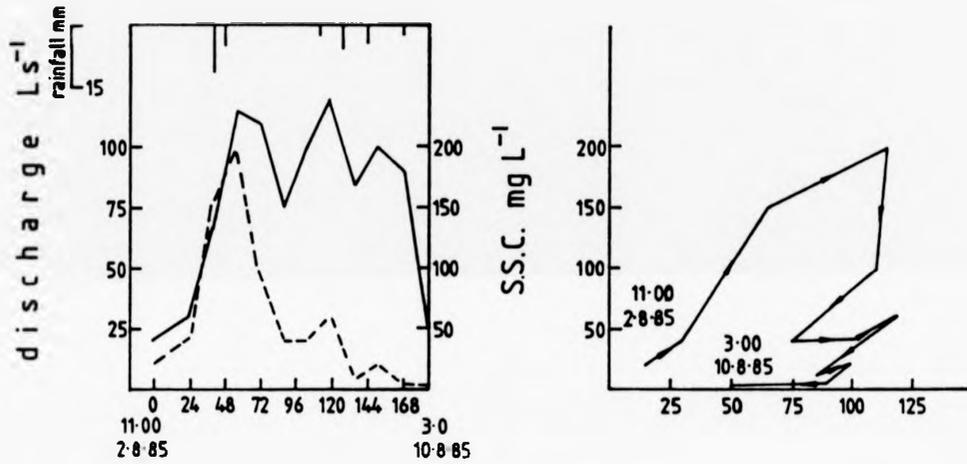
FIGURE 6.4.3.7   Multiple rise with no sediment response
in the third rise
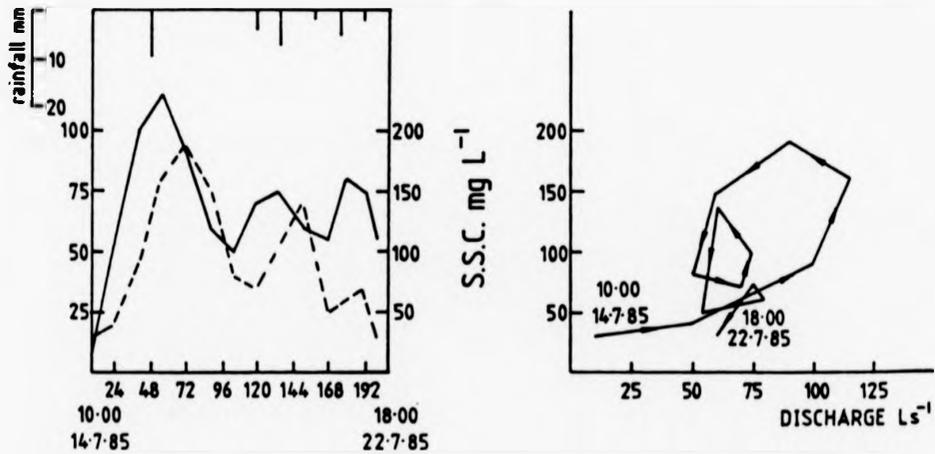
FIGURE 6.4.3.8   Multiple rise with sediment lag

7. Random response

The final type of response is an apparently random one, where
there is no identifiable pattern to the response of sediment during
a storm event.   This is by far the most common response pattern
observed, with more than 10 examples out of the total sample of
45 hydrographs.   It was observed in the catchment and involved
the entire range of storm events from the smallest to the largest
with a range of rainfall intensities and antecedent moisture con-
ditions.   The example shown is in Fig. 6.4.3.10.

Discussion

In this study more emphasis has been placed on analysis of indivi-
dual storm events leading to the development of the hysteresis loop
(Fig. 6.4.3.3).   The data have been presented both in the form of
hydrographs and hysteresis loops.   The hysteresis loop is regarded
here as merely a method of presenting the data which simply shows the
sequential relationship between discharge and sediment concentration
through time.   It must be stressed that in most cases no simple smooth
hysteresis curve is found if the raw data are plotted.   Some form of
smoothing function is required to produce a loop from the often complex
response of discharge and sediment concentration.   Care must be taken
in using smoothing functions in the search for a hysteresis effect so
that the original relationships are not completely obliterated, leading
to a meaningless result.   Perhaps the hydrograph is still the most
accurate method of illustrating the behaviour of discharge and sediment
concentration during storm events, although hysteresis loops are a use-
ful tool in highlighting more general trends.

In this study the most striking result is the complexity of sedi-
ment behaviour during storms, up to four different types of response
occurring in the catchment over the two year period.

There is no simple relationship between suspended sediment concen-
tration and discharge, and any relationship which might exist is variable
through time and space.   The behaviour of sediment is not solely depen-
dent on discharge, but is related to other factors.   As concentrations
are relatively low, there is considerable energy available for the
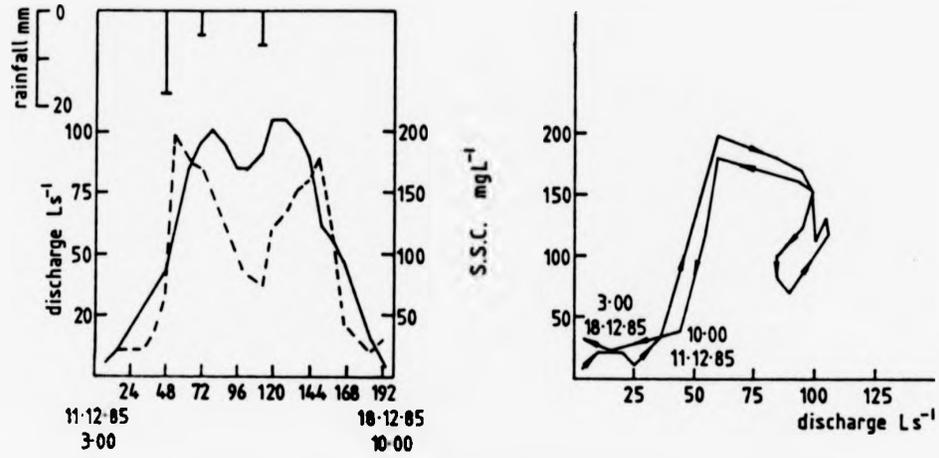
FIGURE 6.4.3.9   Multiple rise with sediment lead and lag
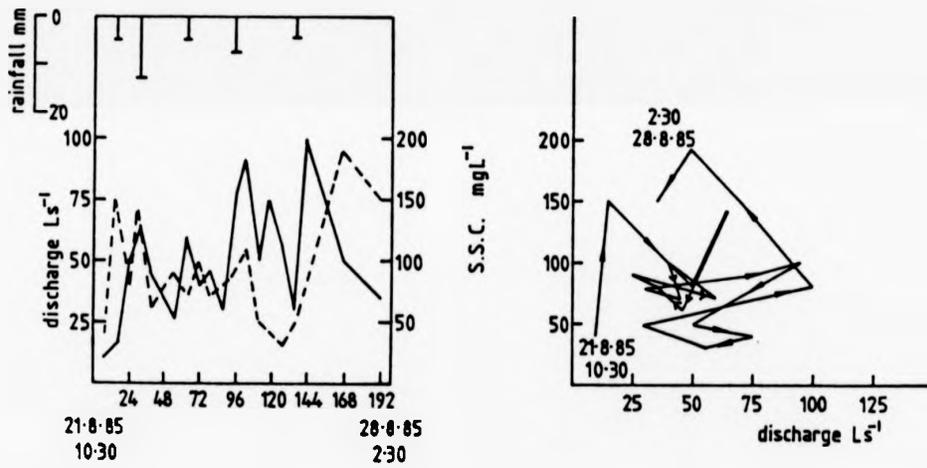
FIGURE 6.4.3.10   Random response

transport of suspended sediment and the limiting factor appears to be the availability of material of suspended size which can be detached from the surface or elsewhere. In the catchment area the soils have an abundance of clay-sized material which dominates the suspended load, but it is often not freely available for transport by tributary streams. The availability of fines is controlled by some release mechanism and certainly in this study it appears that the clay material is much more difficult to entrain while wet. The availability of free sediment during a particular storm is considerably increased if antecedent moisture conditions are dry.

Despite the complexity of response, a number of general conclusions can be drawn. In the catchment during the study period, there was a threshold storm size below which there was virtually no sediment response. This threshold was not constant for a particular time and was probably related to a combination of rainfall intensity, antecedent soil moisture levels, and total rainfall. In storms where a sediment response occurred, random responses were by far the most common, involving all sites and a wide range of storm magnitudes and types. In this type of response, discharge is not a limiting control of sediment concentration. The single rise events were generally produced by single simple storms. Sediment lags (Type 3) were generally associated with small storms with low rainfall intensities. Type 2, where sediment concentration and discharge correspond, was associated with larger events. The traditional model of sediment lead giving a clockwise hysteresis (Type 1) was the most common single rise type and covered a range of storm size, intensity and antecedent moisture conditions. The catchment exhibited two of the different single rise sediment responses. Generalisations are made difficult, however, because of the small number of single rise responses sampled, particularly Types 2 and 3.

The multiple-rise responses were all associated with the larger storm events and all exhibited sediment lead or lag or a combination of both. The important characteristic in events of this type is the sediment depletion which commonly occurs with each subsequent stream rise. The initial stream peak results in high sediment concentrations, while the concentration rise was progressively lower with each subsequent stream rise (Fig. 6.4.3.6). This is despite the fact that

in most cases the catchment was relatively dry when the storm commenced; and as the storm progressed and the catchment became wet it might be expected that a greater proportion of the catchment was contributing surface runoff and so the potential source area of sediment was increased. Clearly the supply of available suspendable material is finite and the availability diminishes as the storm progresses, despite the increase in potential source area.

A graphic illustration occurred during a storm when the catchment had undergone selective logging during October and November 1985. With this disturbance the availability of sediment was high, with large amounts of disturbed soil material. While sediment concentrations were much higher than normal, the response still showed sediment depletion with virtually no response in the third major stream rise, despite the apparent abundance of available sediment (Fig. 6.4.3.7).

It appears that in the catchment some mechanism operates to make difficult the entrainment of suspendable sediment as the storm progresses and the soil becomes wet. The response is repeated if a period of more than about 2-3 weeks elapses between storm events, possibly indicating that it is not weathering which is the controlling factor. There does not appear to be any seasonal pattern in the occurrence of this sediment depletion response as it has been observed throughout the study period, in particular since October 1984 to April 1986.

The relationship between sediment concentration and stream discharge is not exact for two reasons:

Firstly, the peak sediment concentration occurs several hours before the peak discharge, so that for a short time, between the passing of the two peaks, there is an inverse relationship between the two parameters.

Secondly, and more important, low flows in summer carry more sediment than similar low flows in winter, while moderate and high flows carry less sediment.

These seasonal relationships are the result of the variable amounts of leaves, debris and biota transported by the low summer flows, and the

occurrence of the high winter flows at a time when more sediment is available for transportation.

Conclusion

With the recognition of the dominance of storm events in the transport of suspended sediment, it is essential that attempts are made to obtain detailed data for all storm events in any study of sediment transport. In the Coombs Brook catchment, the great variability in the type of sediment response, both spatially and temporally, indicates that there is no simple constant relationship between discharge and suspended sediment concentration such as is suggested in the traditional use of sediment rating curves. In the catchment, sediment concentration also appears to be related to the availability of suspendable material which becomes much more difficult to entrain when wet. There is a requirement for an integrated examination of not only discharge and suspended sediment concentration, but also the entrainment mechanism and the possible variable source areas of sediment during storm events related to changing areas of surface runoff and bank erosion.

The hysteresis loops, on suspended sediment response curves, for Station 1 on Coombs Brook correspond to many of the types described by Gregory and Walling (1973), Burt et al. (1983), Van Sickle and Beschta (1983), Wood (1977), and Olive and Rieger (1984). Olive and Rieger's classification (1984), based on small forest catchments in south-east New South Wales, is the most appropriate for the Macclesfield Forest area.

CHAPTER   SEVEN

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CHAPTER SEVEN

FACTORS AFFECTING STREAM WATER CHEMISTRY

This chapter demonstrates the way in which the natural or back-
ground water quality of the catchment is regulated by a large number of
processes and catchment characteristics.   The water quality intimately
reflects the overall structure and operation of the catchment ecosystem.

7.1 PRECIPITATION CHEMISTRY

7.1.1 Introduction

Precipitation chemistry, as measured in this study, reflects both
wet and dry fallout as atmospheric inputs to the catchment, the two
forms of accession of ions to the ecosystem being expressed as bulk
precipitation.   The major chemical constituents of rainfall are Na^+,
K^+, Ca^{2+}, Mg^{2+}, Cl^- and SO_4^{2-} ions, together with a variety of nitrog-
enous compounds.   The concept that rainwater has an average composi-
tion is misleading, in that concentration can vary markedly in time
and space.   Concentrations in rain in south-eastern Australia and
northern Europe range from 0 to 83 mg 1^{-1} Na^+, 0-11 mg 1^{-1} K^+, 0-25
mg 1^{-1} Ca^{2+}, 0-28 mg 1^{-1} Mg^{2+}, 0-139 mg 1^{-1} Cl^-, 0-6.5 mg 1^{-1} SO_4^{2-},
and pH 3.9 - 7.7 (Carroll, 1962).

Bulk precipitation was sampled weekly for two years at two sites
(Fig. 3.2.1), with specific conductivity, pH, and Ca^{2+}, Mg^{2+}, Na^+, K^+,
SO_4^{2-}, PO_4^{3-}, NO_3^-, and Cl^- concentrations being determined for each sample
(Table 7.1.1.1(a) and (b) and Fig. 7.1.1.1(a) and (b)).

Precipitation quality varies greatly from week to week, concentra-
tions occasionally being five times the mean value for a particular
parameter.   Seasonal variations in chemical composition and concentra-
tion reflect the influence of source areas, such as sea spray, heavy
metals from industrial pollution, and soil dust.   Variation in wind

TABLE 7.1.1.1   SUMMARY STATISTICS FOR THE BULK PRECIPITATION QUALITY DATA

(a) - Site 1

	pH	Con $K/\mu s\ cm^{-1}$	Ca^{2+}	Mg^{2+}	Na^+	K^+	SO_4^{2-}	PO_3^{4-}	Cl^-	NO_3^-
Mean	5.3	22.3	0.88	0.29	1.6	1.01	3.38	0.40	2.01	2.24
Median	5.3	20.3	0.50	0.20	1.2	0.74	3.30	0.30	2.0	2.10
Standard deviation	0.139	17.7	1.32	0.418	2.83	1.42	3.40	0.12	0.24	1.52
Maximum	5.7	45.7	7.70	2.20	9.10	8.24	15.5	0.5	7.9	8.20
Minimum	4.9	12.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

(b) - Site 2

	pH	Con	Ca^{2+}	Mg^{2+}	Na^+	K^+	SO_4^{2-}	PO_3^{4-}	Cl^-	NO_3^-
Mean	5.28	22.0	0.87	0.28	1.54	1.04	3.1	0.40	2.0	2.20
Median	5.20	20.0	0.70	0.20	1.00	0.63	3.0	0.30	1.9	2.00
Standard deviation	0.155	8.3	0.484	0.176	1.78	1.50	3.4	0.13	0.24	1.70
Maximum	5.40	49.7	2.00	0.600	8.90	7.16	14.9	0.79	7.80	9.40
Minimum	4.8	12.04	0.20	0.0	0.20	0.0	0.0	0.0	0.0	0.0

t-tests reveal no significant differences between the means of each element for Station 1 and Station 2.
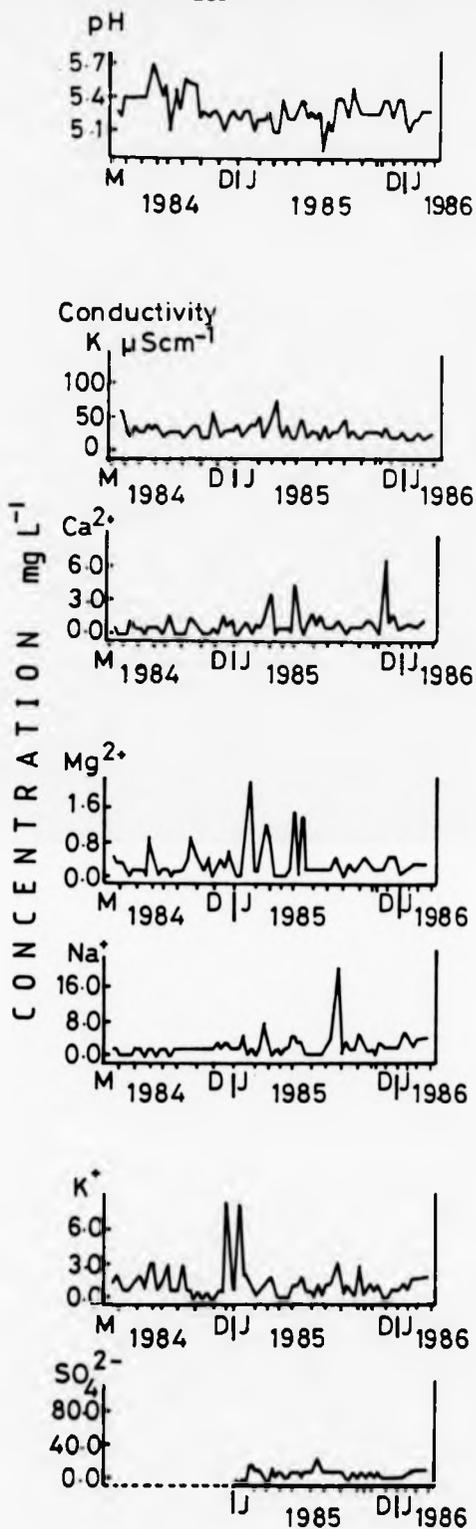
FIGURE 7.1.1.1 (A)

The variation in the actual levels of the seven species for the bulk precipitation samples - rain gauge 1.
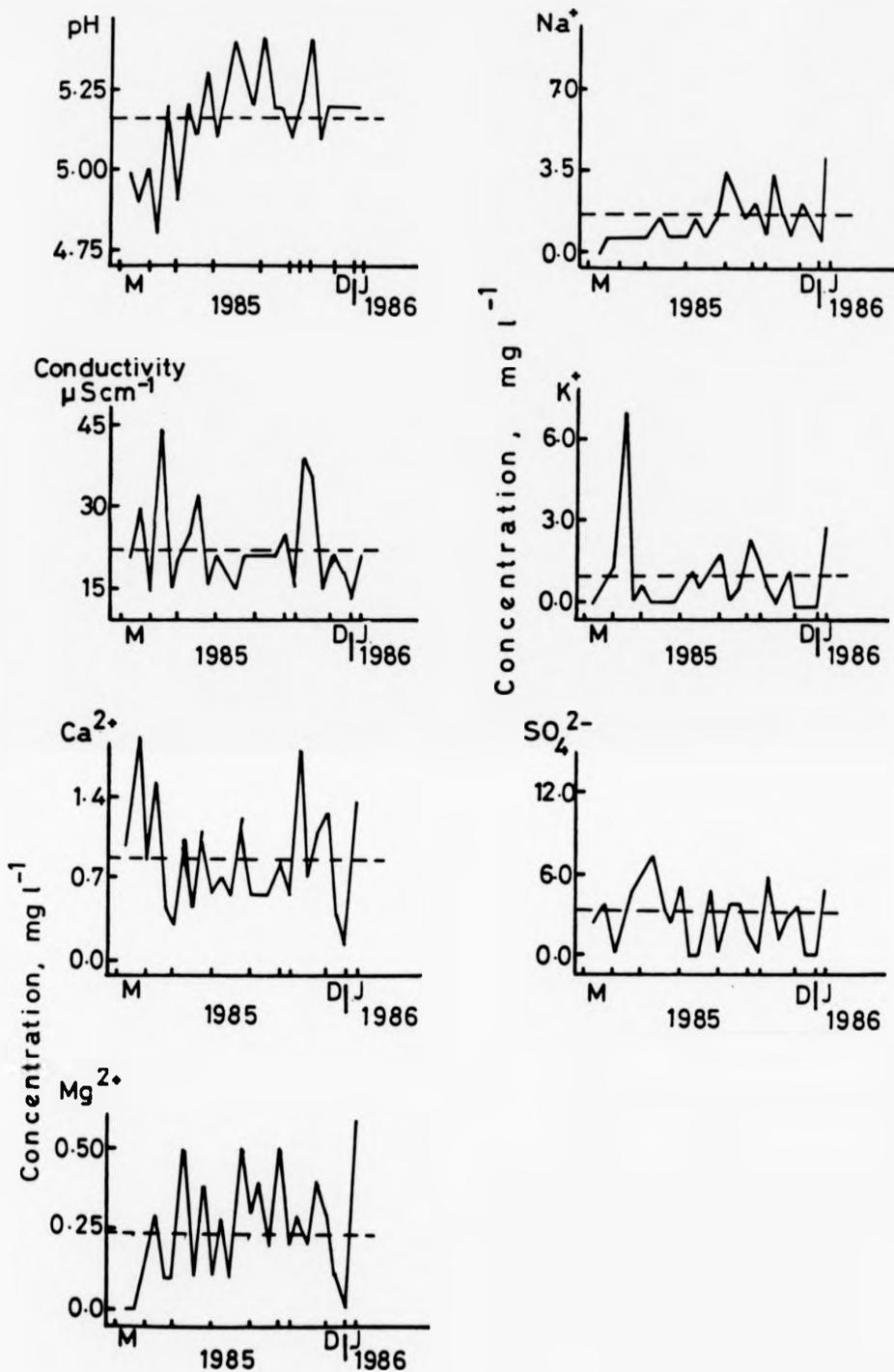
FIGURE 7.1.1.1 (B)

The variation in the actual levels of the seven species for the bulk precipitation samples - rain gauge 2.

direction causes changes in the source of major ions, affecting the salts in precipitation.

In terms of a small catchment area, it is difficult to distinguish the origin of solutes in bulk precipitation. Undoubtedly, most of the chemicals in precipitation will be derived from outside the study area, particularly the solutes in rain. However, some of the dust particles in dry fallout may have originated within the 800 ha catchment. Concentration at the two precipitation sampling sites did not differ significantly. Both wet and dry fallout is homogeneously distributed throughout the catchment area being supplied from extensive permanent sources such as the sea (Table 7.1.1.1(a) and (b)). In subsequent discussion, the data from the two stations can be combined to represent the nature of precipitation chemistry throughout the catchment.

7.1.2 Results and Discussion

Generally, the solute content of precipitation varies within narrow limits but with occasional concentrations of up to five times the mean value (Fig. 7.1.1.1(a) and (b)). The variability would be more pronounced if individual rainfall events were sampled rather than being contained in a weekly bulk sample. Acidity tends to be higher from December to May. A longer period of sampling is necessary to establish if there is any recurrent seasonal pattern in the major constituents of precipitation.

From Fig. 7.1.1.1(a) and (b) it may be suggested that any seasonal variation in Mg^{2+}, Na^+ and Cl^- at the catchment is swamped out by a heavy and continuous influx of these elements at all seasons from the sea. This would further imply a different source for Ca^{2+} and K^+, which are usually assumed to be mainly of terrestrial origin in the British Isles.

7.1.2.1 Temporal variability

The seasonal pattern of bulk precipitation chemistry was further examined by plotting periodic, average concentrations of cations at both Sites 1 and 2 (Fig. 7.1.1.1(a) and (b)).

The data are for four-week periods (over two years for Site 1 and one year for Site 2). Although the data appear to be slightly variable, trends in concentrations were observed at both sites.

Concentrations of Mg^{2+} and K^+ were generally highest during December-February and lowest during March-June; while Ca^{2+} concentrations were generally highest during February-June and lowest during July-October. A second peak concentration also occurred for some of these cations during autumn. At both sites, Na^+ concentration was more variable and did not show a consistent year-to-year pattern. High Na^+ concentrations frequently occurred during winter (November-March), but also occurred at other times of the year. Gambell and Fisher (1966) reported similar seasonal patterns of Ca^{2+} concentrations in eastern North Carolina and south-eastern Virginia, but found higher K^+ concentrations during the summer and highest Mg^{2+} concentrations during late autumn and early spring. The concentrations at both sites were moderately variable. The slight variability appears to be due to either the relative influence of dry fallout or contamination (Table 7.1.1.1). The influence is especially evident during periods which receive little precipitation (May, July and September 1985), an observation similar to that of Gambell and Fisher (1966).

Investigators of the factors influencing ions in precipitation chemistry emphasise the need to examine carefully the contributions of dry fallout to stream water chemistry in forested ecosystems, because some elements in dry fallout may give rise to higher concentrations than rainfall inputs through a variety of chemical reactions. Also, most of the dry fallout deposited in collectors is probably caused by the process of gravitational settling and represents only one mechanism for deposition of materials on surfaces. Since the ratio of forest vegetation surface to ground surface ranges between 5 and 20 to 1, aerosol impaction on vegetation could account for large inputs (Eriksson, 1955).

7.1.2.2 Magnitude of chemical components

The chemistry of bulk precipitation at two sites in the Coombs Brook showed that the relative contributions of cations were similar, with $Na^+ > K^+ > Ca^{2+} > Mg^{2+}$, while anions measured at both sites were ranked $SO_4^{-2} > NO_3^- > Cl^- > PO_4^{3-}$ (Table 7.1.2.2).   Seasonal data on bulk precipitation concentrations suggest that non-marine processes largely control the deposition of Ca^{2+}, Mg^{2+} and K^+, while Na^+ is primarily of marine origin in this region of England.

No significant variation between gauges was found.   The variation in the amount of precipitation between Sites 1 and 2 does not exceed 50 mm per year.   This indicates that the composition of precipitation varies little across the catchment, and that it is determined by the air mass producing precipitation rather than by local variations in topography.   Our results show the importance of quantifying the contributions of dry fallout to the chemical loads in forest ecosystems and suggest the need to examine the magnitude and chemical composition of aerosol impaction on vegetation surfaces.

7.1.3 The Sources of Cations and Anions in Precipitation

Cations and anions in precipitation originate from a variety of sources, including oceanic spray, terrestrial dust, gaseous pollutants (Chapter 1).

Some elements are associated with the acidity of rain, such as NO_3^-, SO_4^{2-}, and the negative loading of pH.   Their main sources in precipitation in the Macclesfield Forest are the oxidation of gaseous oxides of S^{2-} and N_2 released by industrial processes (from Manchester and Sheffield) and the burning of fossil fuels, especially motor vehicle exhaust emissions (Douglas, 1972).   This factor is thought to reflect the influence of industrial pollution and the burning of fossil fuels, and is responsible for acidity of the precipitation. Investigations of the pH of precipitation at Glendye (Reid et al., 1980) and Hubbard Brook (Likens et al., 1977) and Norway (Snekvik et al., 1973) found that it was more related to NO_3^- than SO_4^{2-} concen-

tration, and it may be significant that SO_4^{2-} concentrations in the catchment area are higher than those of NO_3^- (Table 7.1.1.1(a) and (b) and Table 7.1.2.2), and concentrations of both of them exceed those of other species.

The relative importance and sources of solutes in precipitation may be expressed in terms of three factors:

$$SO_4^{2-} > NO_3^- > Cl^- > Na^+ > K^+ > Ca^{2+} > Mg^{2+} > PO_4^{3-}$$

Factor (1)	Factor (2)	Factor (3)
(Industrial	(Oceanic spray)	(Terrestrial
pollutants)		dust)

Factor 3, which is dominated by Ca^{2+} and K^+ as a major and SO_4^{2-} as a minor (Table 1.3.1), is thought to reflect the influence of terrestrial dust, which is known to be a major source of these species in precipitation.   However, atmospheric H_2SO_4 attacks airborne particles of silicate minerals to release soluble cations such as Ca^{2+} and K^+ (Reid, 1979).

The previous discussion suggests that three main factors influence the composition of precipitation in Macclesfield Forest, which are, in significant order: industrial pollution, oceanic spray, and terrestrial dust.   Firstly, the dominant influence of industrial pollutants is to be expected, as Macclesfield Forest is surrounded by industrial areas on all sides.   Secondly, the importance of oceanic spray is to be expected, as Macclesfield Forest is situated about 80 km from the coast.   The operation of these factors is supported by the ionic ratios of the precipitation.   The Na^+/Cl^- and Na^+/Mg^{2+} ratios are close to those of sea water (Table 7.1.3.1) and indicate a maritime source for these ions.   The Na^+/Ca^{2+} and Na^+/K^+ and Cl^-/SO_4^{2-} ratios are, however, much lower in precipitation and are highly variable: Ca^{2+}, K^+, and SO_4^{2-} would thus appear to be derived from other sources (Table 1.3.1).   Concentrations of Fe, Mn and PO_4^{3-} are low, and are probably derived from terrestrial dust.   Thus, the above discussion suggests the operation of three main factors on the chemistry of precipitation, similar to those discussed by Sugawara (1967), Reid et al.

TABLE 7.1.2.2   ANNUAL ACCESSION OF CHEMICAL ELEMENTS TO THE GROUND FROM PRECIPITATION

Site 1 Water/year	Annual precipitation (mm)	Ca^{2+}	Mg^{2+}	Na^+	K^+	SO_4^{2-}	PO_3^{4-}	Cl^-	NO_3^-
				Kilograms per hectare per year					
1984-1985	870.1	7.65	2.52	12.18	8.78	29.4	3.48	17.4	19.49
1985-1986	1038.2	9.13	3.01	14.53	10.48	35.1	4.15	20.8	23.25
Study period	1908.3	16.78	5.53	26.71	19.26	64.5	7.63	38.2	42.74
Site 2									
1984-1985	920.1	8.09	2.66	12.88	9.29	31.09	3.68	18.49	20.61
1985-1986	1088.2	9.57	3.15	15.23	10.99	36.78	4.35	21.87	24.37
Study period	2008.3	17.66	5.81	28.11	20.28	67.87	8.03	40.36	44.98
Site 2 - Site 1	100+	0.88+	0.28+	1.4+	1.02+	3.37+	0.4+	2.16+	2.24+

TABLE 7.1.3.1 COMPARISON OF THE RATIOS OF CONCENTRATIONS (meq) OF IONS
IN SEA WATER WITH THOSE IN PRECIPITATION AT MACCLESFIELD
FOREST FOR THE 24-MONTH PERIOD FROM MAY 1984 – APRIL 1986

Ratio	Precipitation (study area) meq	Sea water (based on data in Krauskopf (1967) meq
Na^+/Cl^-	1.23	0.880
Na^+/Mg^{2+}	29.2	4.415
Na^+/Ca^{2+}	1.5	22.78
Na^+/K^+	2.69	48.19
Cl^-/SO_4^{2-}	0.805	9.37
Ca^{2+}/SO_4^{2-}	0.624	0.361

(1980) and Reid (1979).

The pH of precipitation appears to be associated with emissions of gaseous nitrogen and sulphur oxides by industrial processes. It showed little variation during the study year, averaging 5.3 (Table 7.1.1.1), and is similar to the values found at Hubbard Brook (Likens et al., 1977) and East Anglia (Edwards, 1971).

The phosphorus concentration in precipitation does not exceed 1.0 mgl^{-1}, and showed little variation during the year. The phosphorus content of precipitation is generally very low (Gore, 1968).

As can be seen from Table 7.1.3.2, the concentrations of NO_3^- are higher in precipitation at Coombs Brook than at some Scottish stations: NO_3^- originates mainly from industrial pollution. Likens et al. (1977) have shown a steady increase in the NO_3^- concentration of precipitation from 1963 to 1974 at Hubbard Brook, and a similar trend could be occurring in Britain. The analyses of precipitation in Britain quoted here (Stevenson, 1968) were made in the early 1960s, and the nature of pollution may have changed significantly since then.

However, Fe and Mn was determined on most samples. All were present at $0-0.001$ mg 1^{-1} for Fe, $0.0-0.03$ mg 1^{-1} for Mn. No systematic variation during the year could be detected. Similar concentrations have been reported from other areas: Snekvik et al. (1973) found an average Fe concentration of 0.056 mg 1^{-1} in Norwegian precipitation; Likens et al. (1977) found only trace amounts of Fe and Mn at Hubbard Brook; and Rutherford (1967) found average concentrations of 0.69 mg 1^{-1} in rain and 0.89 mg 1^{-1} in snow for Fe in southeast Ontario.

The analysis of these metals determines the total amount of these elements which have passed through the 0.22 μm filter paper, so they are probably present as fine-grained, colloidal oxides and hydroxides. Their main source in Coombs Brook is probably soil-derived atmospheric dust, but there may also be some contribution from industrial processes (Chapter 1).

TABLE 7.1.3.2   MEDIAN CONCENTRATIONS OF CHEMICAL SPECIES IN PRECIPITATION ($mg\ 1^{-1}$) AT

MACCLESFIELD FOREST COMPARED WITH NORTH BRITISH (SCOTTISH) STATIONS[*]

Species	Coombs Brook precipitation 1984-1986	Glendye precipitation 1977-1978	Stornoway precipitation 1959-1964	Aberdeen precipitation 1959-1964	Aberdeen Air 1959-1964 $\mu g\ m^{-3}$
SO_4^{2-}	1.15	1.5	2.4	2.1	20 (Jan.) 7 (July)
Cl^-	2.01	2.4	28.0	5.7	6.0
NO_3^-	2.24	1.0	0.2	0.3	n.d.
NH_4^+	n.d.	0.03	0.2	0.3	2.6
Na^+	1.6	1.25	17.0	4.6	3.1
K^+	1.01	0.12	0.9	0.4	1.4
Mg^{2+}	0.29	0.18	1.9	0.6	0.8
Ca^{2+}	0.88	0.45	1.1	1.1	1.4

[*]Sources: Scottish data (1959-64) - after Stevenson, 1968

Glendye data (1977-78) - after Reid, 1979

Summary

Precipitation in Coombs Brook is very dilute, with an average total dissolved solids content of approximately 15.0 mg 1^{-1}. It is controlled by three major influences:

(1) Industrial pollution. This is the major source of SO_4^{2-} and NO_3^-, through emissions of gaseous nitrogen and sulphur oxides. This factor controls the pH of precipitation. It is more important overall than oceanic spray and shows less marked seasonal variation (Fig. 7.1.1.1(a) and (b)).

(2) Oceanic spray. This is thought to account for the Na^+, Mg^{2+} and Cl^-. It shows seasonal variation, being dominant in early winter and of much less importance in the summer (Fig. 7.1.1.1(a) and (b)).

(3) Terrestrial dust. This is considered to be the major source of Ca^{2+}, K^+, Fe, Mn, and PO_4^{3-}. It is slightly less important than industrial pollution, but shows a different trend (Fig. 7.1.1.1(a) and (b)).

7.2 THROUGHFALL AND STEMFLOW

7.2.1 Introduction

The chemical composition of the water that reaches the forest floor differs greatly from that of the incident precipitation (Table 7.2.1.1). Only about 5% of the incident precipitation actually reaches the ground of the forest ecosystem directly without contact with trees. The remainder passes through the forest canopy as throughfall and stemflow which remove nutrients from the canopy, adding them to the forest floor and stream channel. In this process, throughfall and stemflow are greatly enriched in Ca^{2+} (about 10 times), Mg^{2+} (five times), Na^+ (three times), K^+ (five times), SO_4^{2-} (seven times), NO_3^- (four times), and Cl^- (eight times) (Table 7.2.1.2). Hydrogen ion concentration also increases as the rain passes through the canopy in the coniferous trees.

There are various sources for the dissolved substances in throughfall and stemflow, but their relative importance is not entirely clear (Eaton et al. 1973): (1) Some nutrients are contained in the incident precipitation; (2) Some of the nutrients may have been impacted aerosols that are washed off by the incident precipitation. These two portions should be considered as a part of the chemical flux from outside the ecosystem. Similarly, (3) nutrients with a normal gaseous phase, which were incorporated directly on or into the plant and then removed from tissues by incident precipitation, should be considered as meteorologic inputs. The remaining nutrients in throughfall and stemflow, which have been leached from the vegetation tissues or associated microflora, are part of the ecosystem's internal nutrient cycle and should not be considered as part of the meteorologic flux. As a result of these processes, there are temporal variations in the chemical species during the study period (Table 7.2.1.3 and Fig. 7.2.1.1). Some specific data are presented later in this section.

7.2.2 Seasonal Changes in Chemical Components of Throughfall

The mean monthly concentration of Ca^{2+} and Mg^{2+} in the throughfall remained rather constant during June, July and August (Tables

TABLE 7.2.1.1　　SUMMARY OF STATISTICS FOR THE THROUGHFALL DATA* (1984-1986)

	pH	Conductivity	Ca^{2+}	Mg^{2+}	Na^+	K^+	SO_4^{2-}	NO_3^-	Cl^-
Mean	3.97	264	9.2	1.48	4.85	5.77	24.4	8.68	15.7
Median	3.85	146	4.3	1.0	3.40	3.30	20.2	6.95	13.2
Standard deviation	0.837	305	11.0	1.43	5.14	5.14	32.6	4.81	6.7
Maximum	6.5	1545	58.0	6.70	31.1	21.2	99.0	22.8	36.0
Minimum	2.5	44	1.0	0.30	0.30	0.70	5.6	2.4	6.8

*Values are in mg 1^{-1}

TABLE 7.2.1.2   AVERAGE CHEMICAL COMPOSITION OF INCIDENT PRECIPITATION
AND THROUGHFALL UNDER DIFFERENT TYPES OF TREES
DURING 1984-1986*

Material	Precipitation above canopy	Precipitation under canopy (throughfall and stemflow)	Net increase in concentration
Ca^{2+}	0.88	9.2	+ 8.3
Mg^{2+}	0.29	1.48	+ 1.19
Na^+	1.6	4.85	+ 3.25
K^+	1.01	5.77	+ 4.76
SO_4^{2-}	3.38	24.4	+21.0
NO_3^-	2.24	8.68	+ 6.44
Cl^-	2.01	15.7	+13.69
pH	5.3	3.97	1.33 pH units

*Values are in mg l^{-1}

TABLE 7.2.1.3   AVERAGE MONTHLY pH AND CONDUCTIVITY LEVELS AND CONCENTRATIONS OF MAJOR SOLUTES (in mg 1^{-1}) IN THROUGHFALL IN THE COOMBS BROOK CATCHMENT

Month & Year	pH	Conductivity $\mu s\ cm^{-1}$	Ca^{2+}	Mg^{2+}	Na^+	K^+	SO_4^{2-}	PO_4^{3-}	NO_3^-	Cl^-
Oct. 1984	4.7	143.5	3.4	0.74	3.3	8.4	-	0.20	-	-
Nov. 1984	3.6	203.7	6.6	1.1	3.2	7.6	-	0.17	-	-
Dec. 1984	3.9	200.1	10.1	1.7	5.0	4.6	22.0	0.39	8.7	12.4
Jan. 1985	3.1	320.0	28.3	2.7	6.3	7.3	95.0	0.08	15.5	48.8
April 1985	3.5	470.8	17.6	1.8	6.8	1.9	59.3	0.08	10.1	15.6
May 1985	3.5	232.0	11.0	1.0	2.4	1.3	20.0	0.01	11.5	9.0
June 1985	3.5	276.7	3.6	0.97	1.3	1.23	27.3	0.1	7.8	13.6
July 1985	3.9	455.8	3.5	0.8	6.7	2.8	72.5	0.52	4.0	14.3
Aug. 1985	4.0	188.9	4.4	0.79	3.2	2.0	26.2	0.46	9.2	15.3
Sept. 1985	4.0	139.2	3.5	4.2	4.4	9.2	18.2	0.25	4.4	24.0
Oct. 1985	4.7	198.5	6.3	1.5	5.9	8.7	41.1	0.59	5.36	20.0

-250-
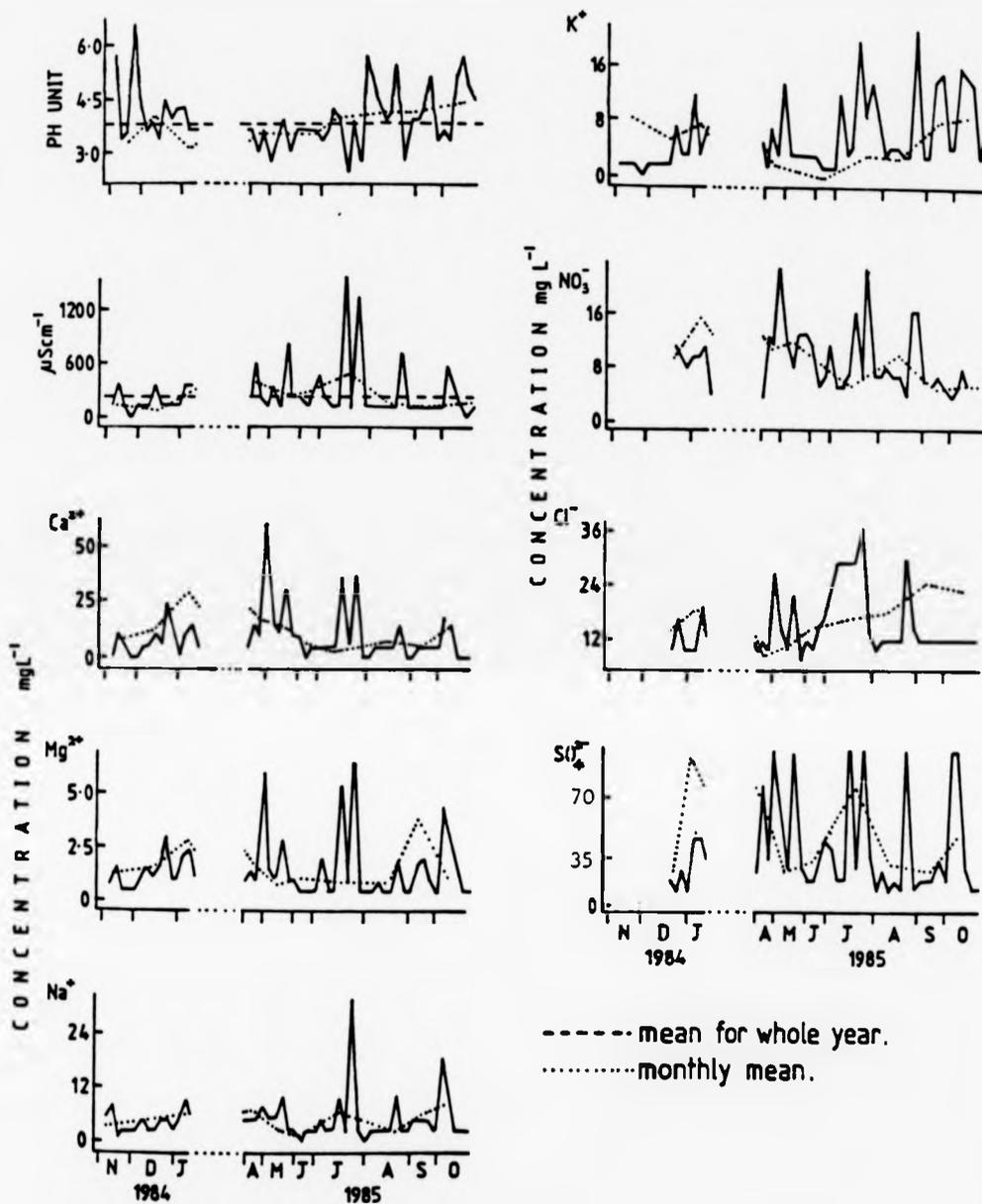
FIGURE 7.2.1.1

Seasonal changes in chemical components of throughfall (November 1984 - October 1985)

7.2.2.1 and 7.2.2.2). However, Ca^{2+} and Mg^{2+} concentrations reach their summer maxima in September, just prior to leaf senescence. The concentrations of these two elements then declined somewhat following senescence and during leaf-fall. The concentrations of the other elements were variable during the summer; however, like Ca^{2+} and Mg^{2+}, they reached maxima during September and then declined following senescence (Table 7.2.2.3).

The levels of PO_4^{3-} did not change much (possibly declined somewhat) during the entire summer, but also declined following senescence. Conversely, K^+ and Cl^- remained at relatively low levels during the early summer, increasing in the autumn to maxima following senescence. Therefore, maximum leaching of K^+ occurred after leaf abscission. The difference in behaviour of Ca^{2+}, Mg^{2+}, NO_3^-, SO_4^{2-} and Na^+ compared with that of K^+ and Cl^- appears to result from different locations of the various components in the leaves. A sharper decrease would be expected in the concentration of elements associated with organic molecules, particularly Ca^{2+}, in the throughfall following senescence or when the supply of these elements to the leaves has been cut off. However, the more leachable elements such as K^+ might be expected to continue at a high level following senescence, or even be exaggerated due to the deterioration of the leaf cuticle (Fig. 7.2.1.1).

The ageing of leaves, whether due to physical damage or to physiological changes in the leaves, is probably the dominant factor in the increase of K^+ concentration in throughfall during the growing season. Ageing may also be the most significant factor in the increased loss of Ca^{2+} and Mg^{2+}. Increased evapotranspiration is a function of higher temperatures and normally becomes more important as the growing season progresses. Because of this, salts are lost more rapidly from leaves at high temperatures than at low (Fig. 7.2.2.2).

The total supply of the various elements within the forest canopy varies throughout the summer. The degree to which elements are removed from the crowns of trees also varies to some extent between species. The deciduous trees lose more nutrients than conifers during the summer months, but conifers continue to lose nutrients throughout the winter months.

TABLE 7.2.2.1 AVERAGE OF CHEMICAL CONCENTRATION ($mg\ l^{-1}$) IN PRECIPITATION AND THROUGHFALL UNDER DIFFERENT TYPES OF TREES, AND NET AMOUNT OF ELEMENT REMOVED FROM EACH SPECIES ($mg\ l^{-1}$)

(1) Chemical composition:

	Precipitation	Hard Buckler Fern	Coniferous tree - Sitka spruce	Deciduous tree - Common Alder	Common Hawthorn	Shrub Guelder Rose	Lesser Found Sedge	Pinus sylvestris
pH	5.3	3.5	3.3	4.2	4.0	6.1	6.2	4.2
Conductivity	22.3	369.0	624.6	100.5	115.0	272.7	75.3	176.4
Ca^{2+}	0.88	9.5	16.4	3.85	13.5	13.9	2.93	5.23
Mg^{2+}	0.29	4.1	4.2	1.08	1.6	4.9	0.99	1.11
Na^+	1.4	13.1	22.7	2.8	4.5	8.4	2.47	6.0
K^+	1.01	13.4	9.6	2.7	13.5	24.0	5.7	2.96
SO_4^{2-}	3.38	56.5	103.5	12.9	17.6	44.4	10.7	31.6
PO_4^{3-}	0.40	0.305	1.67	0.28	1.14	0.18	0.67	0.14
NO_3^-	2.24	6.38	11.6	19.4	11.6	10.3	2.9	7.2
Cl^-	2.01	11.9	37.2	11.0	10.2	14.0	9.0	11.2
S^{2-}	1.1	18.6	34.1	4.2	5.8	14.6	3.5	10.4

(2) Net removal of element:

		Hard Buckler Fern	Coniferous tree - Sitka spruce	Deciduous tree - Common Alder	Common Hawthorn	Shrub Guelder Rose	Lesser Found Sedge	Pinus sylvestris
Conductivity		334	589	65	80	237	41	141
Ca^{2+}		8.6	15.5	3.0	12.6	13.0	2.1	4.3
Mg^{2+}		3.7	3.8	0.75	1.27	4.57	0.66	0.78
Na^+		11.1	20.7	0.77	2.47	6.38	0.44	3.97
K^+		12.3	8.5	1.6	12.4	22.9	4.6	1.8
SO_4^{2-}		53.2	100.2	9.6	14.3	41.1	7.4	28.3
PO_4^{3-}		-0.58	0.78	-0.61	0.25	-0.71	-0.22	-0.75
NO_3^-		2.18	7.4	15.2	7.4	6.1	-1.3	3.0
Cl^-		5.3	30.6	4.4	3.6	7.4	2.4	4.6
S^{2-}		17.4	32.9	3.0	4.6	13.4	2.3	9.2

TABLE 7.2.2.2   <u>NET REMOVAL OF MATERIAL IN THE CATCHMENT</u>
<u>DURING THE STUDY PERIOD</u> $(kg\ ha^{-1}\ y^{-1})$

| Period | | Quantities supplied to the ground | | Removal from the canopy |
		Through-fall	Rain-fall	Net removal of material by the throughfall
1984-1985	H^+	0.931	0.043	0.888
1985-1986	H^+	1.11	0.051	1.05
1984-1985	Ca^{2+}	80.04	7.6	72.4
1985-1986	Ca^{2+}	95.5	9.13	86.3
1984-1985	Mg^{2+}	12.8	2.52	10.28
1985-1986	Mg^{2+}	15.3	3.01	12.29
1984-1985	Na^+	42.1	12.2	29.9
1985-1986	Na^+	50.3	14.53	35.77
1984-1985	K^+	50.2	8.78	41.4
1985-1986	K^+	59.9	10.5	49.4
1984-1985	SO_4^{2-}	299.3	29.4	269.9
1985-1986	SO_4^{2-}	357.1	35.1	322.0
1984-1985	NO_3^-	75.5	19.49	56.0
1985-1986	NO_3^-	90.1	23.25	66.9
1984-1985	Cl^-	136.6	17.4	119.2
1985-1986	Cl^-	162.9	20.8	142.1

TABLE 7.2.2.3   NUTRIENT CONTENT OF PRECIPITATION, THROUGHFALL AND STEMFLOW ALONG WITH NET LEACHING FOR THE FOREST CANOPY DURING THE PERIOD OCTOBER 1984 – OCTOBER 1985 (EXCEPT FEBRUARY AND MARCH 1985 – SNOW PERIOD)

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Period	Precipitation type	Kilogram per hectare									
		Ca^{2+}	Mg^{2+}	Na^+	K^+	SO_4^{2-}	PO_4^{3-}	NO_3^-	Cl^-	S^{2-}	H^+
Oct. 1984	Throughfall & stemflow	3.28	0.71	3.19	8.1		0.19				0.018
	Rainfall	0.8	0.425	1.64	0.937		-				0.004
	Net removal	2.48	0.285	1.55	7.16		-				0.014
Nov. 1984	Throughfall & stemflow	10.6	1.8	5.1	12.2		0.272				0.401
	Rainfall	0.192	0.048	2.24	0.48		-				0.009
	Net removal	10.4	1.75	2.86	11.7		-				0.392
Dec. 1984	Throughfall & stemflow	6.63	1.07	3.15	2.89	13.86	0.245	5.48	7.8	4.57	0.077
	Rainfall	0.44	0.20	1.01	1.26	5.04	0.044	3.59	2.14	1.66	0.004
	Net removal	6.18	0.87	2.14	1.63	8.82	0.201	1.89	5.66	2.91	0.073
Jan. 1985	Throughfall & stemflow	18.1	1.73	4.03	4.7	60.8	0.051	9.92	31.2	20.1	0.500
	Rainfall	0.48	0.46	1.15	1.47	5.76	0.064	4.9	2.3	1.92	0.004
	Net removal	17.6	1.27	2.88	3.23	55.0	-0.013	5.02	28.9	18.1	0.496

/Continued

TABLE 7.2.2.3 (Continued)

Period	Precipitation type	Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	SO$_4^{2-}$	PO$_4^{3-}$	NO$_3^{-}$	Cl^{-}	S^{2-}	H^{+}
					Kilogram per hectare						
April 1985	Throughfall & stemflow	19.3	1.98	7.48	2.09	64.9	0.088	11.1	17.2	21.4	0.349
	Rainfall	1.65	0.66	2.2	0.572	4.51	0.022	10.3	1.76	1.43	0.006
	Net removal	17.6	1.32	5.28	1.51	60.3	0.066	0.8	15.4	19.9	0.343
May 1985	Throughfall & stemflow	7.04	0.64	1.53	0.832	12.8	0.064	7.36	5.76	4.2	0.201
	Rainfall	0.51	0.236	0.96	0.50	5.5	0.128	4.8	2.04	1.79	0.003
	Net removal	6.53	0.404	0.57	0.332	7.3	-0.064	2.56	3.72	2.41	0.198
June 1985	Throughfall & stemflow	3.42	0.921	1.23	1.16	25.9	0.009	7.41	12.92	8.5	0.298
	Rainfall	0.67	0.133	0.579	0.75	13.2	0.779	5.6	7.79	4.3	0.006
	Net removal	2.75	0.788	0.651	0.41	12.7	-0.77	1.81	5.13	4.2	0.292
July 1985	Throughfall & stemflow	2.59	0.592	4.9	2.07	53.6	0.384	3.2	10.5	17.6	0.091
	Rainfall	0.43	0.148	6.6	1.18	5.03	1.92	2.59	10.5	1.6	0.004
	Net removal	2.16	0.444	-1.7	0.89	48.5	-1.53	0.61	0.0	16.0	0.087

/Continued

TABLE 7.2.2.3 (Continued)

Period	Precipitation type	Ca^{2+}	Mg^{2+}	Na^+	K^+	SO_4^{2-}	PO_4^{3-}	NO_3^-	Cl^-	S^{2-}	H^+
					Kilogram per hectare						
Aug. 1985	Throughfall & stemflow	4.1	0.734	2.90	1.86	24.3	0.427	8.5	14.2	8.0	0.692
	Rainfall	0.58	0.223	2.4	1.11	2.6	1.11	2.2	8.6	0.85	0.003
	Net removal	3.5	0.511	0.50	0.75	21.7	-0.683	6.3	5.6	7.15	0.089
Sept. 1985	Throughfall & stemflow	13.5	2.01	2.11	4.4	8.7	0.12	2.1	11.5	2.8	0.048
	Rainfall	0.34	0.158	0.864	0.206	2.54	0.17	2.16	3.12	0.81	0.002
	Net removal	13.16	1.85	1.24	4.19	6.16	-0.05	0.0	8.38	2.0	0.046
Oct. 1985	Throughfall & stemflow	4.5	1.09	4.3	6.35	30.0	0.430	3.9	14.6	9.9	0.013
	Rainfall	0.138	0.065	0.408	0.540	0.547	0.102	3.2	1.31	0.182	0.004
	Net removal	4.36	1.02	3.89	5.81	29.4	0.328	0.7	13.29	9.71	0.009
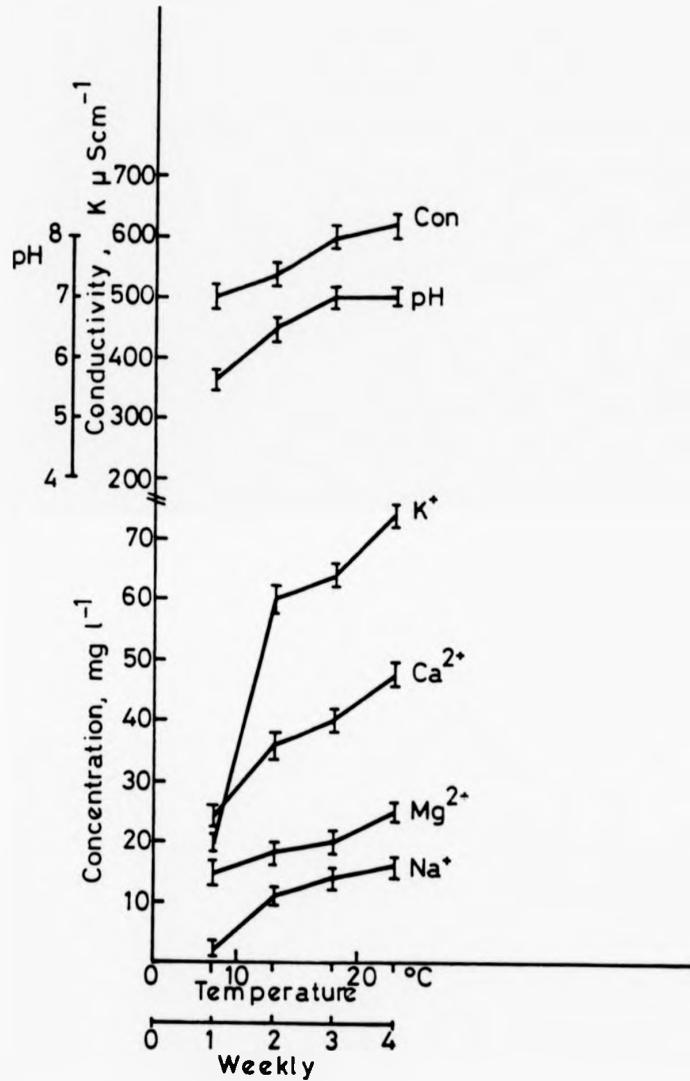
FIGURE 7.2.2.2

The influence of temperature on concentrations of
individual elements determined on samples stored
in the laboratory and analysed at weekly intervals

As shown earlier in Coombs Brook, some elements were removed to a greater degree from one species than from another (Table 7.2.2.1). However, in only two cases was this difference very marked: Ca^{2+}, Na^+, SO_4^{2-}, Cl^- and S^{2-} under Sitka spruce, and Ca^{2+}, Na^+, K^+ and SO_4^{2-} under Guelder rose. If this is compared with the other analyses of tree species (Table 7.2.2.1), major differences in the concentrations emerge, with the following elements greatly exceeding the mean values in throughfall beneath certain species: Ca^{2+} (2, 4, 5 species), Mg^{2+} (1, 2, 5 species), Na^+ (1, 2 species), K^+ (1, 4, 5 species), SO_4^{2-} (1, 2, 5 species), NO_3^- (2, 3 species), Cl^- (2 species) and S^{2-} (1, 2, 5 species) (Table 7.2.2.1).

Elements of predominantly non-ionic form, such as nitrogen and phosphorus, which are associated with plant tissues and storage, are much slower in their rate of cycling and, to varying degrees, require decomposers to complete the cycle.

To represent the leachability of the various elements from the forest canopy, a ratio was developed between the net amount of each element removed from the forest canopy during (a) the summer, and (b) the winter, and the removal in the month of July, which was taken to represent a standard for a dry month. These ratios (Table 7.2.2.4) are indicative of the leachability and, to a degree, indicate the mobility of each of these elements within the tree during the study period. The order of importance of leaching was $Cl^- > NO_3^- > Ca^{2+} > K^+ > Mg^{2+} > Na^+ > SO_4^{2-}$, for the 1984-1985 study period, and $Na^+ > Cl^- > NO_3^- > Ca^{2+} > K^+ > Mg^{2+} > SO_4^{2-}$ for the 1985-1986 study period.

One complication in the measurement of leaching from the forest canopy is the possibility of dry fallout, as discussed in Section 7.1. However, the extremely high leaching for Na^+ represents contamination of the forest canopy from the atmosphere. The presence of relatively large amounts of Cl^- in the throughfall may also support this.

The pH of the precipitation at Coombs Brook is low, having a mean pH of 5.3 (0.005 H^+) during this study. On the other hand, the pH of the throughfall had a mean pH of 3.9 (0.126 H^+), indicating acidification as the rain washes through the coniferous trees - especially the Sitka spruce and Buckler Fern.

TABLE 7.2.2.4   RELATIONSHIP BETWEEN THE NET AMOUNT OF EACH COMPONENT REMOVED IN THROUGHFALL AND STEMFLOW FROM THE CANOPY DURING THE STUDY PERIOD TO TOTAL STANDING (MONTH) OF EACH COMPONENT IN THE THROUGHFALL DURING JULY

Study period: 1984-1985

| | Kilograms per hectare per year | | | Kilograms per hectare per month | | | |
	Throughfall & stemflow	Rainfall	Net removal in throughfall	Throughfall in July	Rainfall in July	Net removal in July standard	Ratio*
Ca^{2+}	80.0	7.65	72.3	3.89	0.16	3.73	19.3
Mg^{2+}	12.8	2.52	10.28	0.71	0.16	0.55	18.6
Na^+	42.1	12.2	29.9	2.2	0.50	1.7	17.5
K^+	50.2	8.78	41.4	2.9	0.71	2.19	18.9
SO_4^{2-}	299.3	29.4	269.9	24.5	2.31	22.1	12.2
NO_3^-	75.5	19.5	56.0	3.0	1.19	1.81	30.9
Cl^-	136.6	17.4	119.2	8.2	4.8	3.4	35.0

1984-85:   The order of importance of leaching $Cl^- > NO_3^- > Ca^{2+} > K^+ > Mg^{2+} > Na^+ > SO_4^{2-}$
1985-86:   The order of importance of leaching $Na^+ > Cl^- > NO_3^- > Ca^{2+} > K^+ > Mg^{2+} > SO_4^{2-}$

Study period: 1985-1986

Ca^{2+}	95.5	9.13	86.3	8.4	0.43	7.97	10.8
Mg^{2+}	15.3	3.01	12.29	1.5	0.147	1.35	9.10
Na^+	50.3	14.5	35.77	6.1	4.9	1.7	21.0
K^+	59.9	10.5	49.4	6.4	1.61	4.79	10.3
SO_4^{2-}	357.1	35.1	322.0	53.2	4.9	48.3	6.6
NO_3^-	90.1	23.2	66.9	6.6	2.5	4.1	16.3
Cl^-	162.9	20.8	142.1	17.9	10.5	7.4	19.2

$*Ratio = \dfrac{\text{Net removal in throughfall}}{\text{Net removal in July standard}}$

7.2.3 Stemflow

In the present study at Coombs Brook, the concentration of the various elements was generally higher in the stemflow samples, but seasonally paralleled that in throughfall. However, the initial chemical composition of the stemflow is difficult to determine. Stemflow chemistry is somewhere between the composition of the rain and that of the throughfall, depending on how far the water has passed through the canopy before becoming stemflow. The sampling of stemflow on the catchment which had been tagged with Ca^{2+} found that, after leaf abscission, stemflow contained Ca^{2+} at much lower concentrations than when tree supported foliage, indicating that direct leaching from the bark probably does not contribute as much to the chemical composition of the stemflow as does the leaching of the leaves. However, the leaching of the bark of trees is a complex process, often involving large populations of mosses, lichens and micro-flora. The exchange between stemflow and these organisms may mask the leaching characteristics of the bark.

Stemflow accounts for a small amount of the total canopy leaching, mostly because less than 5% of the total precipitation passes through the forest canopy as stemflow. However, stemflow may be important because it is deposited in a small area around the base of the tree.

7.2.4 Magnitude of Chemical Components of Throughfall and Stemflow

To provide quantitative estimates for the intrasystem cycle of the Coombs Brook ecosystem model, the amounts of each element removed from the forest canopy were calculated (Table 7.2.2.2).

Samples were not taken on a random basis and the sampling did not cover a full two years. However, from information already available for this ecosystem, it was possible to estimate the amounts of various nutrients removed from the overstorey of this stand during the period of the collections. This was accomplished by calculating the species contribution to the forest canopy and the amount of element removed from each species. Tables 7.2.2.1 and 7.2.4.1 show more chemical composition information on fresh leaves, and the com-

TABLE 7.2.4.1   CHEMICAL COMPOSITION OF PLANTS (FRESH LEAVES) - COOMBS BROOK FOREST (mg 1^{-1})

Number	Type of Plant	Ca^{2+}	Mg^{2+}	Na^+	K^+	SO_4^{2-}	PO_4^{3-}
1	Hard Buckler fern	53.9	35.8	9.45	155.4	57.4	18.9
2	Coniferous tree Sitka spruce	17.9	2.7	1.2	15.3	4.4	7.01
3	Deciduous tree Common alder	104.2	15.3	2.3	23.7	18.7	8.78
4	Common hawthorn	193.6	18.6	2.7	76.4	64.5	12.2
5	Guelder rose shrub	184.6	40.9	3.2	68.5	37.7	10.4
6	Lesser found sedge	14.4	6.9	2.9	93.5	28.1	12.1
7	Coniferous tree Pinus sylvestris (Scots pine)	70.0	5.75	3.7	52.4	24.7	6.6
	Stemflow (fresh material) average	28.9	0.40	1.13	2.09	4.96	2.12

parison between both Tables 7.2.2.1 and 7.2.4.1 will explain how much each species is able to leach elements by rainfall. For example, the fresh leaves had the ability to leach out at least six times more of each element than throughfall.

7.2.5 Summary

Interception by the canopy may affect the chemistry of the throughfall in a number of ways:

(a) First, the precipitation itself contains chemicals, and any of these chemicals which are retained in the canopy during a single storm will not appear in the throughfall of that storm.

(b) Second, nutrients may leach from the leaf into water intercepted by the leaves and then be deposited as salts on the leaf surface as the water evaporates.

(c) Third, although there is almost always a net increase in the concentration of nutrients in throughfall over that in the original precipitation (Tables 7.2.2.1, 7.2.4.1 and 7.2.2.4), it is apparent that nutrients can be absorbed into the leaves from the water or be taken up by the micro-flora on the surface of the leaves and branches.

(d) Fourth, the leaching of elements from the forest canopy by precipitation is dependent on a number of factors. First, an element must be present, indicating either a biological requirement or a non-selective uptake of the element by the plant. For example, elements which are present in large amounts in the fresh leaves are leached in larger absolute amounts (Table 7.2.4.1 and Fig. 7.2.2.2). However, in some cases leaching is independent of the amounts present within the leaves. This difference seems to be related to where the element is held in the biological material.

(e) Fifth, it has been demonstrated that, at higher temperatures, the concentration of the element is remarkably high due to evaporation effect (see Fig. 7.2.2.2).

7.3 SOIL WATER CHEMISTRY

7.3.1 Introduction

Soil water samples were collected at 12 pits in the Coombs Brook catchment (Fig. 3.2.1). Chemical analysis was carried out, in addition to pH and conductivity measurement, in the laboratory (Table 7.3.1.1). This section deals with the spatial and temporal variations in soil water quality in relation to the soil chemistry and type and the hydrological conditions which determine the quality of stream water. Infiltration and redistribution of water within soil profiles are important in this thesis, as they influence chemical reactions and sediment transfer. The nature of the soil profiles affects such water movement and is therefore discussed in this chapter.

In simple terms, the quality of water held within the groundwater reservoir will reflect that of the soil water table and further water/ rock interactions occurring within the groundwater body. In more detail, we may define the primary controls on the solute content of soil water as the original chemical quality of the water entering the zone of saturation: the distribution, solubility, exchange capacity, and exchange selectivity of the minerals in the rock.

Soil water solute concentrations frequently tend to increase with depth, and this feature may be related to the slower rates of groundwater movement at depth and, therefore, to the lack of flushing of soluble components, particularly those attributable to a saline depositional environment, which may be retained as adsorbed ions on clay minerals or as interstitial water.

7.3.2 Results and Discussion

Broadly, the catchment has two major soil groups: (a) the stagnohumic and humic gleys, particularly in the centre of the catchment, and (b) the brown earths and brown podzolics in the north and south-west, although the boundary between them is often indistinct (Fig. 2.4.1(a)). At each of the 12 pits, water samples were collected weekly at three different depths: 20, 50 and 90 cm, and the water level in each pit was recorded.

TABLE 7.3.1.1   SUMMARY STATISTICS FOR THE SOIL WATER QUALITY DATA AT DIFFERENT DEPTHS

(20 cm, 50 cm, 90 cm)*

(a)   20 cm depth

	Rain-fall mm	Water level cm	pH	Conduc-tivity	Ca^{2+}	Mg^{2+}	Na^+	K^+	SO_4^{2-}	NO_3^-	Cl^-
Mean	34.1	5.17	3.96	158.6	4.46	1.00	2.54	1.24	13.3	1.26	1.35
Median	30.0	2.00	4.10	153.8	4.65	1.15	1.90	0.20	12.8	0.0	0.0
Stand.deviation	33.7	6.47	1.0	55.2	5.00	1.09	2.91	2.39	15.3	3.73	4.39
Maximum	100.0	20.0	4.7	255.2	18.1	3.90	10.4	9.40	47.5	17.2	17.4
Minimum	0.0	0.0	3.7	82.8	4.6	1.2	1.8	0.41	12.7	2.9	11.0

(b)   50 cm depth

	Rain-fall mm	Water level cm	pH	Conduc-tivity	Ca^{2+}	Mg^{2+}	Na^+	K^+	SO_4^{2-}	NO_3^-	Cl^-
Mean	32.7	24.2	4.5	160.7	11.36	2.67	5.14	3.91	32.2	5.42	11.7
Median	29.0	27.8	4.5	165.6	12.8	2.60	4.7	0.95	33.6	5.94	11.7
Stand.deviation	33.7	12.5	1.09	62.1	4.52	1.16	2.05	9.09	11.4	0.889	4.6
Maximum	100.0	49.0	6.5	326.5	22.8	5.90	8.20	39.7	52.7	5.94	15.0
Minimum	0.0	4.5	3.9	94.6	1.1	1.1	1.9	0.16	9.9	4.4	8.5

(c)   90 cm depth

	Rain-fall mm	Water level cm	pH	Conduc-tivity	Ca^{2+}	Mg^{2+}	Na^+	K^+	SO_4^{2-}	NO_3^-	Cl^-
Mean	30.9	52.6	5.97	236.8	23.47	6.05	7.74	1.74	43.6	5.91	17.0
Median	29.0	55.0	6.25	233.5	23.65	4.25	8.25	1.12	43.6	6.1	17.0
Stand.deviation	33.9	23.0	0.889	40.6	4.97	3.87	1.84	2.23	9.71	1.62	–
Maximum	100.0	88.0	7.1	335.1	31.4	11.7	11.9	10.2	57.8	12.7	20.0
Minimum	0.0	9.0	4.4	139.2	0.80	0.10	1.5	0.0	0.0	2.9	17.0

*Calculated value, based on weekly measurements

- Rainfall – mm unit   - conductivity – μScm^{-1} unit
- Water level – cm unit   - element – mg 1^{-1} unit
- pH – pH unit

Soil pH in both gleys and brown earths at three depths - the surface litter, the underlying humus and the lower part of the mineral soil - changed from 3.4 at the surface to 6.5 at a depth of 50 cm or more (Tables 7.3.1.1 and 7.3.2.1 and Fig. 7.3.2.1). The gley soil, however, is more acid than the brown soil, especially at 90 cm depth. The decrease in acidity at such depth is probably due to the leaching of exchangeable bases from calcareous materials in the profile.

Drainage conditions are important in determining soil acidity in freely draining soils. Hydrogen ions (H^+) replace exchangeable ions (e.g. Ca^{2+}, Mg^{2+}, Na^+ and K^+) when water is able to percolate through the surface organic layers. This progressively makes the soil more acid (as H^+ increases). The exchange takes place on the surface of the microscopic particles of the soil - clays and humus - which form the clay humus complex. This may explain why the surface layers of the soils in the Coombs Brook catchment are more acid than the lower layers, especially under coniferous trees.

The pH of the soil represents the balance between several soil properties, such as water content, base exchange and micro-biological activity. Since these are variable, soil pH is not constant and shows both annual and monthly fluctuations. Acidity tended to increase during the month of June 1985 (Table 7.3.2.2(a) and (b)). The increase is accentuated by periods of drought and may amount to an entire pH unit. Rainy periods decrease acidity, and, as winter approaches, the soil pH gradually decreases. An increase in pH has also been observed to accompany the thawing of frozen soil.

The cation diagram (Fig. 7.3.2.2) shows that $Ca^{2+} + Mg^{2+}$ concentrations vary between 50% and 90% of the total cation concentration, whilst the relationship between Na^+ and K^+ is variable. The increase in the $\frac{Ca^{2+} + Mg^{2+}}{Na^+ + K^+}$ from 2.75 at 20 cm depth and 2.96 at 50 cm to 5.94 at 90 cm depth indicates the greater amount of $Ca^{2+} + Mg^{2+}$ in the lower parts of the profiles. Although relatively low proportions of Na^+ and K^+ occur in the upper horizons of the profiles, they decrease markedly with depth. It seems that K^+ is derived mainly from organic litter and generally decreases as the organic content declines down the profile.

TABLE 7.3.2.1   CHEMICAL PROPERTIES OF SOIL WATER IN DIFFERENT LOCATIONS (in mg 1^{-1})

Site No.	Soil water/soil type	Depth cm	pH	Ca^{2+}	Mg^{2+}	Na	K^+
1	Gley soil	20	3.9	9.6	2.4	6.6	1.2
		50	4.1	12.8	2.5	5.9	1.8
		90	4.8	23.6	2.7	5.8	0.9
2	Brown soil	20	4.1	5.2	1.4	3.1	1.9
		50	5.1	10.3	3.1	4.2	1.5
		90	6.7	24.7	10.6	8.8	2.3
3	Gley brown soil	20	4.4	11.8	1.7	5.4	8.0
		50	4.5	22.0	2.49	7.9	1.0
		90	5.4	26.8	2.7	8.8	0.97
4	Brown gley soil	20	4.4	11.1	2.7	6.5	3.1
		50	4.8	14.5	2.9	8.0	10.9
		90	6.5	19.1	4.9	7.8	2.9

pH for gley soil
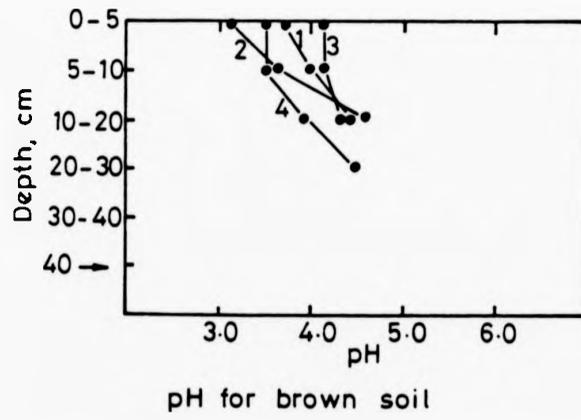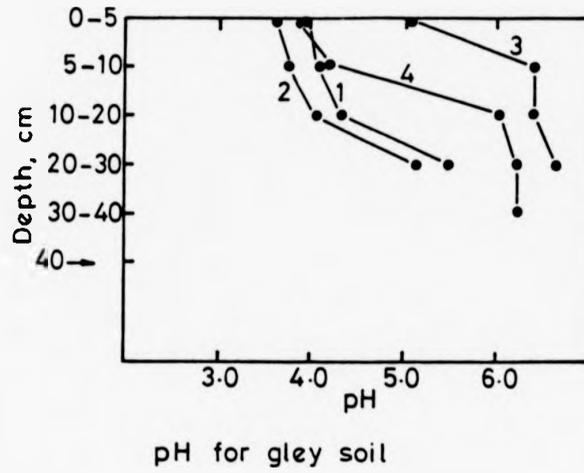
pH for brown soil

FIGURE 7.3.2.1

Variation in soil pH at four sites for both
gley and brown soil

TABLE 7.3.2.2 (a)   SOIL CHEMISTRY FOR THE DROUGHT PERIOD (JUNE 1985) (in Mg 1^{-1})

Soil type	Horizon cm		pH	Ca^{2+}	Mg^{2+}	Na^+	K^+
Brown soil	0- 5	Maximum	3.7	14.0	2.5	5.0	11.5
		Minimum	3.2	6.5	1.7	3.4	6.0
		Mean	3.4	10.3	2.1	4.2	8.7
	5-20	Maximum	4.0	26.0	1.1	5.1	3.0
		Minimum	3.6	6.0	0.7	3.4	2.0
		Mean	3.8	16.0	0.9	4.2	2.5
	20-50	Maximum	4.6	87.5	6.0	4.6	4.2
		Minimum	4.3	15.0	0.9	3.2	3.0
		Mean	4.4	51.2	3.4	3.9	3.6
Gley soil	0- 5	Maximum	3.9	27.0	2.7	5.2	5.4
		Minimum	3.7	10.0	1.6	3.5	5.2
		Mean	3.8	18.5	2.15	4.3	5.3
	5-20	Maximum	4.3	23.0	1.9	6.2	3.7
		Minimum	4.0	6.5	0.9	3.8	3.5
		Mean	4.15	14.7	1.4	5.0	3.6
	20-50	Maximum	5.3	76.5	4.9	5.6	5.3
		Minimum	5.2	62.0	3.7	4.4	5.2
		Mean	5.25	69.2	4.3	5.0	5.25

TABLE 7.3.2.2 (b)   SOIL CHEMISTRY IN A WET PERIOD (OCTOBER 1985) (in Mg 1^{-1})

Soil type	Horizon cm		pH	Ca^{2+}	Mg^{2+}	Na^+	K^+
Brown soil	0- 5	Maximum	4.2	16.7	3.5	5.0	17.6
		Minimum	3.2	6.5	1.7	3.2	6.0
		Mean	3.6	12.8	2.5	3.9	10.8
	5-20	Maximum	4.2	18.1	2.5	5.1	9.4
		Minimum	3.6	6.0	0.7	0.85	2.0
		Mean	3.8	8.7	1.3	2.5	4.7
	20-50	Maximum	4.6	21.0	7.5	4.6	4.3
		Minimum	4.3	9.5	0.9	1.45	3.0
		Mean	4.4	15.1	3.9	2.9	3.8
Gley soil	0- 5	Maximum	5.1	27.0	25.0	5.2	8.5
		Minimum	3.7	10.0	2.0	1.75	5.2
		Mean	4.1	16.3	7.8	3.5	6.1
	5-20	Maximum	6.3	88.5	32.0	8.0	10.5
		Minimum	4.0	5.0	0.8	1.5	2.1
		Mean	5.2	48.1	11.4	4.15	5.3
	20-50	Maximum	6.5	89.2	48.0	5.6	6.7
		Minimum	5.2	62.0	3.7	1.6	4.0
		Mean	5.8	76.1	20.6	3.5	5.3
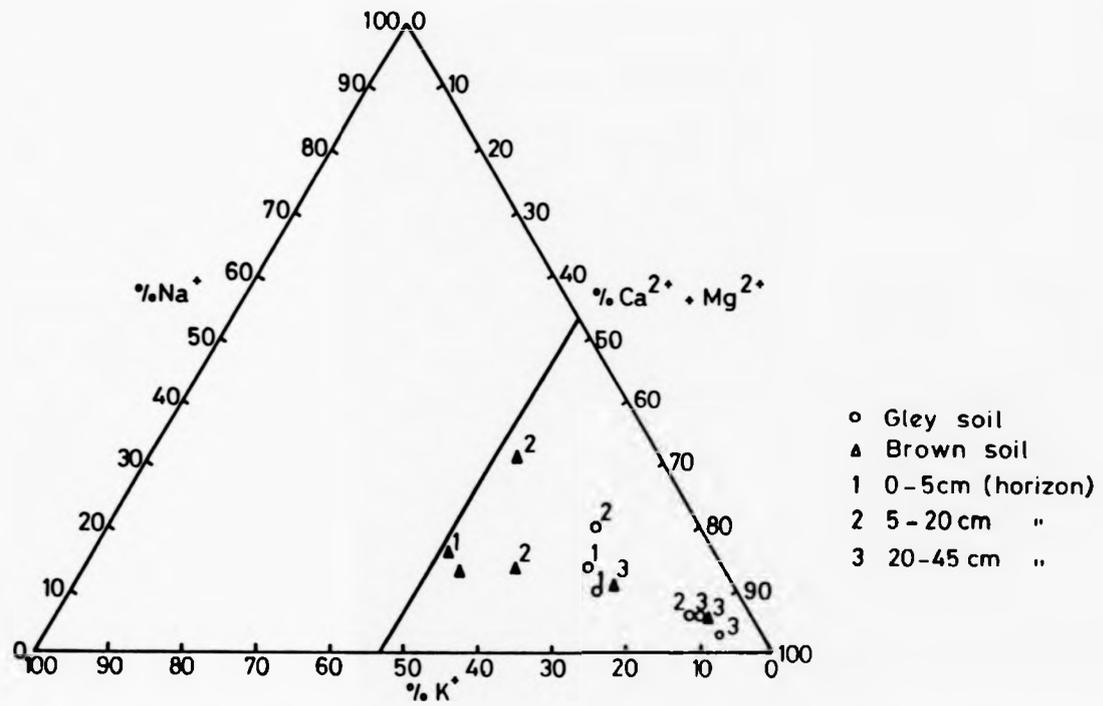
FIGURE 7.3.2.2   The cation diagram shows the variation in the cation in both gley and brown earth soil

Soil water was sampled at each of four profile sites, using shallow wells, or pits, down to depths of approximately, 20, 50 and 90 cm (Fig. 3.2.1). As each well depth represents a soil horizon, the data from different sites may be compared. Soil water near the surface contains less Ca^{2+} and Mg^{2+} than that from deeper levels (Table 7.3.2.1). Water from the brown soil has lower concentrations than that from the gley soil. In addition, the soil from the pits in the upper part of the catchment contains higher concentrations of Ca^{2+} and Mg^{2+} than that from further downstream (Table 7.3.2.3). This could be because the water at the upper sites has had closer contact with bedrock fragments than that in the largely alluvial and colluvial debris further downstream. Water at 20 cm depth contains higher concentrations of Na^+ and K^+ than that at 50 cm depth, reflecting the atmospheric source of Na^+ and the role of organic matter in the supply of K^+. Concentrations of K^+ tend to reflect the rate of litter fall to the soil and the frequency of saturated flow conditions.

The pH appears to vary with vegetation type (Table 7.2.2.1). To highlight the effect of vegetation on pH, two different sites were selected for sampling, both having different vegetation types, coniferous and deciduous (Table 7.3.2.4). Ovington (1954) suggested that the individual tree species influence the pH gradient of the soil, as the leaf fall of different trees is initially quite different in character, so that the rate and processes of decomposition vary, as does pH. Deciduous hardwood trees tend to delay the development of soil acidity at the surface and to produce a less acid soil. Coniferous trees have much more acid litter (Section 7.2). The most striking feature is that the soils at the coniferous site are more acid than those at the deciduous site (Table 7.3.2.4), reflecting the acidifying effect of the organic matter substances produced by coniferous trees. When these substances dissolve in rainwater they produce weak acids that drip onto the soil below and acidify the surface horizons. An increase in pH at the bottom of these profiles could be a result of the leaching down of calcareous materials from the upper horizons. This increase is more noticeable under the coniferous than the deciduous trees, as indicated by comparing profiles 1A and 2A on Table 7.3.2.4.

Two factors account for the decrease in K^+ down the soil profiles.

TABLE 7.3.2.3   SOIL CHEMISTRY IN THE UPPER AND LOWER PARTS OF THE CATCHMENT

| | **Brown soil** | | | | **Brown soil** | | |
| | Upper catchment | | | | Lower catchment | | |
	pH	Ca^{2+} mg l^{-1}	Mg^{2+} mg l^{-1}		pH	Ca^{2+} mg l^{-1}	Mg^{2+} mg l^{-1}
Maximum	4.6	87.5	6.0		4.6	21.0	7.5
Mean	4.0	22.9	2.6		3.9	12.9	2.4
Minimum	3.2	6.0	1.0		3.5	6.0	0.7
	Gley soil				**Gley soil**		
Maximum	6.5	99.0	48.0		5.2	76.5	6.2
Mean	5.6	70.4	25.3		4.2	28.6	4.5
Minimum	3.8	11.9	2.0		3.7	5.0	3.2

TABLE 7.3.2.4   SOIL pH RESULTS UNDER TWO DIFFERENT TYPES OF TREE

Site 1 (Coniferous trees): pH results

		Profile		
cms	1A	1B	1C	1D
0- 5	3.2	3.5	3.4	3.6
5-10	3.5	3.6	3.4	3.6
10-15	3.5	3.7	3.5	3.8
15-20	3.6	3.7	3.5	3.8
20-25	3.8	3.7	3.7	4.0
25-35	5.2	4.4	3.8	5.3
35-45	5.9	5.2	3.9	5.9
>45	6.1	5.8	4.0	6.0

Site 2 (Deciduous trees): pH results

		Profile		
cms	2A	2B	2C	2D
0- 5	5.0	4.0	3.9	4.3
5-10	5.1	4.1	3.9	4.4
10-15	5.2	4.2	4.0	4.5
15-20	5.3	4.3	4.3	4.7
20-25	5.3	4.3	4.4	4.8
25-35	5.3	4.3	4.4	4.9
35-45	5.3	4.4	4.5	5.0
>45	5.6	4.5	4.7	5.2

Saturated flow conditions and leaching are more prevalent in the upper catchment - the pits flow more frequently, and litter returns to the soil from the trees - which have the effect of decreasing absolute K^+ concentrations.

Movement of water through the soil causes horizons to gain or lose constituents. Clay minerals are commonly translocated from the A to B horizon. In some cases, a water table within several feet of the surface (20 cm) can cause the upward movement of water and the subsequent evaporation of water and deposition of salt on the surface, as happened at Sites 2 and 4.

In absolute terms, the concentration of Ca^{2+}, Mg^{2+}, and Na^+ in the gley soil water are higher than those found in the brown soil water, whilst pH levels are higher in gley soil water than those of brown soil water. In the catchment area it is unusual to find soil water or mineral soils with a pH reading of less than 3.5; in fact, pH 4.0 might more correctly be given as the lower limit frequently encountered. It is unusual to find a soil water or mineral soil with a pH of more than 7.0 (Table 7.3.2.5).

7.3.3 Temporal Variability

Temporal variations in solute concentrations in soil water are greater than spatial variations (Table 7.3.1.1). Precipitation inputs change the depth to the water table and the height of water in the shallow wells, while conductivity appears to increase at the onset of a wet period as readily soluble chemicals accumulated in the soil over dry periods are flushed down to 90 cm depth (Fig. 7.3.3.1).

The cation concentrations are at their lowest in winter, increasing through summer to autumn, when they reach a peak. The greatest temporal variability tends to occur in the upper horizons. It is here that the greatest concentrations of soluble chemicals are found due to evapotranspiration and litter fall return. Lower in the profiles, leaching, when it occurs, is more prolonged and not so flashy, so concentrations tend to remain more stable, although they follow a similar concentration and dilution pattern to the upper horizon.

Electrical conductivity determinations of soil water (Table

TABLE 7.3.2.5   COMPARISON BETWEEN CHEMICAL CONCENTRATIONS OF SOIL AND SOIL WATER

Gley soil - Site 1

Depth cm	pH	Soil Ca^{2+}	K^+	pH	Soil water Ca^{2+}	K^+
0-20	4.1	16.3	6.1	3.9	10.2	1.67
20-50	5.2	48.1	5.3	4.1	13.7	0.938
>50	5.8	76.1	5.3	4.8	23.7	0.860

Brown soil - Site 2

Depth cm	pH	Ca^{2+}	K^+	pH	Ca^{2+}	K^+
0-20	3.65	12.8	10.8	4.0	6.01	1.1
20-50	3.8	8.7	4.7	4.8	11.1	0.942
>50	4.4	15.1	3.8	6.7	24.7	2.0

Brown gley soil - Site 3

Depth cm	pH	Ca^{2+}	K^+	pH	Ca^{2+}	K^+
0-20	3.45	10.3	8.78	4.35	7.2	1.7
20-50	3.8	16.0	2.5	4.5	21.1	1.14
>50	4.4	51.2	3.6	5.36	26.6	1.05

Gley brown soil - Site 4

Depth cm	pH	Ca^{2+}	K^+	pH	Ca^{2+}	K^+
0-20	3.8	18.5	5.3	4.4	14.2	1.9
20-50	4.15	14.7	3.6	4.8	13.9	2.58
>50	4.25	69.2	5.25	6.3	21.3	3.37
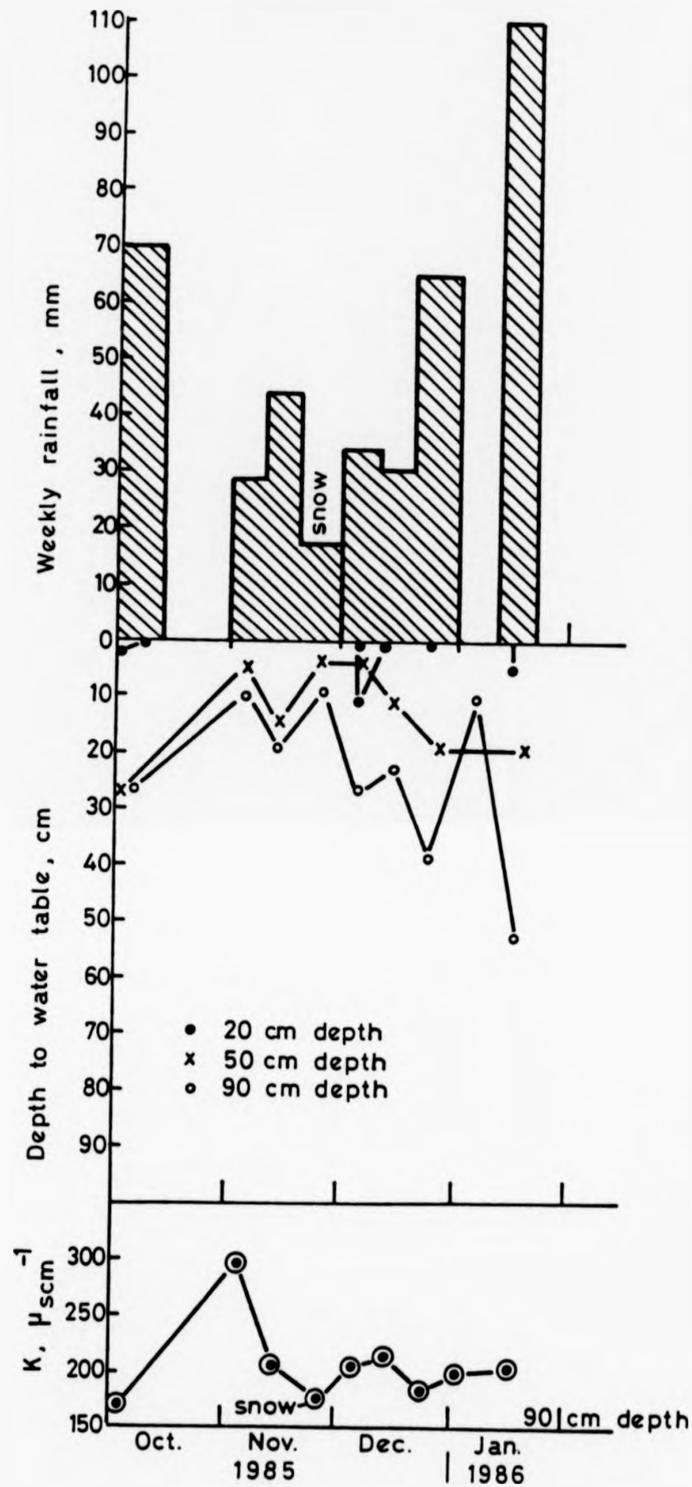
FIGURE 7.3.3.1   Relationship between water table and precipitation at Site 1.   Calculated value based on weekly measurements.

7.3.1.1) indicate an overall range from 82 to 335 μScm^{-1}, with maximum values of 255 at 20 cm, 326 at 50 cm and 335 at 90 cm. The 20 cm maximum was the product of runoff after a dry period, while the other two were samples taken when stream water had a conductivity of 464 μScm^{-1}.

7.3.4 Chemical Mobility

The mobilities of the four major cations (Table 7.3.4.1) were calculated by comparing soil water compositions with soil composition:

$$\text{mobility} = \frac{\text{proportion of chemical in soil water}}{\text{proportion of chemical in soil}}$$

The soil and soil water analysis (Table 7.3.4.1) show that the cations can be divided into two groups: Ca^{2+} and Mg^{2+} are the most mobile, while Na^+ and K^+ have moderate mobility. The sequences are similar to those presented by Miller (1961) and Anderson and Hawkes (1958). In the first group, Mg^{2+} appears to be slightly more mobile than Ca^{2+}: K^+ is generally less mobile than Na^+ in all the horizons. This reflects the recycling of K^+ by the biomass and supply of Na^+ by rainfall. The mobilities of Ca^{2+} and Mg^{2+} are always of the same order of magnitude, while Na^+ and K^+ mobilities are of another order, but similar to each other:

20 cm	$Mg^{2+} > Ca^{2+} < Na^+ \gg K^+ >$	Gley soil water/soil
50 cm	$Mg^{2+} > Ca^{2+} < Na^+ \gg K^+ >$	" " " "
90 cm	$Ca^{2+} > Mg^{2+} < Na^+ \gg K^+ >$	" " " "
20 cm	$Ca^{2+} > Mg^{2+} < Na^+ \gg K^+ >$	Brown earth soil water/soil
50 cm	$Mg^{2+} > Ca^{2+} < Na^+ \gg K^+ >$	" " " " "
90 cm	$Mg^{2+} > Ca^{2+} < Na^+ \gg K^+ >$	" " " " "

7.3.5 Summary and Conclusions

The salts in both soil profiles and soil water in the catchment area can be derived from five major possible sources, namely:

1. Rainwater containing cyclic salts from the ocean and terrestrial sources.

TABLE 7.3.4.1   MOBILITY FOR THE FOUR MAJOR CATIONS, COOMBS BROOK CATCHMENT (in mg 1^{-1})

Gley/soil water

cms	Ca^{2+}	Mg^{2+}	Na^+	K^+
20	10.0	2.3	6.3	1.8
50	13.0	2.6	7.0	1.4
90	23.0	2.7	5.9	1.6

Brown/soil water

Ca^{2+}	Mg^{2+}	Na^+	K^+
8.8	1.8	3.8	1.7
14.8	4.4	3.4	2.3
26.5	11.0	8.5	1.6

Gley soil

20	41.3	4.3	0.53	14.0
50	127.6	9.3	0.85	7.9
90	133.1	30.1	1.73	4.4

Brown soil

30.0	4.8	0.75	13.9
20.0	2.56	0.47	6.4
71.0	4.7	1.28	4.4

The mobility calculation:

Gley soil water/soil

20	0.24	0.53	11.8	0.10
50	0.10	0.27	8.2	0.17
90	0.17	0.08	3.4	0.36

Brown soil water/soil

0.29	0.3	5.0	0.12
0.74	1.7	7.2	0.35
0.37	2.3	6.6	0.36

2. Upward movement of dissolved salts from a shallow water table and the soil.

3. Deposition of aeolian soil parent material.

4. Biotic activity is greatest near the surface. Other important nutrient elements that accumulate in organic matter include PO_4^{3-} and S^{2-}. Table 7.3.5.1 shows a decreasing content of organic matter is found with depth. In addition to PO_4^{3-} and S^{2-}, a decreasing content is found with depth.

5. The vegetation has a major effect on soil formation.

The observations reported in this section lead to the following conclusions:

1. That at low pH the soil contains a high level of Na^+ and K^+, and low level of Ca^{2+} and Mg^{2+}, whereas high pH soil contains high levels of Ca^{2+}, Mg^{2+} and low levels of Na^+ and K^+.

2. The pH values in the catchment increase slightly from the surface layers to a maximum at the 90 cm depth. The trend of pH values may be related to the effects of alkaline earth metals; the higher their concentration, the lower the hydrogen ion concentration.

3. The pH of the soil water samples lay between 7.0 and 3.7. At the lowest pH values, the soil water is more acid than both precipitation and stream water. However, the down-profile reduction in acidity is a major control of the pH of drainage waters entering the stream. Strongly alkaline soils (pH greater than 8) are absent, probably because of the gradual salinization of the soil.

4. The vegetation has a major effect on soil formation. A plot of the pH results illustrates clearly the influence of a tree and its canopy upon the chemical properties of the soil (Table 7.3.2.4).

TABLE 7.3.5.1   THE ORGANIC MATTER AT THE CATCHMENT AND SO_4^{2-} AND PO_4^{3-} CONTENT

Soil type	Site No.	0-5 cm	5-20 cm
Brown earth	1	28%	12%
	2	36%	10%
	3	29%	8%
	4	18%	4%
Gley soil	1	38%	15%
	2	24%	11%
	3	28%	9%
	4	9%	8%
Maximum		38%	15%
Mean		26%	9%
Minimum		9%	4%

	0-20 cm	30-35 cm	>40 cm
Mean SO_4^{2-}	16.0	8.0	6.0
Mean PO_4^{3-}	0.317	0.055	0.009

5.   Close to the tree trunk the soil was moderately acid,
     with pH values of less than 4.0 at a distance of about
     6.0m. However, the pH rises to about 5.0, and these
     values were characteristic of the rest of the area beneath
     the canopy.

6.   Variation in soil properties under trees is certainly not
     entirely due to variations in water distribution. For
     example, Zinke (1962) reported that the pattern of several
     properties of surface soil under single forest trees was
     developed with radial symmetry to tree, varying systema-
     tically with distance from the tree stem. He further
     stated that these patterns are predictable. However, he
     felt that stemflow was not a major influence for the par-
     ticular trees in his studies. He concluded that the patterns
     were due mainly to differences between effects of bark
     litter, leaf litter, and the adjoining opening or neighbour-
     ing trees. In addition to consideration of variations in
     water quantities under trees due to throughfall, crown drip,
     and stemflow, differences in chemical constituents in these
     waters must also be considered.

7.   The overall nature of the pH results suggest that coniferous
     trees have an acidifying effect upon the soil. This is
     widely accepted, for it seems that coniferous trees produce
     organic substances which, when dissolved in rainwater, pro-
     duce weak acids. These leach the soluble nutrients from
     the topsoil.

8.   Conversely, the trees increased the nitrogen content of
     the underlying soil, apparently because the nitrogen is
     released during decay of the tree litter. Thus, the areas
     receiving most litter displayed the highest nitrogen content.

9.   The character of the litter derived from a single tree
     varies considerably. This reflects the variations in
     nutrient accumulation and in organic composition of the
     different parts of the plant.

10. Nutrient contents are highest in leaf material and lowest in the stem or trunk. This influences the rate of decomposition and the release of nutrients into the soil.

11. The cationic composition of the soil waters lies along the same line of variation as river water. This may indicate that the composition of soil water and river water varies in the same way and is probably controlled by the same processes.

7.4 RELATIONSHIP OF WATER CHEMISTRY TO LITHOLOGY AND SEDIMENT

7.4.1 Introduction

The analyses used in this section (Tables 7.4.1.1 and 7.4.1.2 and Appendix 2) indicate the relationships which can be expected under the best conditions.   The constituents of stream water most likely to be derived directly from solution of minerals in rocks and soil are dissolved silica (about 88%) and cations (about 12%) (see Table 7.4.1.2).   Although cation-anion balance must be maintained in all solutions, the anions may be derived in large part from non-lithologic sources.   For example, rocks serve as sources of SO_4^{2-} through direct solution (Tables 7.4.1.1 and 7.4.1.2).

The anions in rainfall are balanced by cations, partly H^+, but also with other cations.   However, these cations from non-lithologic sources are a relatively unimportant contribution to stream water cations.   A general relationship between mineral composition of the stream water and that of the solid minerals with which the water has been in contact is to be expected (Hem, 1970).

Rocks in the catchment are complex mixtures of minerals which differ widely in their stability toward, or solubility in, water.   The bulk composition of the rock (Table 7.4.1.2) is given for general information, although it may not adequately show the presence of the more soluble components likely to influence the composition of water circulating through the rock.   Relatively minor components of rocks may control major features of the composition of circulating groundwater (Hem, 1970).   The variability of the bedrock and parent material and water and air system obviously imposes difficulties in applying a strict chemical-equilibrium model.

7.4.2 Geochemistry of the Surface Waters

The Macclesfield Forest is underlain chiefly by sedimentary rocks ranging in age from the Carboniferous Millstone Grit series to Quaternary.   Comparison of the chemistry of the stream waters with the areal extent of the simplified geologic units may involve considerable error because of lithologic differences within the generalised

TABLE 7.4.1.1   RESULTS OF SOLUTE CONCENTRATION OF PRECIPITATION, THROUGHFALL, SOIL WATER, ROCK WATER AND STREAM WATER (1984-1986)

Table 7.4.1.1(a)   Mean and Standard Deviations of Weekly Solute Data (mg l^{-1})

Solute	Bulk precipitation Mean	Stand. Dev.*	Throughfall Mean	Stand. Dev.*	Soil water (90 cm) Mean	Stand. Dev.*	Soil water (50 cm) Mean	Stand. Dev.*	Soil water (20 cm) Mean	Stand. Dev.*	Rock water Mean	Stand. Dev.*	Stream water Mean	Stand. Dev.*
H^+	0.005	–	0.125	–	0.001	–	0.030	–	0.109	–	0.00004	–	0.00003	–
Ca^{2+}	0.88	1.32	9.2	11.0	23.4	4.97	11.36	4.52	4.46	5.0	21.0	–	21.4	3.53
Mg^{2+}	0.33	0.418	1.48	1.43	6.05	3.87	2.67	1.16	1.00	1.09	7.6	–	8.79	1.44
Na^+	2.03	2.83	4.85	5.14	7.74	1.84	5.14	2.05	2.54	2.91	35.1	–	7.37	1.52
K^+	1.14	1.42	5.77	5.14	1.74	2.23	3.91	9.09	1.24	2.39	24.5	–	2.04	6.54
SO_4^{2-}	8.6	15.6	34.4	32.6	43.6	9.71	32.2	11.4	13.3	15.3	46.3	–	24.2	4.42
NO_3^-	4.5	0.21	8.68	4.81	5.91	1.62	5.4	0.889	1.26	3.73	–	–	9.86	2.32
Cl^-	4.2	2.9	15.7	6.71	17.0	1.2	11.7	4.6	1.35	4.39	–	–	15.8	5.71

*Stand. Dev. = Standard Deviation

Table 7.4.1.1(b)   Ratio of Mean Solute Concentration to Concentration in Bulk Precipitation ($mg\ l^{-1}$)

Solute	Throughfall	Soil water (90 cm)	Soil water (50 cm)	Soil water (20 cm)	Rock water	Stream water
H^+	25.0	0.2	6.0	21.8	0.008	0.006
Ca^{2+}	10.5	26.5	12.9	5.1	23.8	24.3
Mg^{2+}	4.48	18.3	8.09	3.03	23.0	26.6
Na^+	2.4	3.8	2.5	1.25	17.3	3.6
K^+	5.06	1.5	3.4	1.08	21.4	1.78
SO_4^{2-}	4.0	5.0	3.7	1.54	5.4	2.8
NO_3^-	1.9	1.15	1.2	0.28	–	2.2
Cl^-	3.7	4.04	2.7	0.32	–	3.76

Table 7.4.1.1(c) Ratio of $\dfrac{Ca^{2+} + Mg^{2+}}{Na^+ + K^+}$ (in meq)

Precipitation	Throughfall	Soil water (90 cm)	Soil water (50 cm)	Soil water (20 cm)	Rock water	Stream water
0.728	1.932	5.98	3.06	2.67	0.916	6.27

Table 7.4.1.1(d)　　Minimum, Maximum and Range of Solute Concentration (mg 1^{-1}) (1984-1986)

Solute	Bulk Precipitation			Throughfall			Soil water (90 cm)			Soil water (50 cm)			Soil water (20 cm)			Stream water		
	Min.	Max.	Range	Min.	Max.	Range	Min.	Max.	Range	Min.	Max.	Range	Min.	Max.	Range	Min.	Max.	Range
Ca^{2+}	0.2	7.7	7.5	1.0	58.0	57.0	0.80	31.4	30.6	1.1	22.8	21.7	4.6	18.1	13.5	13.5	27.5	14.0
Mg^{2+}	0.0	2.2	2.2	0.3	6.7	6.4	0.10	11.7	11.6	1.1	5.9	4.8	1.2	3.90	2.7	4.6	13.0	8.4
Na^+	0.2	9.1	8.9	0.3	31.1	30.8	1.5	11.9	10.4	1.9	8.2	6.3	1.8	10.4	8.6	2.8	14.5	11.7
K^+	0.0	8.2	8.2	0.70	21.2	20.5	0.0	10.2	10.2	0.16	39.7	39.5	0.41	9.40	8.9	0.21	65.2	65.0
SO_4^{2-}	0.0	15.5	15.5	5.6	99.9	94.3	0.0	57.8	57.8	9.9	52.7	42.8	12.7	47.5	34.8	12.0	38.5	26.5
NO_3^-	0.0	10.4	10.4	2.4	22.8	20.4	2.9	12.7	9.8	4.4	5.9	1.5	2.9	17.2	14.3	4.4	15.4	11.0
Cl^-	0.0	22.5	22.5	6.8	36.0	29.2	17.0	20.0	3.0	8.5	15.0	6.6	11.0	17.4	6.4	9.1	46.9	37.8

Table 7.4.1.1(e)   Ratio of Mean Solute Concentration to Mean Cl^- Concentration ($mg\ l^{-1}$)

Solute	Bulk Precipitation	Throughfall	Soil water (90 cm)	Soil water (50 cm)	Soil water (20 cm)	Stream water	Sea water*
Ca^{2+}	0.209	0.585	1.3	0.974	3.33	1.34	0.02
Mg^{2+}	0.078	0.095	0.359	0.230	0.74	0.534	0.07
Na^+	0.48	0.312	0.452	0.435	1.88	0.465	0.56
K^+	0.27	0.369	0.1	0.333	0.918	0.132	0.02
SO_4^{2-}	2.04	2.19	2.5	2.75	9.85	1.52	–
NO_3^-	1.07	0.55	0.347	0.461	0.933	0.610	–

Table 7.4.1.1(f)   Ratio of Mean Solute Concentration to Mean Cl^- Concentration (meq)

Solute	Bulk Precipitation	Throughfall	Soil water (90 cm)	Soil water (50 cm)	Soil water (20 cm)	Stream water
Ca^{2+}	0.370	1.036	2.435	1.717	5.855	2.395
Mg^{2+}	0.228	0.2748	1.037	0.6654	2.164	1.622
Na^+	0.7457	0.4762	0.7019	0.6772	2.907	0.719
K^+	0.2461	0.3331	0.0925	0.3027	0.8342	0.116
SO_4^{2-}	1.511	1.617	1.893	2.031	7.286	1.130
NO_3^-	0.6123	0.3161	0.1987	0.2639	0.534	0.3567

* After Holden (1966)

Table 7.4.1.1(g)   Mean Weekly Solute Concentration (meq)

Solute	Bulk Precipitation	Throughfall	Soil water (90 cm)	Soil water (50 cm)	Soil water (20 cm)	Rock water	Stream water
H^+	0.0049	0.1240	0.00099	0.0297	0.1081	0.000039	0.00002
Ca^{2+}	0.0439	0.4590	1.1676	0.5668	0.2225	1.0479	1.0678
Mg^{2+}	0.0271	0.1217	0.4976	0.2196	0.08226	0.62517	0.7230
Na^+	0.0883	0.2109	0.3366	0.2235	0.11049	1.5268	0.3205
K^+	0.02914	0.1475	0.0444	0.0999	0.0317	0.6264	0.0521
SO_4^{2-}	0.1790	0.7162	0.9077	0.6704	0.2769	0.9639	0.5038
NO_3^-	0.0725	0.1400	0.0953	0.0871	0.0203	-	0.1590
Cl^-	0.1184	0.4428	0.4795	0.3300	0.0380	-	0.4457

| | TABLE 7.4.1.2 | DATA OF BEDROCK AND SOIL DRIFT ANALYSES |

Bedrock analyses

Result No.		Ca^{2+}	Mg^{2+}	Na^+	K^+	SO_4^{2-}	Fe	Mn
1	Rock powder + rainwater (mg 1^{-1})	21.0	7.6	35.1	25.0	46.3	2.0	1.3
2	Rock powder + distilled water (mg 1^{-1})	1.6	0.9	18.3	12.2	8.4	1.6	0.08

Bulk rock analyses (% = 100)		SiO_2	Al_2O_3	Fe_2O_3	MgO	CaO	Na_2O	K_2O	TiO_2	MnO	P_2O_5
3	Bedrock (A)	88.01	6.95	1.10	0.24	0.05	1.23	2.23	0.08	0.09	0.02
	" (B)	79.1	12.5	3.87	1.15	0.15	1.34	1.19	0.44	0.07	0.09
	" (C)	90.07	6.12	1.69	0.24	0.05	0.89	0.65	0.14	0.10	0.04

Trace element values for rock (ppm)

4

	Sample Number						
	1	2	3	4	5	6	7
Nb	n.d.	5	1	14	2	1	1
Zr	91	93	182	307	277	135	166
Y	5	9	18	36	16	12	12
Sr	116	43	45	58	45	44	76
Rb	43	25	28	76	16	24	36
Ni	10	8	41	80	8	33	11
Cr	29	40	52	155	48	37	42
Ce	24	35	50	88	52	45	43
Nd	11	13	22	44	21	24	20
V	7	8	13	33	2	8	7
La	10	3	14	38	15	19	9
Tia	480	1432	2521	5496	1906	1847	1608
Ba	544	135	225	332	103	255	290
Sc	3	4	8	13	5	5	5

TABLE 7.4.1.2 (Continued)

Soil drift deposition (100 cm depth)

Result No.		Ca^{2+}	Mg^{2+}	Na^+	K^+	SO_4^{2-}	Fe	Mn
5	A	73.6	4.7	1.56	0.16	2.36	0.03	0.15
	B	133.1	30.1	1.73	4.41	4.75	0.05	0.75

units.   Because low flows are dominated by groundwater discharge, highly influenced by the mineral content of the rocks, analyses of stream water at low flow were used to illustrate the relationship of stream water chemistry to catchment geology (Table 7.4.2.1).

To understand the evolution of drainage water chemistry in relation to weathering, it is necessary to study both the solid and the liquid phases of the rock of the precipitation-soil-stream water complex.   Solute budgeting studies usually take the entire catchment as their accounting unit, within which the nutrient balance is provided as a lumped calculation.   Studies of water-rock interaction and soil genesis have been largely aspatial also, relating to single or typical soil profiles (as explained earlier in this chapter).   The study of nutrient cycles in natural ecosystems usually includes measurement of soil-water solutes, as well as other components of the hydrological cycle.

The relative enrichment of solutes passing through the system (Table 7.4.1.1) may be expressed by the ratio of the mean concentration of the solute at a given sample location to the concentration of that solute in bulk precipitation.   These results indicate enrichment in rock water samples, with Ca^{2+}, Mg^{2+}, Na^+ and K^+ as the most significant cations in the samples.   On the other hand, only part of the enrichment in the throughfall samples, especially of K^+, is believed to be only partly transferred to the stream water, as some is incorporated into the nutrient cycle following absorption in the soil.   Concentrations of Ca^{2+} and Mg^{2+} increase greatly in soil, rock, and stream water, probably as a result of the high levels of both ions on exchange sites within the soil and rock.

The interpretation of such data relies on a combination of hydrological, pedological and biogeochemical factors.   Such data may indicate the locus of solutional erosion within the catchment system, but still may not indicate spatial variations within the system.

Soil chemistry changes vertically (Table 7.4.1.1), by solute uptake and the capacity of the soil to neutralise percolating acidic water related to the chemistry and level of readily available solutes in the soil.   Because of the soil changes, solute uptake in the soil decreases

TABLE 7.4.2.1   COMPARISON BETWEEN THE CHEMISTRY OF BULK BEDROCK,
                  DEEP SOIL AND LOW-FLOW WATER SAMPLES

	Average of bedrock bulk analyses (ppm)	Soil at the valley bottom (drift deposition) (ppm)		Stream water at low flow (ppm)
		80 cm	100 cm	
Ca^{2+}	1102	71.0	133.0	26.0
Mg^{2+}	5522	8.8	30.0	11.0
Na^+	10280	1.6	1.3	9.4
K^+	12239	3.0	4.4	1.4
SO_4^{2-}	–	4.5	4.7	39.0
PO_4^{3-}	174	*	*	20.6
Cl^-	–	–	–	47.0
NO_3^-	–	–	–	15.0
Fe	7623	*	*	0.18
Mn	697	3.96	0.75	0.03

	Concentration of leachable element in soil (ppm in dry soil)**	
Ca^{2+}	710	1330
Mg^{2+}	88	300
Na^+	16	13
K^+	30	44
SO_4^{2-}	45	47
PO_4^{3-}	–	–
Cl^-	–	–
NO_3^-	–	–
Fe	–	–
Mn	39	7.5

*   Below the limit of detection

** Equation used = $\dfrac{\text{ppm in leach x volume solution (100)}}{\text{soil (solid) (in grams)}}$

= ppm of leachable element in soil

upslope, with a consequent increase in solutional denudation at the soil/bedrock interface. Observations of soil water solutes confirmed that soil water concentrations increased towards the lower parts of slopes.

Two special cases need to be mentioned: the role of acid rain and the cation exchange processes in the soil.

Firstly, the reaction of acid rain with bare rock surfaces on the slopes and in the channels may produce side reactions changing the original composition of the stream water. Experiments (Table 7.4.1.2) show an increase in ionic composition of the water when rock powder is dissolved in acid rain, but no increase when such powder is dissolved in distilled water. Acid rainwater runs rapidly over the bare rock, probably passing through some decomposing rocks, before entering the rock-lined stream channels.

Secondly, changes in chemical composition of waters passing through soil and rock materials mainly involve relatively rapid cation exchange reactions with soil colloidal materials, and slow acid hydrolysis reactions which decompose primary minerals. In this study examples are given of the results of these processes during flow-through of acid gley brown earth soils into surface waters. This pattern is modified during periods of high water discharge. The proportion of flow that takes different routes through the land surface, and the contact time with soil or rock, are therefore important for water composition. Sources of acidity can be generated within soil, when chemically reduced material in anaerobic environments is exposed to air by changes in the soil water regime.

7.4.3 Chemicals of Sediment Transformation during Fluvial Transport

The chemistry of sediments in fluvial transport in Macclesfield Forest (Appendix 2.1 and Appendix 2.2) is discussed here not as a source of chemistry, but as a dynamic process of sediment movement in the stream. The results indicate changes in sediment chemistry during fluvial transport, and two special cases need to be mentioned.

Firstly, the largest particles, coarse sands, contain lower concentrations than the smaller silt and clay sizes. This is due to the

large particles being derived from the sandstone source, which contains
a low level of cation, and to solution during transportation processes
in the stream system.

Secondly, the finer-grained silt and clay contains higher concen-
trations than the sand and coarse material.   Perhaps this arises
because clays can absorb more elements than big coarse sand particles.

In contrast to the fine material in the bed load, the suspended
sediment contains a low level of concentration because of the dilution
process within the system, and maybe the fine bed material had a
different history from that of the suspended material, perhaps reflect-
ing the contrast between soil surface sources and bank erosion sources
of sediment noted by Stott (1985).   The bed load silt clay potentially
has a greater capability to absorb and adsorb elements than the fine
and coarse sands (Appendix 2.1(d) and Appendix 2.2).

7.5 SUMMARY AND CONCLUSIONS

Apart from the problems associated with snow collection and analy-
sis, there are several significant points which arise from the precipi-
tation chemistry data (Fig. 7.5.1 and Table 7.4.1.1). Firstly, with
the exception of K^+, there is a consistent and progressive increase in
solute concentration between bulk precipitation volume and solute con-
centrations from all sources. Secondly, there is a greater difference
between the concentration of Ca^{2+} and Mg^{2+} in stream water and bulk
precipitation than for other solutes analysed. Thirdly, Na^+ and Cl^-
concentrations vary more in bulk precipitation than other solutes
(Fig. 7.5.1).

Weekly values of soil water solute concentrations at three depths
in the soil profile (0.5 cm to >50 cm) and soil water concentration
profiles (20-50-90 cm) (Section 7.3), indicate a general increase in
Ca^{2+}, Na^+, and Mg^{2+} concentration with increasing depth in the soil
profile, particularly during dry periods. Concentration of K^+ indi-
cates the opposite trend, whereas the concentration gradient for Cl^-
is variable. Comparison of soil water behaviour with other sources
indicates a marked reduction in the seasonal amplitude of soil water
concentrations, which is thought to reflect a significant buffering
effect. In soil water Ca^{2+} and Mg^{2+} are more concentrated than in
bulk precipitation samples.

However, it is interesting to note that, after the drought, solutes
were more concentrated in both soil water and stream water, but, except
for K^+ in throughfall, did not affect other components of the solute
cycle. It would appear that an excess of accumulated particulate
matter on leaf surfaces, often assumed to be a significant solute
source (e.g. Tamm and Troedsson, 1955), did not occur during the
drought, since this excess was not detected in subsequent throughfall
samples. These results suggest that the increase in solute concen-
tration in stream water may be related to solute supply in the soil
resulting from a number of factors. Firstly, evaporation may produce
an increase in soil water solute concentrations and a tendency for
crystallisation to occur. Secondly, increased concentrations may
result from mineralisation following long droughts (e.g. Birch, 1960).
Subsequent wetting is likely to dissolve accumulated salts (e.g.
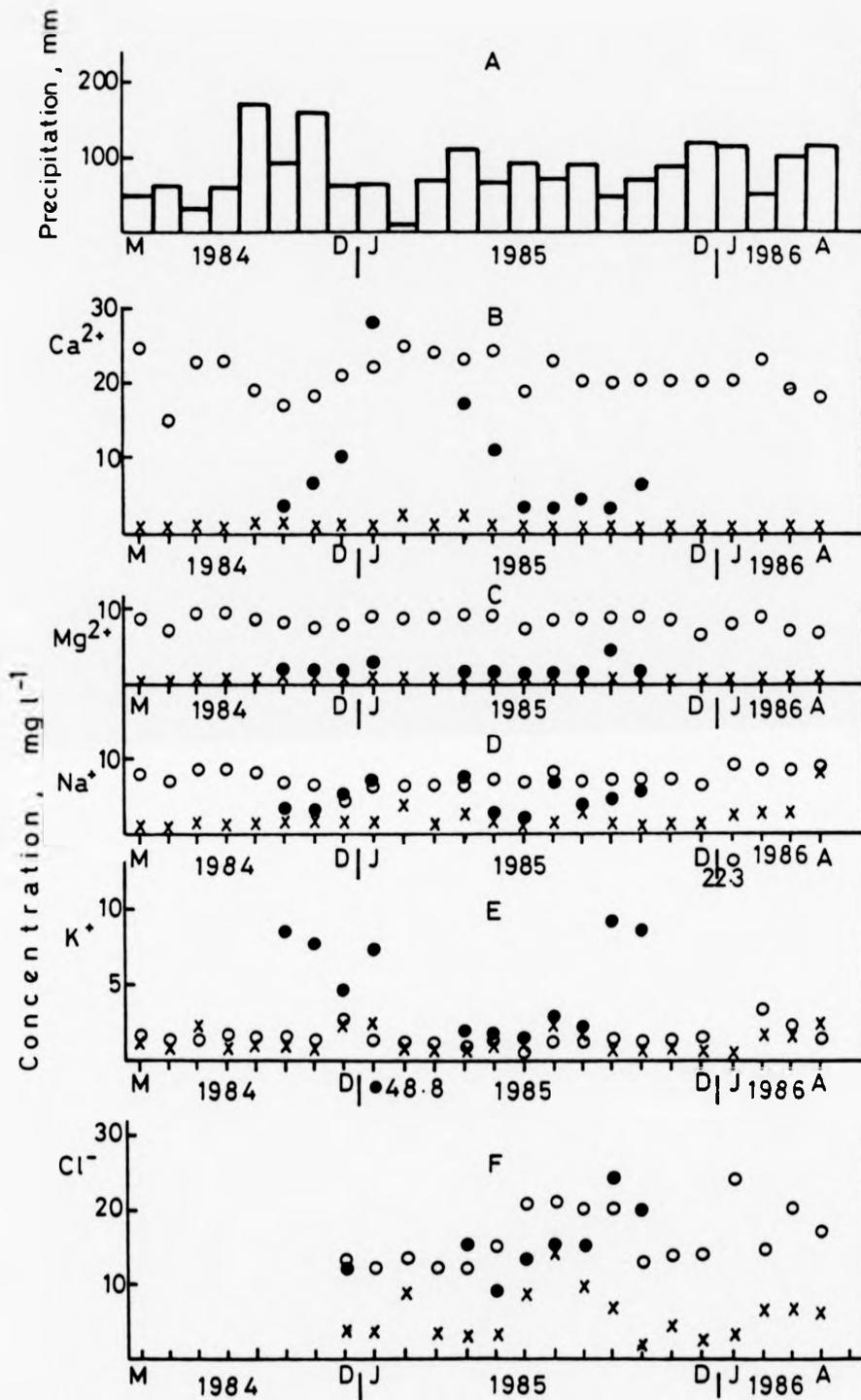
FIGURE 7.5.1   Concentration of major cations and anions in bulk
precipitation, throughfall and stream water samples
(monthly data)   /Continued
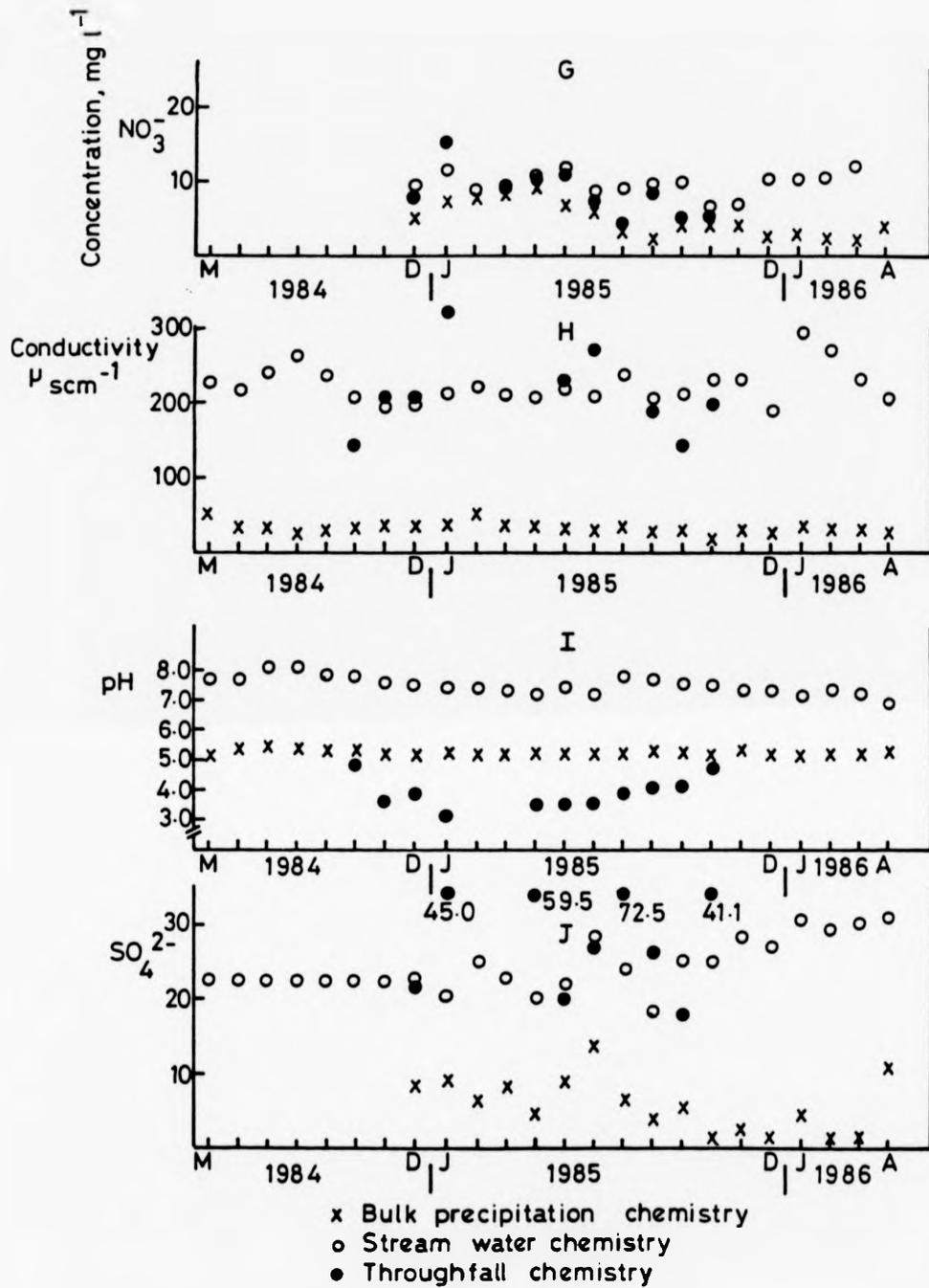
FIGURE 7.5.1 (Continued)

Walling and Foster, 1975).

The relative enrichment of all solutes is expressed by three ratios. Firstly, by relating the mean concentration of Cl^- to the concentration of all other solutes for the same sample location (Table 7.4.1.1(e)). Secondly, each solute is expressed as a ratio of its concentration in bulk precipitation (Table 7.4.1.1(b)). Thirdly, by using the equation $\dfrac{Ca^{2+} + Mg^{2+}}{Na^+ + K^+}$ for the same sample location (Table 7.4.1.1(c)). The most significant contrast between bulk precipitation and throughfall samples occurred with respect to K^+ concentrations which increased by fivefold, and Ca^{2+}, Na^+, Mg^{2+}, SO_4^{2-}, and Cl^-, with increases of between 2.4 and 10.5 times. A relative increase in K^+ concentrations of this magnitude cannot be attributed solely to the interception of wind-borne salts and/or particulate material, since this would be reflected in a major increase in the ratio of Cl^- to other solutes (Table 7.4.1.1(e)). It has been demonstrated (e.g. Bormann et al., 1969) that K^+ is a major element in nutrient cycling. Therefore, K^+ may be lost to leaf surfaces and increase concentration in throughfall samples. Subsequent stages in K^+ movement do not reflect this high concentration, especially in soil water solution. This may result from rapid adsorption on the soil exchange complex before recycling or soil buffering and nutrient cycling effects.

Similar behaviour is exhibited by Ca^{2+} and Mg^{2+}. Both are present in bulk precipitation in low concentrations and experience high Ca^{2+} and low Mg^{2+} enrichment by the process of throughfall. In contrast, both are strongly enriched in soil water solutions (Table 7.4.1.1(b,c,d)).

High concentrations of Na^+, SO_4^{2-}, NO_3^- and Cl^- are present in bulk precipitation in the ratio of approximately 1:2 respectively (in the same proportion as they occur in sea water). A slight preferential enrichment of Na^+ in soil solutions may result from the fact that Na^+ is weakly adsorbed by the soil (Hem, 1970), whereas Cl^- is not. This may also account for the relative decrease in the Cl^-:Na^+ ratio in stream water samples.

In soil water solutions NO_3^- was detectable for only short periods and yet was always detectable in the stream water. This may be a

result of accumulated windblown fertilisers derived from nearby farm-
land or a result of oxidation processes as soil water entered a sur-
face water environment.

Movement of water through a soil profile and into a stream results
in an exchange of minerals until an equilibrium is reached between the
soil solutions and exchange sites on the soil.   Smith and Dunne
(1977) have shown that this condition may be reached within a few hours
of water entering the soil profile.   In an attempt to obtain some
indication of the interaction between exchangeable cations, exchange
capacity and soil water concentrations, soil samples were collected
during July 1985.   The results (Section 7.3) provide some indication
of the implications of soil chemistry in relation to stream water
chemistry.

In general, exchangeable constituents were more concentrated in
the upper soil horizon and were dominated by the presence of Ca^{2+} and
Mg^{2+}, in contrast to the very low concentration of these elements in
bulk precipitation and throughfall.   The precipitation-dominated
cation Na^+ (Holden, 1966) and K^+ are present in much lower concentra-
tions, but the presence of Na^+ supports conclusions presented earlier.
Results in Section 7.3 show a tendency for an increase in the propor-
tion of all ions on exchange sites with increasing depth in the soil
profile.   Since increasing depth is also likely to be associated with
a slower time of travel for throughflow (e.g. Weyman, 1971), equilibrium
is more likely to be attained in deeper samples, resulting in more
concentrated soil solutions.   These results are generally consistent
with conditions experienced in soil water samples (Section 7.3,
Table 7.3.2.2(a) and (b)), although average K^+ concentrations in soil
water demonstrated an inverse trend.   This difference was attributed
to the bias in available samples introduced as a result of the sampling
programme.   Since soil water samples at 20 cm depth were only collec-
ted during winter and spring months, such levels being devoid of
water at other times, these samples are likely to contain appreciably
higher K^+ concentrations resulting from, for example, litter decompo-
sition and subsequent leaching into the upper soil horizons.

Interpretation of water chemistry behaviour in a small homogene-
ous catchment area does not rely individually upon hydrological, pedo-
logical or biogeochemical factors, but on a combination of all these,

since the interrelationship between individual ions in solution
expresses a sequence of events between an input of bulk precipitation
and an output in stream water. Relative enrichment of ions is selec-
tive, with Ca^{2+} and Mg^{2+} concentrations in soil exchange sites. In
contrast, relative K^{+} enrichment occurs in throughfall samples, but
is not translated to the stream, possibly as a result of soil buffer-
ing and nutrient cycling effects. Concentrations of Na^{+} and Cl^{-} are
high in bulk precipitation samples, which may be interpreted as a
result of close proximity to the sea (approximately 80 km to the west)
and the transport of salt nuclei in the atmosphere, since the $Na^{+}:Cl^{-}$
ratio in bulk precipitation closely approximates the same ratio in sea
water. In contrast, the ratio between Cl^{-} and K^{+}, NO_3^{-}, Ca^{2+}, SO_4^{2-}
showed a marked increase in bulk precipitation, indicating the likely
input of dry fallout. Concentrations of NO_3^{-} and SO_4^{2-} are high in
bulk precipitation samples, which may be interpreted as a result of
close proximity to industrial pollution, which produces these large
ratios of NO_3^{-}/SO_4^{2-} from the boundary area (Manchester and Sheffield),
increasing the H_2SO_4 in the atmosphere.

The results for NO_3^{-} and SO_4^{2-} are of particular interest in view
of their quantitative importance (Table 7.4.1.1(d)), with the exception
of some cases in urban areas where Cl^{-} is important. The excess con-
centrations of these components almost completely governs the acidity
and alkalinity of the precipitation. For this reason, these constitu-
ents, which in Western Europe are mainly derived from terrestrial
(industrial) sources, are of very great importance for the ecosystem.

CHAPTER EIGHT

CHEMICAL VARIATION IN STREAM QUALITY

CHAPTER   EIGHT

CHEMICAL   VARIATION   IN   STREAM   QUALITY

8.1   INTRODUCTION

This chapter describes the variation in the dissolved loads of
the catchment area.   It relates these variations to environmental
and hydrometeorological conditions by considering the dissolved load
in a similar way as the suspended load in the previous chapter.

The overall complex circulation system, comprising many different
factors involving the movement of chemical elements and compounds at,
or near, the earth's surface, has been termed the solusphere, or the
biogeochemical cycle (Hem, 1959;   Gorham, 1961;   Livingstone, 1963).
The factors affecting the movement of substances in solution, like
those influencing suspended sediment concentrations, vary in time and
space within a simple catchment system.   The variations over time in
the output of solutes from a catchment may be viewed as a function of
changing input factors.   A complex set of factors operating in a
catchment input-output system (Table 8.1.1) cause dissolved solids
concentrations to fluctuate in a different way to suspended sediment
concentrations.

Livingstone (1963) considers the relative proportion of surface
and groundwater runoff to be "the most important factor introducing
temporal variability into river water chemistry".   Groundwater has
usually been in contact with the rocks and soils of the catchment area
for a longer time, at different temperature and pH conditions, and
has passed through the soil where oxygen and carbon dioxide conditions
favour solution.   Thus, when groundwater comprises the bulk of river
flow, i.e. during baseflow, solute concentrations are greatest.
When groundwater discharge is diluted by storm runoff, solute concen-
trations decrease.   The solute concentrations vary arithmetically,
while discharges vary geometrically, so the highest flows carry more
solutes despite lower concentrations (Douglas, 1964).

TABLE 8.1.1   FACTORS THAT INFLUENCE THE DISSOLVED LOAD OF
                A STREAM

Input Factors	Effect
Temperature	Influences the solubility of ions, production of NO_3^- and CO_2, evaporation and vegetation.
Rainfall	Dilutes the dissolved load and influences the proportion of surface runoff. Supplies ions to the catchment.
Wind	Influences evaporation. Ions are supplied as dry fallout. Redistribution of precipitates in dust.
Evaporation	Influences concentration of ions in runoff.
Human activity	Introduction of waste material; pollution modifies catchment factors by influencing soil, vegetation and microclimate. Redistribution of chemical elements: fertilisers, food, industrial products, gases, fuels, etc.

Catchment Factors

Geology and soil	Composition, pore size and distribution, infiltration capacity, permeability and transmissibility of rocks and soils all influence the operation of the above factors and the variability of ions for solution.
Soil - fauna	Micro-organisms and bacteria in rocks and soil influenced by input factors, in turn influence the production of gases and encourage solution.
Vegetation	Influences the ions in throughfall and stemflow. Nutrient cycling in aquatic and terrestrial vegetation is important. Control of K^+ and NO_3^- circulation.

Fluctuations in the supply of solutes from the atmosphere represent a source of variation in the dissolved load but not the suspended load. Much of the Na^+, K^+, Cl^- and SO_4^{2-} found in streams is probably brought in by precipitation. The supply of ions from the atmosphere influences the composition of river water indirectly by altering the cation exchange of clay minerals and directly by simply increasing the dissolved load. Although more solutes are supplied to catchments bordering oceans (Stevenson, 1968) or near sources of atmospheric pollution (Gorham, 1958), the effect of atmospheric fallout is most noticeable where the dissolved load is low, for example, in areas of igneous rock. Elsewhere, ions supplied from the atmosphere form such a small proportion of the total solute load that they introduce only minor fluctuations. Other important factors that cause the solute load, but not the suspended load, to vary, include the seasonal withdrawal and release of elements from the land surface by vegetation. The complexity of the interacting biological processes that bring about these fluctuations makes the solute load more difficult to relate to catchment conditions than the suspended load. However, as the biological factors that influence the dissolved load are closely related in the prevailing hydrometeorological conditions, many of these factors may be described relatively easily in terms of measured meteorological parameters. Studies of the nutrient balance of different ecosystems (Crisp, 1966; Franz et al., 1967; Likens et al., 1967; Juang and Johnson, 1967; Ovington, 1965) visualise the solute load of a stream as expressing the output of a catchment ecosystem and as an indicator of the intensity of solutional processes. An ecosystem, at any moment in time, is analogous to a denudation system (Douglas, 1970), so that the ecosystem model, considered by biologists, has much in common with the catchment system model used to provide a framework for this section.

The selection of parameters

The factors influencing the solute load of a river are so interrelated that it is difficult to measure each factor separately. In any case, this is unnecessary, for it would be unreal to isolate individual factors from the total environmental situation in which they operate. Because the factors and the parameters used to measure them are so inter-correlated, allowance must be made for this when

interpreting statistical relationships.

With a few exceptions, the parameters used to measure the various hydrometeorological factors (Table 3(a)) in the previous chapter are again used in this chapter. It is assumed that many of the factors that influence solute loads vary seasonally with changing inputs of radiation and rainfall into the catchment. Temperature, rainfall and runoff parameters, which also vary seasonally, are used to measure the influence of these factors.

8.2   VARIATION OF SOLUTE CONCENTRATION WITH TIME

8.2.1   Introduction

Stream solute levels vary through time as well as in space, because the catchment processes which generate stream-flow and its dissolved content (Fig. 1.3(a) and (b)) are dynamic rather than static in nature.   Most attention in this study has been directed to the effects of hydrological conditions, and more specifically to the nature of the relationship between water chemistry and stream-flow discharge.

This section examines the general characteristics of stream water chemistry in the study catchments, based on the weekly samples from seven sites.   The broad characteristics of these waters can be illustrated by plotting their actual composition as a time series trend (Section 8.2.2).   Solute concentrations can also be studied in terms of their variation during storm events (Section 8.2.3) and in space from point to point in a catchment area (Section 8.2.2).   Finally, relationships between individual ionic concentrations and discharge vary widely (Section 8.3.2).

8.2.2   Seasonal Fluctuations in Water Quality and Seven Sampling Sites

The time series plots of solute concentration reveal that the annual patterns of solute behaviour vary between stations and according to the ion under consideration.   Seasonal fluctuations of Ca^{2+} and Mg^{2+} are more pronounced than those of Na^+ and K^+ concentrations, which are strongly affected by the random impacts of storm events (Figs. 8.2.2.3 and 8.2.2.5).   This section deals with the simple variation during the time for each species.

1.   pH

At all the stations the waters increase in acidity with increasing discharge (Fig. 8.3.2.2).   Precipitation is the largest contributor of hydrogen ion to the system.   The average pH of rainfall at precipitation sampling sites ranges from pH 4.9 to 5.7.   However, the mean pH of stream water at headwater sites, ranging from 7.4 to
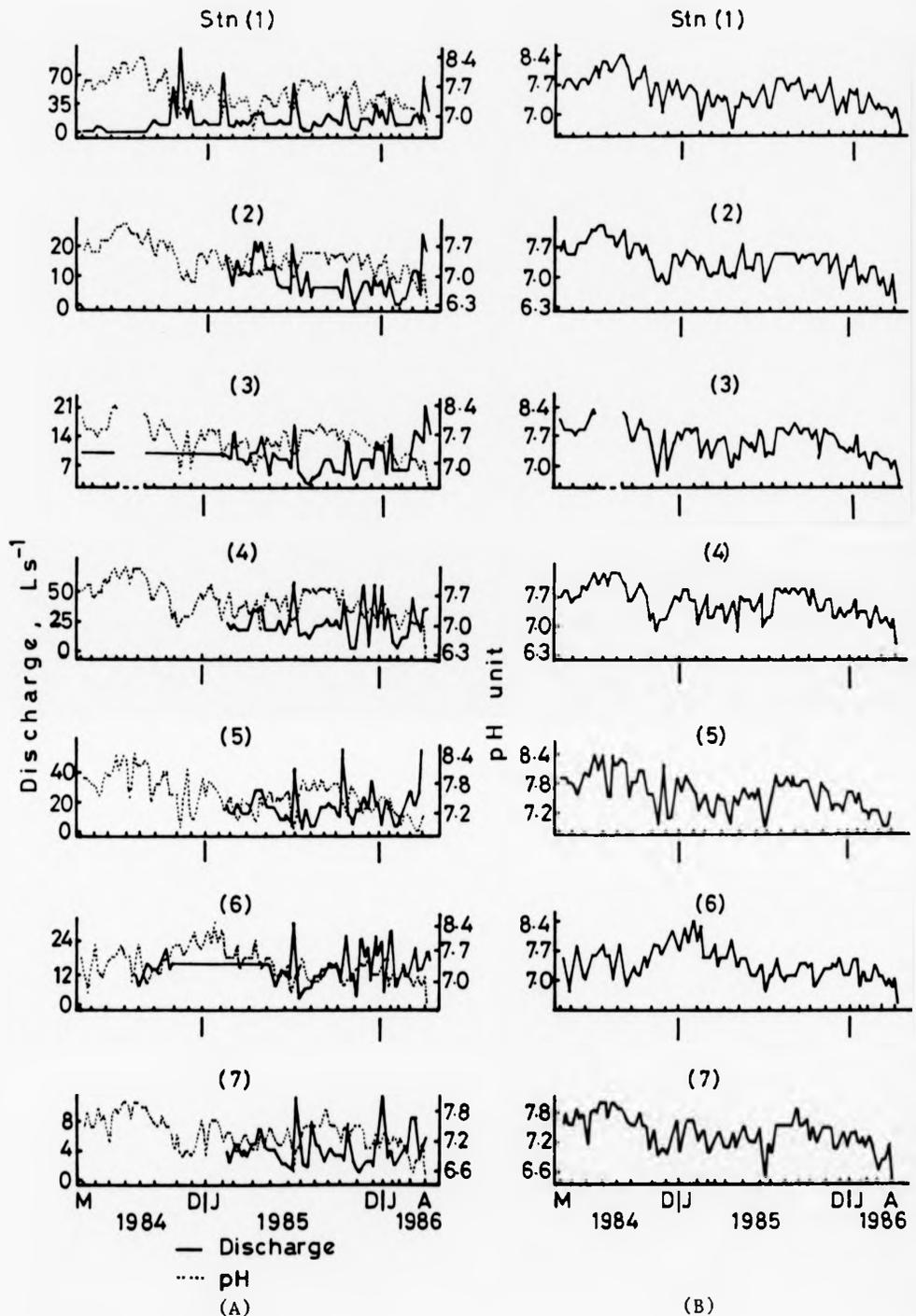
FIGURE 8.2.2.1 (A) & (B)

(A) Relationship between pH and discharge in stream water. Data were obtained weekly during 1984-86

(B) Temporal variation in pH during 1984-86
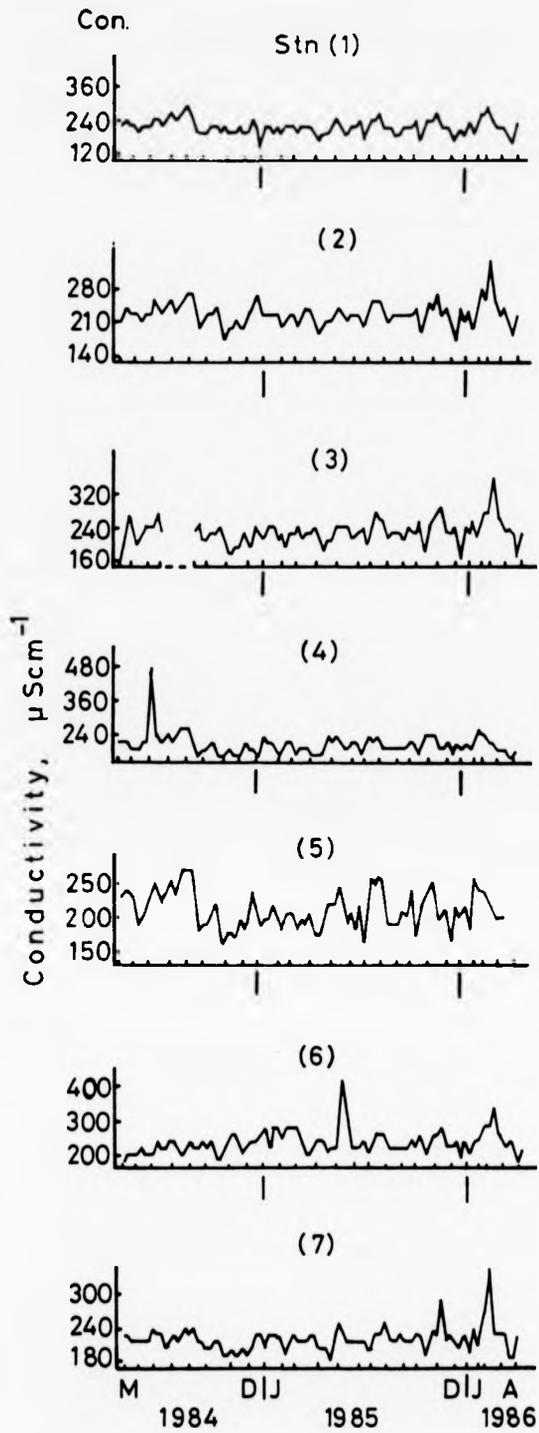
FIGURE 8.2.2.2

Coombs Brook catchment 1984-86
Temporal variation in conductivity ($\mu S\ cm^{-1}$)
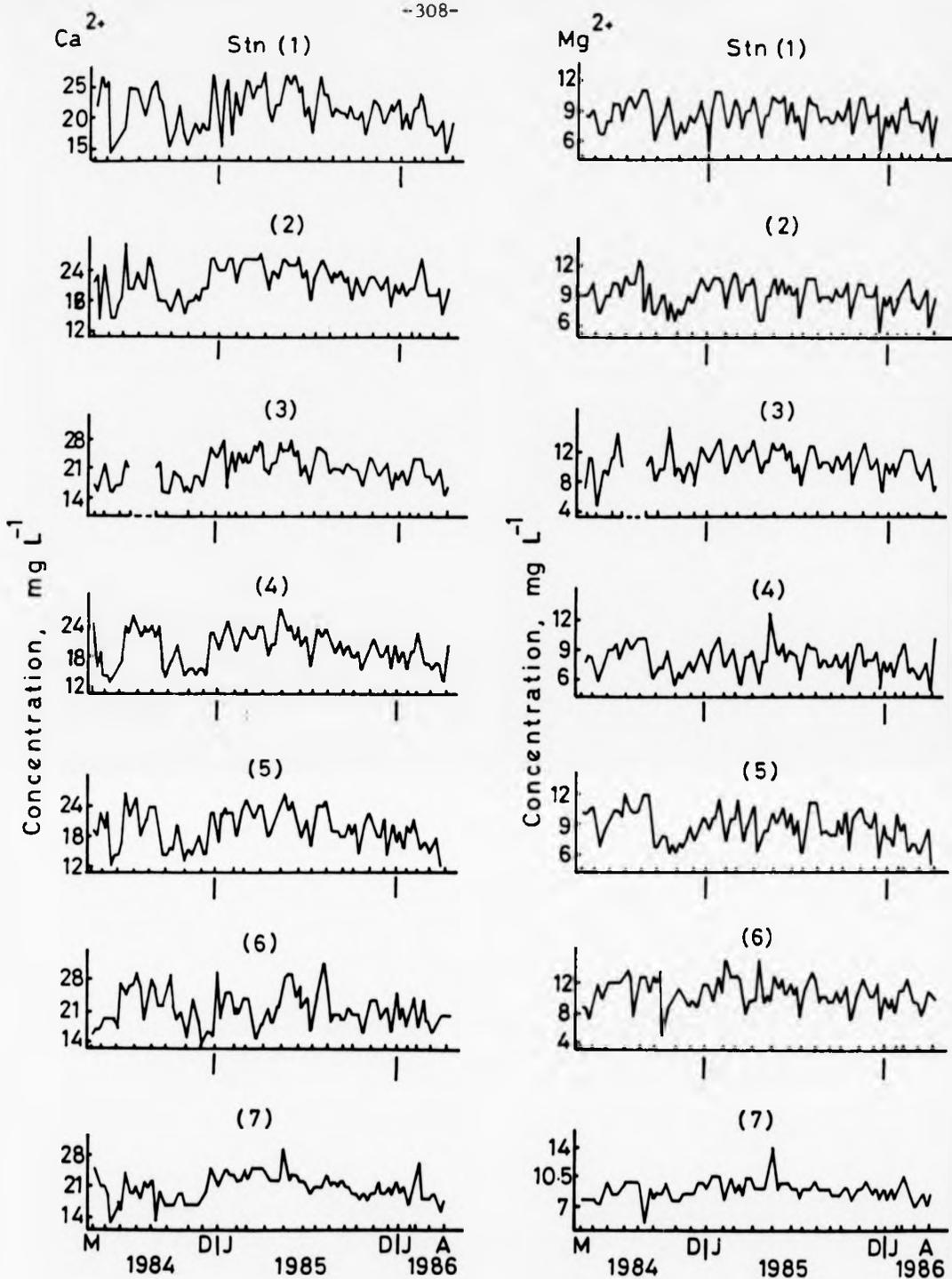
FIGURE 8.2.2.3   Coombs Brook catchment 1984-86
Temporal variation in Ca^{2+} and Mg^{2+} concentration (mg 1^{-1})
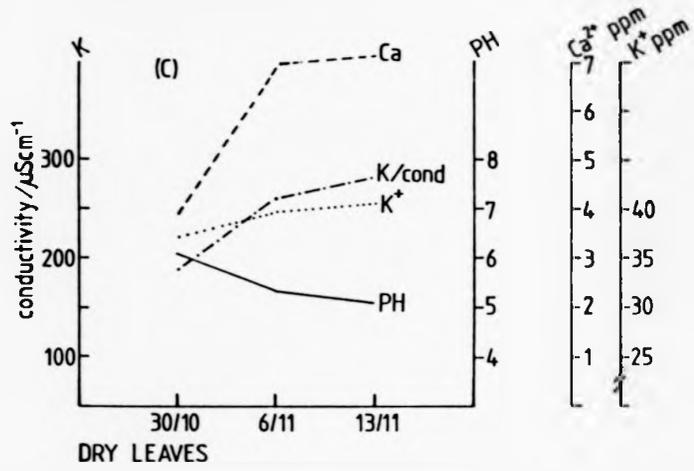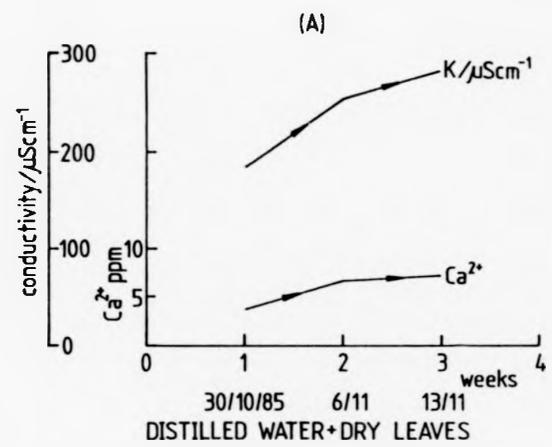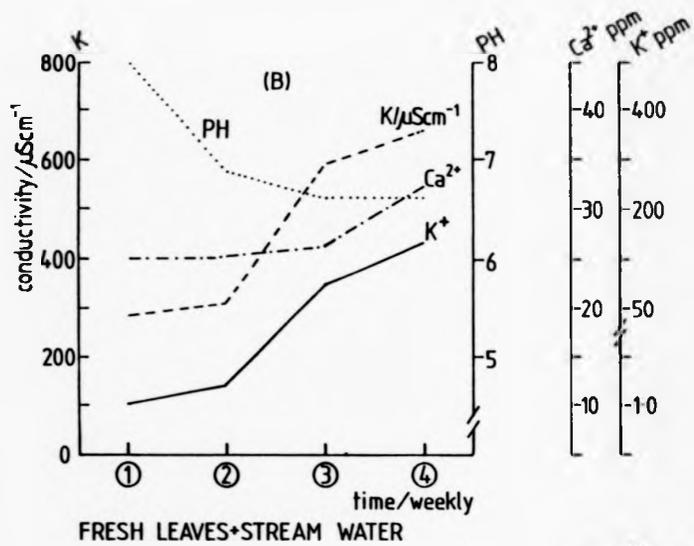
FIGURE 8.2.2.4 (A), (B) & (C)

Leached Ca^{2+} and K^+ concentration from dry and fresh leaves in the catchment area
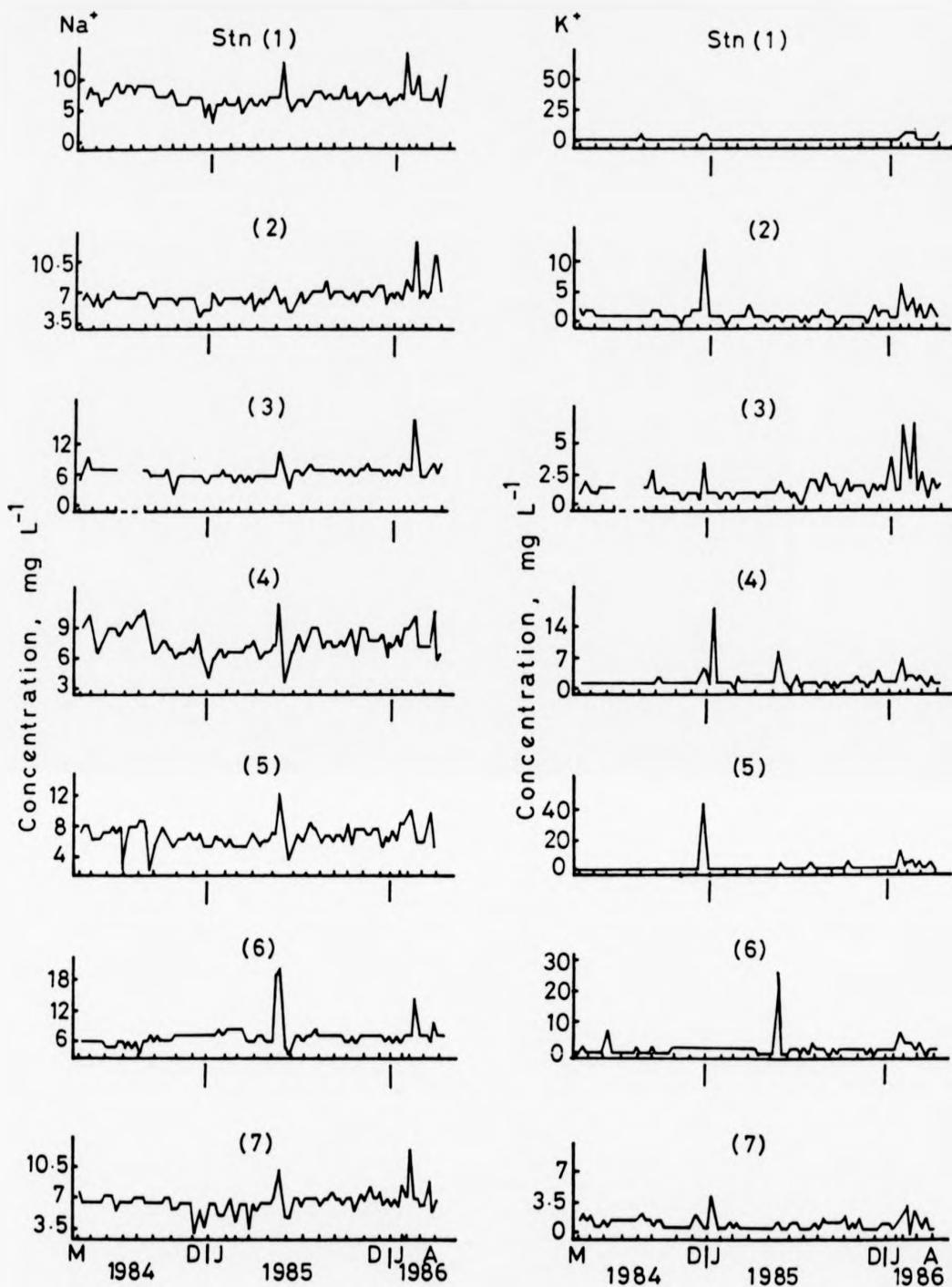
FIGURE 8.2.2.5   Coombs Brook catchment 1984-86
Temporal variation of Na$^+$ and K$^+$ concentrations (mg l^{-1})
at seven sites
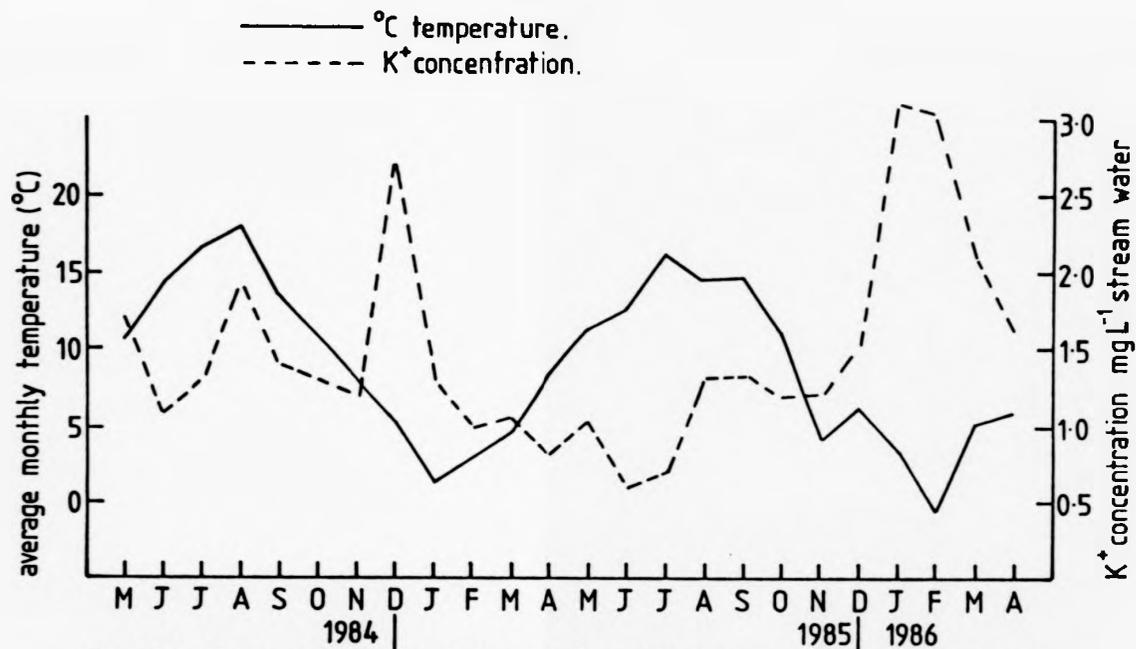
Fig.8·2·2·6. The relationships between K$^+$ concentration in stream water and the monthly average temperature in Coombs Brook during the study period.
(1984-86)

-312-
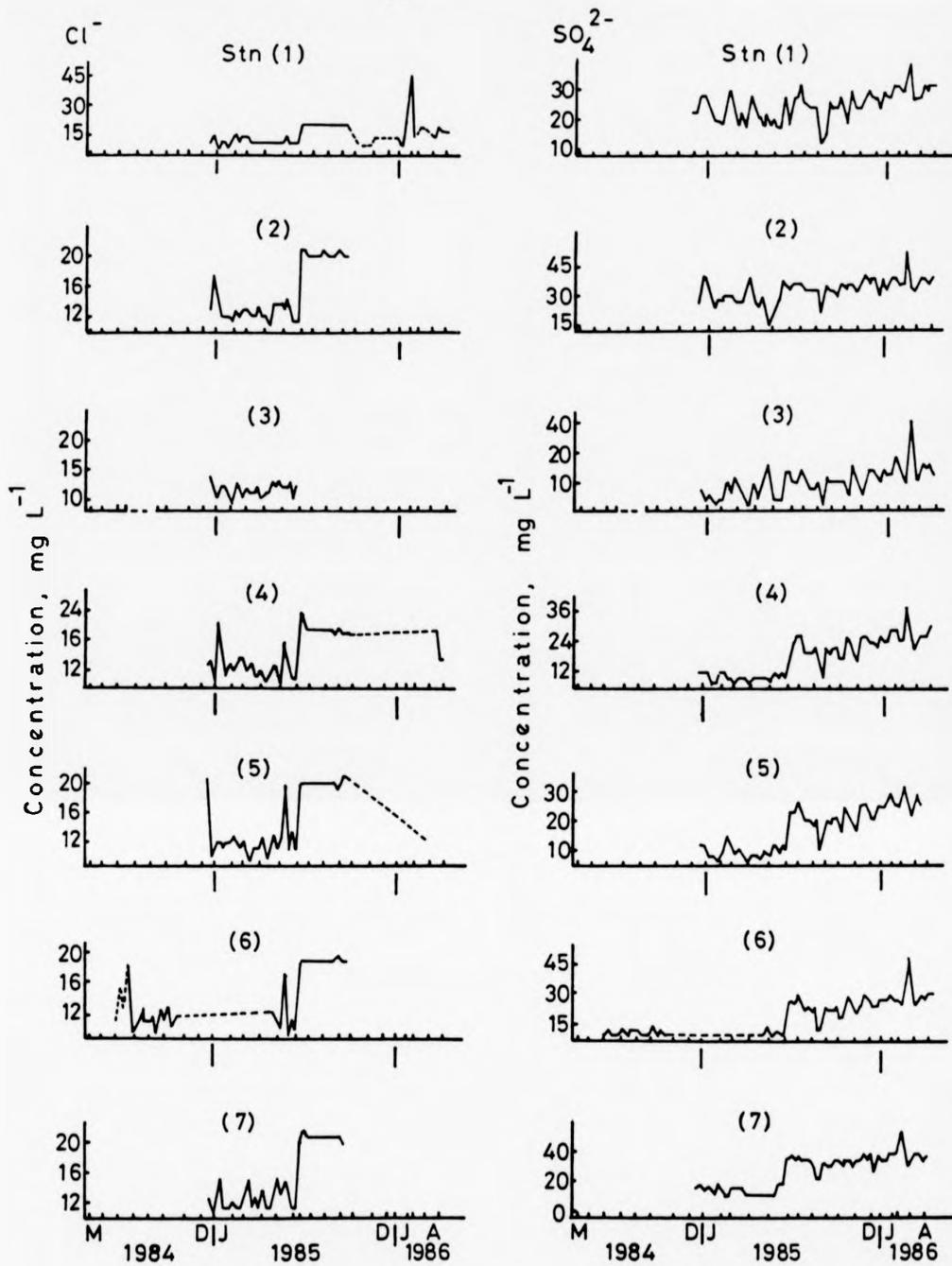
FIGURE 8.2.2.7   Temporal variation of Cl^- and SO_4^{2-} concentration
(mg 1^{-1}) at seven sites in the catchment
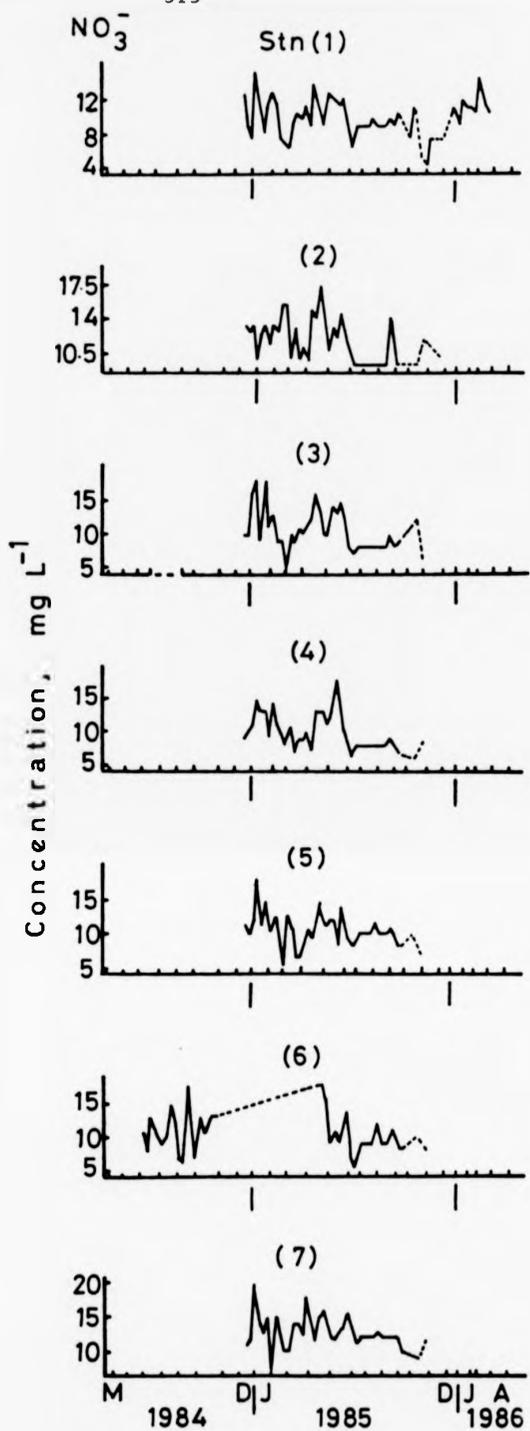
FIGURE 8.2.2.8   Temporal variation of NO_3^- concentration (mg 1^{-1}) at seven sites in Coombs Brook
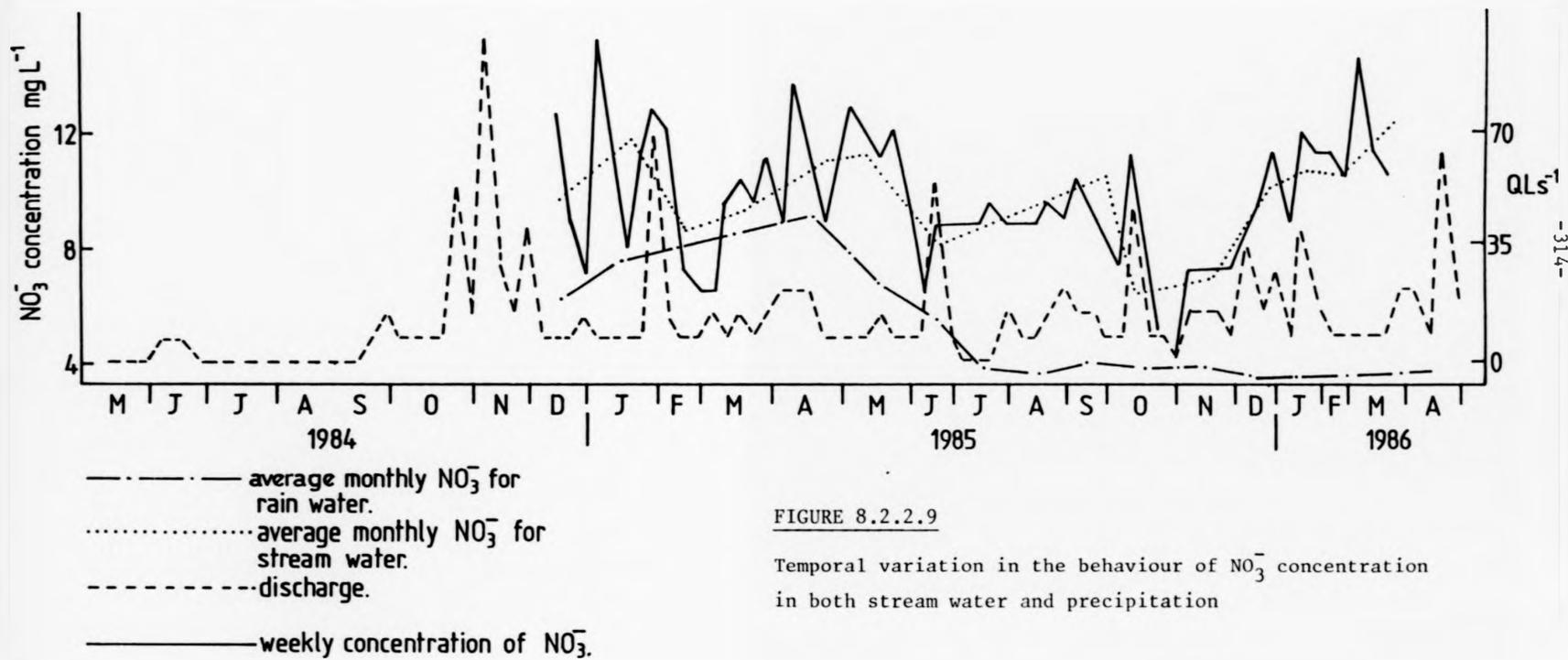
FIGURE 8.2.2.9

Temporal variation in the behaviour of NO_3^- concentration in both stream water and precipitation

—·—·— average monthly NO_3^- for rain water.

················ average monthly NO_3^- for stream water.

------- discharge.

——————— weekly concentration of NO_3^-.
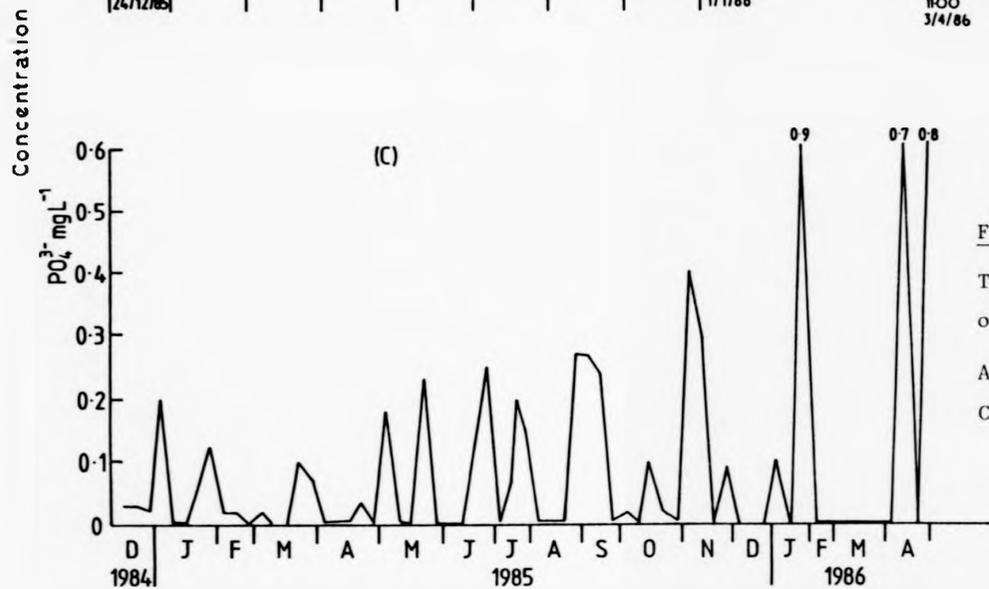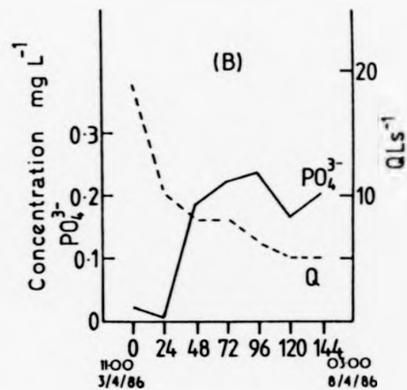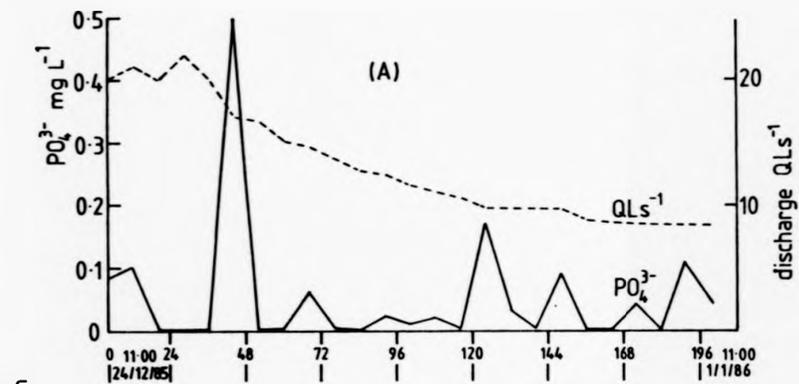
FIGURE 8.2.2.10 (A),(B) & (C)

Temporal variation in the behaviour of PO_4^{3-} concentration

A & B   eight hourly intervals

C   during study period

7.7 (Table 8.2.2.1) is virtually the same as that at Station 1 (7.5). Differences in pH at specific places and times are due to the increasing mixing with the soil throughflow as the water moves downstream (Table 8.2.2.1 and Fig. 8.2.2.1(a) and (b)).

Although runoff is generally alkaline (6.6 - 8.4 pH), especially during dry conditions in summer time, during wet conditions, especially in winter, when quick return flow supplies most of the runoff, the pH range may fall to between 6.6 and 7.3. Thus pH tends to decrease as discharge increases, with a growing contribution of surface runoff and channel precipitation to stream flow.

2. Conductivity

At all sites, specific conductance (Fig. 8.2.2.2) varied greatly throughout the two year study period, being relatively high in dry periods and lower in wet periods. This was mainly due to higher rates of evaporation in dry periods producing higher solute concentrations. However, dilution effects following precipitation events would tend to reduce solute concentrations and specific conductance. The trend in conductivity thus reflects the relative contributions of groundwater and quick return storm flows.

3. Calcium and magnesium

Figure 8.2.2.3 and Table 8.2.2.2 indicate that both the Ca^{2+} and Mg^{2+} show similar responses to changes in discharge. Both are diluted by increasing discharge, more so at Station 1 than at the headwater sites. Although the flattening of the curves at higher discharges at Sites 2, 4 and 7 may suggest the operation of an additional buffering mechanism, it is more likely to be caused by the relatively uniform chemical concentrations found in overland flow. As Gregory and Walling (1973) state, at very high discharge the dilution effect becomes progressively less significant and concentrations are dominated by the near constant solute content of the storm runoff component. The contribution of groundwater to the stream is not necessarily proportional to the runoff (Table 8.2.2.3), the release of Ca^{2+} in litter probably being related to an increase in solubility of litter components as temperatures rise (Fig. 8.2.2.4(a,b,c)). Such factors are difficult to account for and may partly explain the poor prediction

TABLE 8.2.2.1   MEAN pH OF STREAM WATER AT THE SEVEN SAMPLING SITES

Station No.	No. of samples	Mean pH	Standard deviation	Variance
1	99	7.5	0.367	0.135
2	98	7.41	0.368	0.136
3	90	7.5	0.358	0.128
4	98	7.52	0.379	0.143
5	99	7.57	0.378	0.143
6	96	7.38	0.350	0.123
7	97	7.39	0.333	0.111
Total	677	7.43	0.361	0.131

TABLE 8.2.2.2   MONTHLY CALCIUM CONCENTRATION (mg l^{-1}) IN

STREAM WATER AT STATION 1, COOMBS BROOK, 1984-86

	Maximum Ca^{2+}	Minimum Ca^{2+}	Mean Ca^{2+}	Mean daily outflow $l\ s^{-1}$	Rainfall mm/month	No. of storm events
1984-85						
May	27.2	22.2	25.2	4.06	51.4	4
June	17.5	13.5	15.3	6.50	76.1	4
July	25.5	18.5	23.7	3.46	33.9	5
August	26.5	20.5	23.6	3.35	61.8	4
September	23.0	15.0	19.3	13.0	170.2	4
October	22.0	15.0	17.5	19.0	96.7	6
November	19.0	17.0	18.2	47.4	160.2	4
December	27.0	15.0	21.2	11.1	62.4	4
January	26.0	17.5	22.5	14.5	63.5	5
February	26.5	23.5	25.5	9.7	8.4	-
March	27.5	21.0	24.5	10.1	71.6	5
April	27.5	19.5	23.3	20.1	110.7	5
1985-86						
May	27.0	20.4	24.3	11.0	63.9	5
June	22.0	16.5	19.9	12.6	94.6	3
July	26.7	20.4	23.7	5.4	73.5	4
August	21.9	19.7	20.7	13.4	92.8	5
September	22.0	20.3	20.8	11.5	48.0	5
October	23.5	17.1	20.9	13.3	72.8	5
November	21.7	19.2	21.6	13.6	91.0	4
December	22.6	18.4	20.7	24.7	117.0	5
January	21.3	17.7	19.8	23.6	114.9	4
February	24.1	22.4	23.2	8.1	56.0	5
March	22.5	16.8	19.2	19.6	102.2	4
April	19.9	14.4	17.9	23.5	111.5	5

TABLE 8.2.2.3   IONIC RATIOS OF MAJOR ELEMENTS IN COOMBS BROOK,
CALCULATED IN meq PER MILLION

Station No.	Mg^{2+}/Ca^{2+}	Ca^{2+}/Mg^{2+}	$\dfrac{Ca^{2+} + Mg^{2+}}{Na^{+} + K^{+}}$	$\dfrac{Na^{+} + K^{+}}{Ca^{2+} + Mg^{2+}}$
1	0.657	1.52	4.72	0.211
2	0.688	1.45	5.79	0.172
3	0.812	1.23	5.77	0.173
4	0.663	1.506	4.38	0.228
5	0.735	1.360	4.82	0.207
6	0.813	1.229	5.586	0.178
7	0.710	1.408	5.581	0.179

of Ca^{2+} concentrations by the regression models.

The low concentrations of Ca^{2+} and Mg^{2+} in the stream water and in precipitation at Coombs Brook suggest that variations in the atmospheric supply of these ions are unlikely to influence concentrations at Station 1. The release of Ca^{2+} by vegetation may partly account for the autumn increase in the concentration, in particular in the period between 10th September - 19th November, revealed by field observations and experiments. However, seasonally, Ca^{2+} concentrations in Coombs Brook were highest in summer.

4. Sodium and potassium

Concentrations of Na^+ are higher during the summer period with low flows, and lower or more variable in the winter and spring (Fig. 8.2.2.5).

Concentrations of K^+ in the catchment are generally low, ranging from 1.2 to 2.0 mg l^{-1}. The K^+ concentration has a pronounced annual variation, maximum concentrations occurring in the winter months of December, January and February, and minimum concentrations in the summer months of May, June and July (Fig. 8.2.2.5). Unlike the trend noted elsewhere for a positive relationship with the discharge, K^+ shows no distinct relationship to discharge at Station 1 (Fig. 8.3.2.3). The K^+ concentration varies with most of the hydro-meteorological parameters and is associated very significantly with seasonal runoff, temperature variation and catchment wetness variation. Half of the variance is associated with the seasonal runoff variation. The high value of K^+ in throughfall and low value in stream water suggest that much of the K^+ available for solution is cycled through vegetation and is thus not released to stream water except when washed off vegetation during storms. Although the K^+ concentration is inversely related to the mean monthly temperature (Fig. 8.2.2.6), it is positively related to the water temperature. This might be due to evaporation increasing the K^+ concentration, as it does the Na^+ concentration, during the summer.

5. Chloride and sulphate

Most of the variation in the concentration of Cl^- at Sites 1 to 7

which ranges from 9.1 to 47.0 mg l^{-1}, is associated with storm events. The importance of storm events appears to produce a closer relationship of Cl^- concentration to discharge at high, rather than at low, rates of runoff, as indicated by the wide scatter of points at low flows in the discharge:Cl^- concentration relationship (Fig. 8.2.2.7).

The highest SO_4^{2-} concentrations at Sites 1 to 7 were recorded between January, February and March, and the lowest concentrations between May and August (Fig. 8.2.2.7). This seasonal relationship is reflected in a positive association of the SO_4^{2-} concentration with the catchment wetness-runoff component. Concentrations of SO_4^{2-} are high in winter when the catchment is wet and runoff high. Although some SO_4^{2-} may be derived from organic matter, it is probable that most of it is supplied by rainwater washing out atmospheric contaminants.

There are other changes in Cl^- and SO_4^{2-} concentrations, which seem to be independent of discharge variations. During January there was a drop in the concentration which was part of a general decrease in snow period. Again, while there is a general increase in summer, there are also fluctuations from day to day revealed by automatic eight-hourly sampling, which exceed any analytical errors. The concentrations of both Cl^- and SO_4^{2-} vary only slightly in the ranges 16 to 21 mg l^{-1} Cl^- and 20 to 25 mg l^{-1} SO_4^{2-}, and there is no clear explanation except the change in discharge.

6. Nitrate

The concentrations of NO_3^- have a significant positive relationship with discharge, particularly in Site 1 (Fig. 8.2.2.9). During summer-time, NO_3^- is supplied from baseflow, with little being leached from soil. Also periods of high flow result in the addition of increased NO_3^- from the land, while the summer concentrations may be reduced by uptake by plants.

7. Phosphorus

Concentrations of PO_4^{3-} in Coombs Brook (Fig. 8.2.2.10(a) and (b)) do not exceed 1.0 mg l^{-1} in precipitation or stream water. Concentrations appear to be unaffected by discharge or hydrograph state.

Values are highest in summer when baseflow is the dominant source of stream discharge.

Summary of the seasonal variation

Marked seasonal changes in the concentrations of some determinants were observed, particularly at Station 1, where concentrations were often substantially higher than at sites in the headwater stations, 2-7. For example, Ca^{2+} concentrations at Site 1 were generally lower during winter periods and higher during summer periods, but at headwater sites (e.g. Site 7) such a clear pattern was not observed (Fig. 8.2.2.3). The seasonal pattern of variation of concentrations of Mg^{2+} was generally similar to that of Ca^{2+}.

Lower concentrations of K^+ and Na^+ were observed at all sites during the study period (Fig. 8.2.2.5), although all sites (1 to 7) showed no clear seasonal pattern in K^+ and Na^+ concentration.

Concentrations of NO_3^- showed little pattern of change during 1985 and early 1986 (Fig. 8.2.2.9), but most sites were characterised by substantial increases in concentrations (from 4 to 15 mg l^{-1} at Site 1) during winter months, but summer concentrations were similarly variable between sites (Fig. 8.2.2.8).

Concentrations of Cl^- and SO_4^{2-} over the period of study were characterised by rapid fluctuations, particularly in Site 1. Exceptionally low concentrations of Cl^- and SO_4^{2-} were recorded at many sites during the low-flow period. There was no regular seasonal pattern in Cl^- and SO_4^{2-} concentrations at all sites over the period December 1984 - April 1986, except that winter concentrations were consistently highest (see Fig. 8.2.2.7).

Concentrations of PO_4^{3-} fluctuate over such a small range and are so low that it is difficult to explain their temporal and spatial variations. As PO_4^{3-} is often released from decomposition of animal wastes, the random droppings of deer and other forest animals may produce much of the variation.

8.2.3 Variation in Water Quality during Storm Events at Station 1

Introduction

Water levels in the Coombs Brook rise and fall rapidly in response to rainfall, and thus regular weekly sampling tends to include few samples on the rising limb or near the peak of a flood. Relationships between concentration and discharge observed from the weekly samples may not be representative of conditions of rapidly changing flow at the onset of a storm. Therefore, variations during storm events were investigated from the samples collected at eight hourly intervals by an automatic sampler at Station 1.

1. Variation of calcium, magnesium, sodium, potassium, chloride and sulphate

The behaviour of these ions differs during storms, Ca^{2+}, Mg^{2+}, Na^+ and Cl^- showing similar patterns of variation of concentration, but K^+ and SO_4^{2-} behaving quite differently. The variations and trends in Ca^{2+}, Na^+, Cl^- and K^+ concentrations in two storms (Fig. 8.2.3.1(a) and (b)) reflect the hydrological differences between the storms.

The behaviour of Ca^{2+}, Mg^{2+}, Na^+ and Cl^- will be discussed first. All these ions show the 'lag effect'. Concentrations remain steady at the baseflow levels during the early stages of the rise, as stored soil water is flushed into the stream. Then, as water from the shallow sub-surface soil horizons begins to dominate stream flow, concentrations drop. They remain at this level throughout the falling limb of the hydrograph until this water has drained out of the soil and flow is again composed mainly of water from the deeper soil horizons.

This pattern is clearer in the October storm because of the more rapid flushing of water out of the soil in that storm (Fig. 8.2.3.1(a)). The size and steepness of the drop in concentration are smaller in the March storm because the soils became saturated more slowly, and hence the transition from baseflow to flood flow was more gradual. Thus, the drop in concentration varies with the hydrology of the storm. It is most marked when a heavy storm follows a dry spell, as on
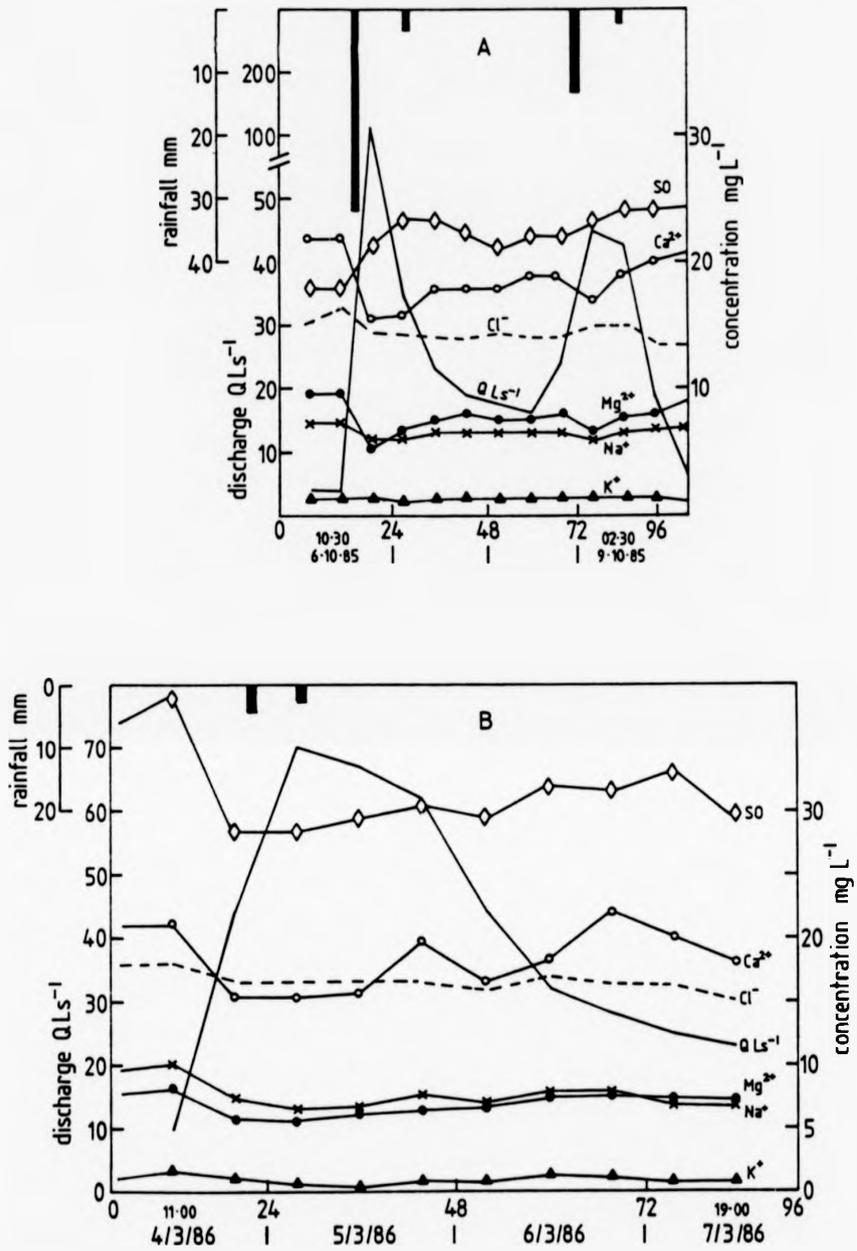
FIGURE 8.2.3.1 (A) & (B)

Temporal contrasts in behaviour of concentrations during storm events

A   in October 1985, and

B   in March 1986
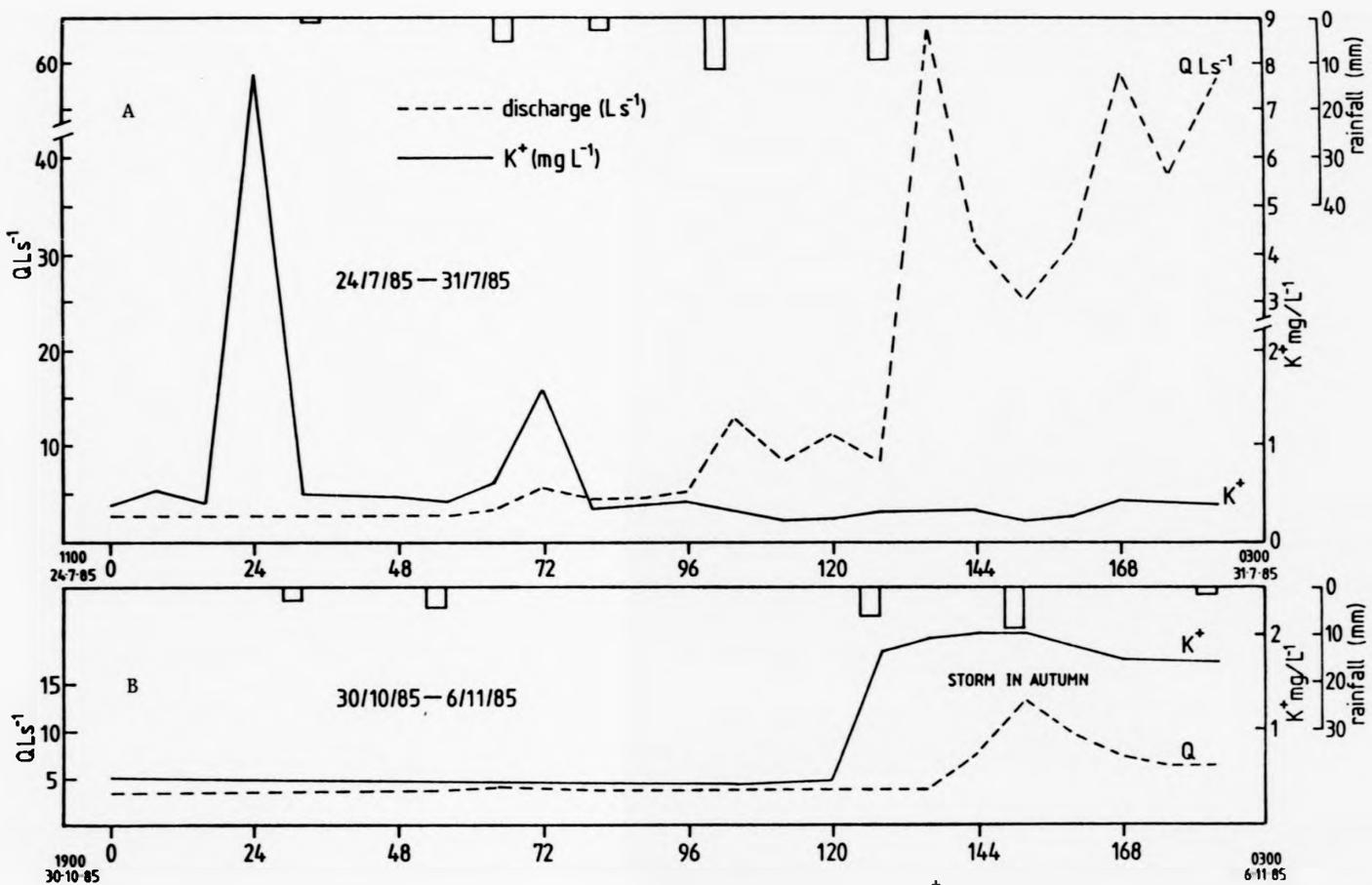
FIGURE 8.2.3.2 (A) & (B)   Temporal contrasts in the behaviour of K$^+$ concentrations during storm events in summer and autumn 1985
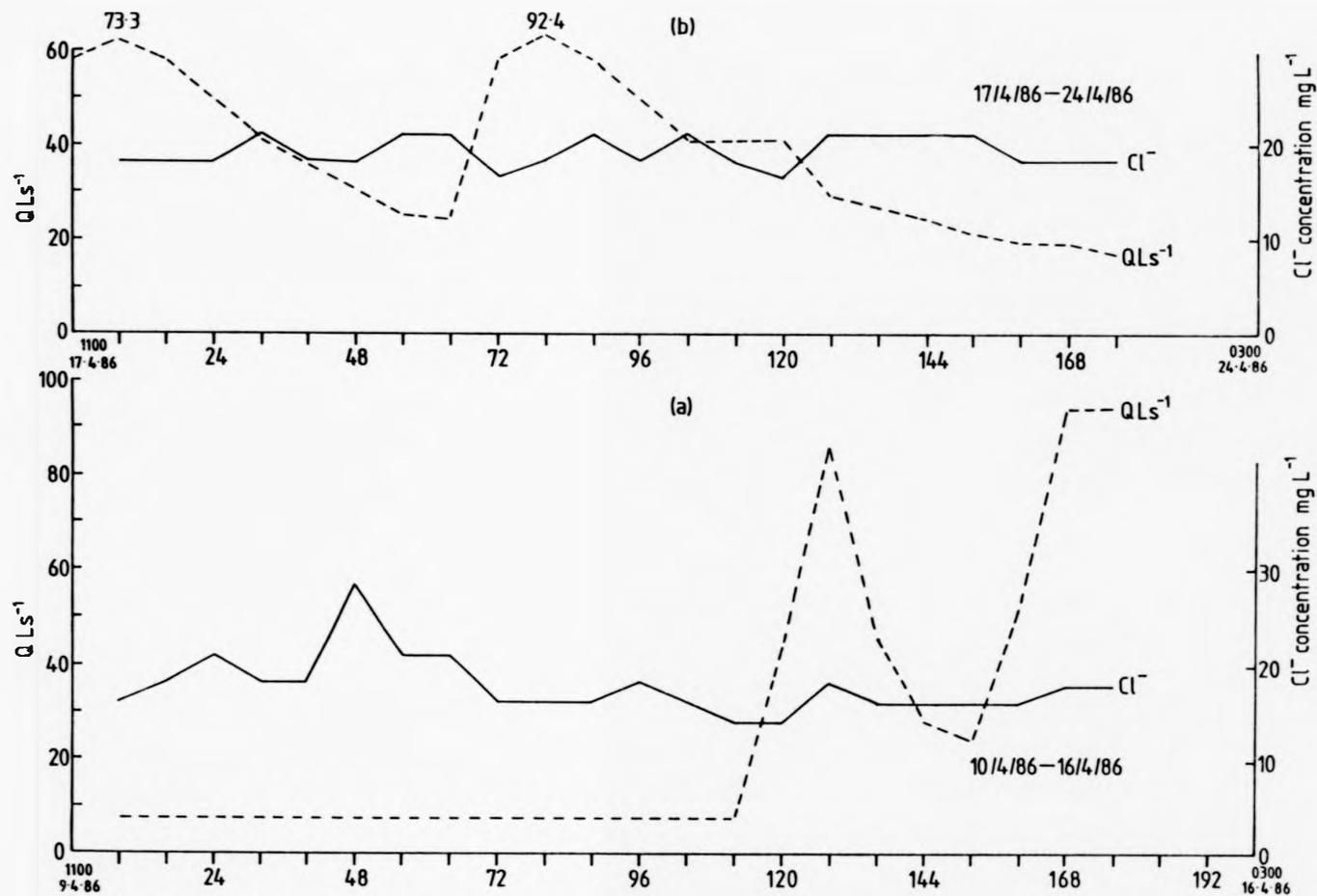
FIGURE 8.2.3.3 (a) & (b)   Temporal variations in stream flow quality, variations in the behaviour
of Cl$^-$ concentrations during: (a) 9th-16th April 1986; (b) 17th-24th April, 1986
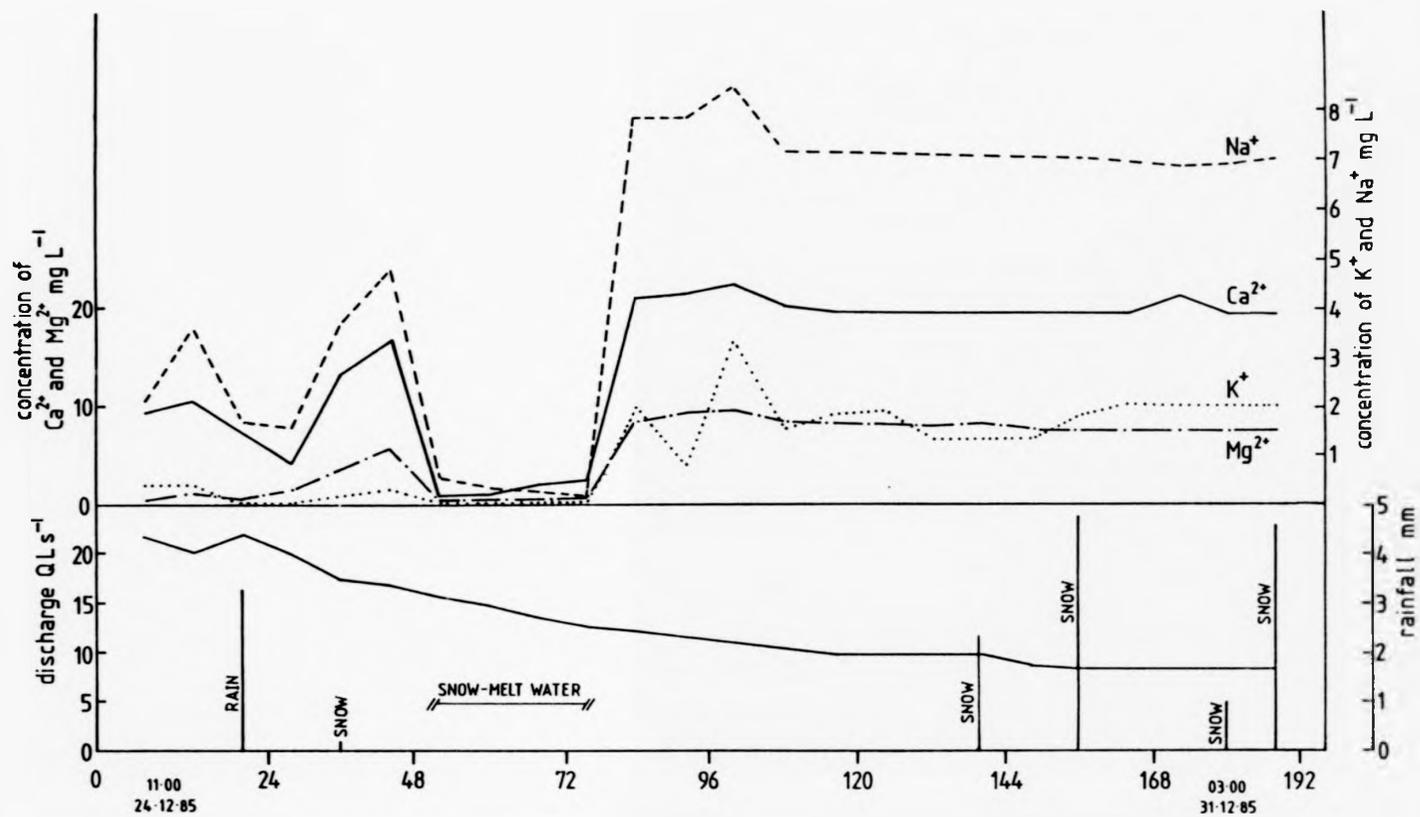
FIGURE 8.2.3.4   Temporal variations in stream flow quality, variations in the behaviour of individual ion concentrations during the period 24-12-85 to 31-12-85
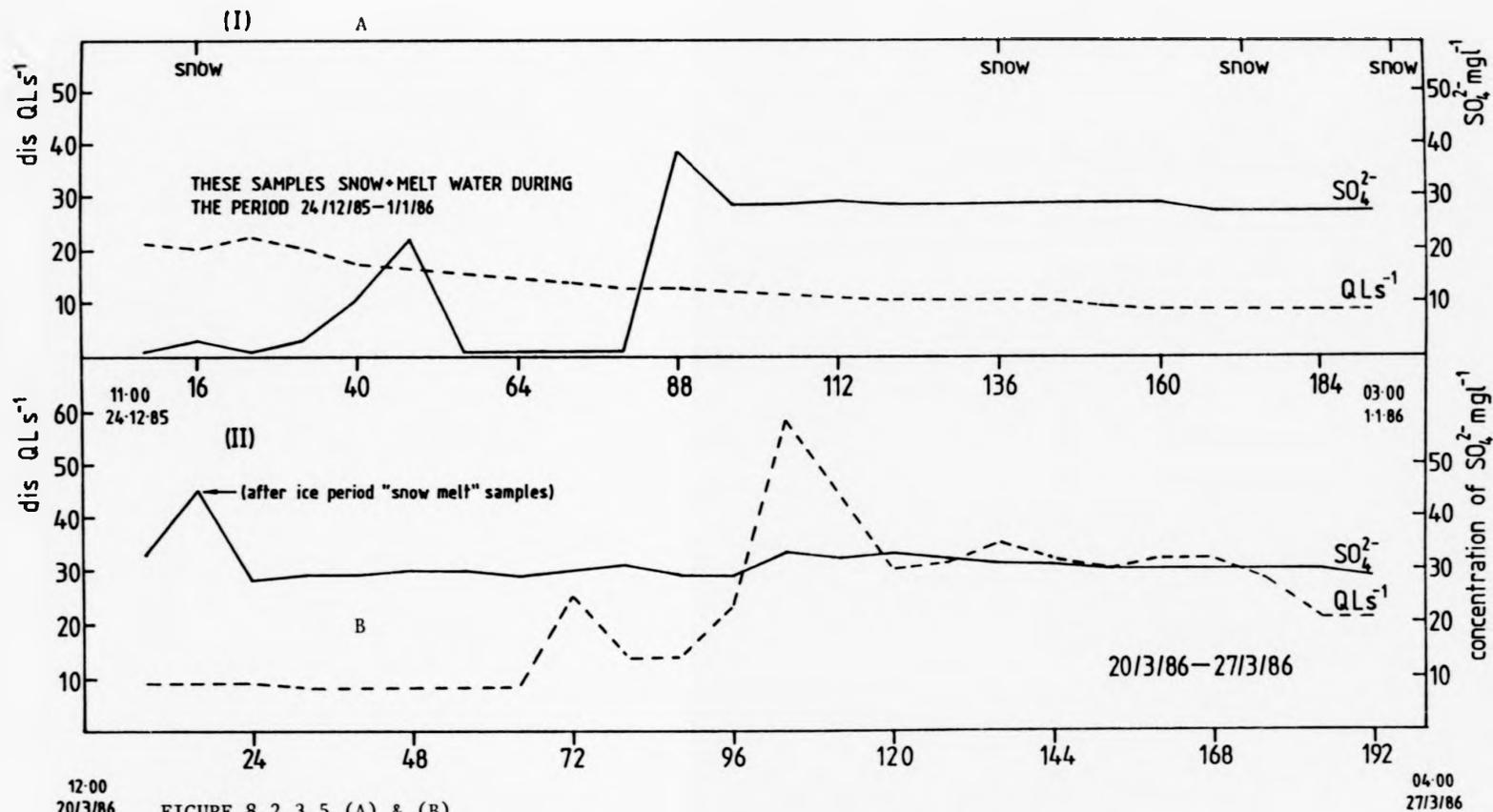
FIGURE 8.2.3.5 (A) & (B)

Temporal variations in stream flow quality, variations in the behaviour of SO_4^{2-} concentrations during (I) 24-12-85 to 1-1-86, and (II) 20-3-86 to 27-3-86
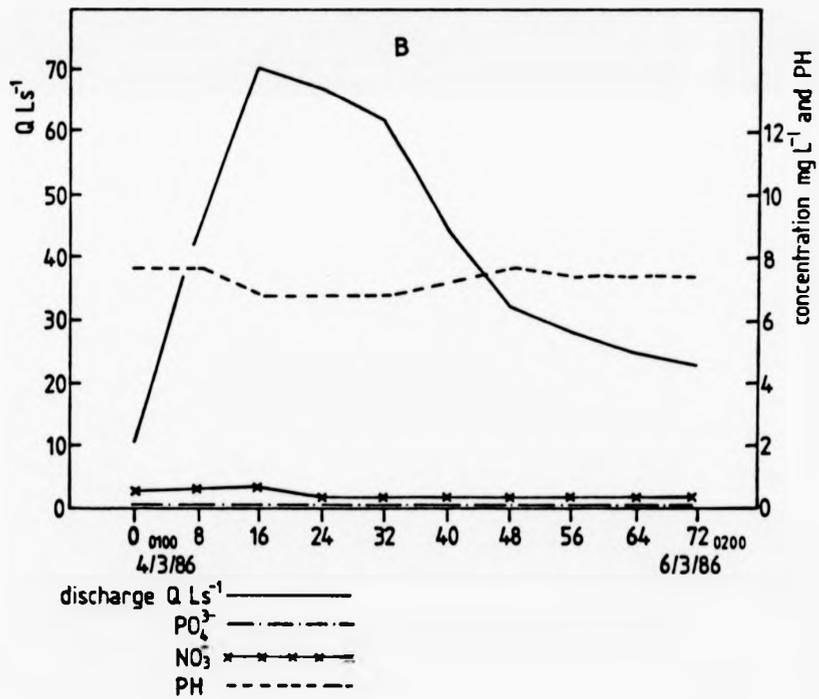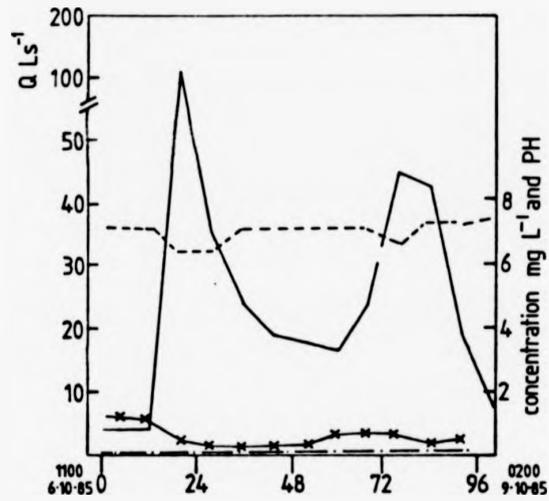
FIGURE 8.2.3.6 (A) & (B)

Variation of pH, PO_4^{3-} and NO_3^- concentration during storm events in Coombs Brook

A - October 1985   B - March 1986

6th October 1985. Any subsequent storm, while the soils are still saturated, will result in a much smaller drop in concentration, as shown by the storms on 6th and 9th October 1985 (Fig. 8.2.3.1(a)).

Although the overall pattern is the same for all four ions, there are slight differences between the patterns of the ions (Fig. 8.2.3.1(a) and (b)). A smaller overall drop in concentration is shown by Cl^- than the other ions. A significant drop in concentration of Ca^{2+}, Mg^{2+} and Na^+ is shown during the storms, but, whereas Ca^{2+} and Mg^{2+} concentrations remain low for a long time, Na^+ concentrations begin to rise slowly soon after peak flow (Fig. 8.2.3.1(a)). This behaviour is reflected in the weekly samples, those at high flows being richer in Na^+ relative to Ca^{2+} than those at low flows.

As in the weekly samples, K^+ behaves differently from the other cations. Its concentration rises during the rising limb and peak flow periods of the storm, then falls sharply and remains low throughout the falling limb. This trend is much more pronounced in the November storm (Fig. 8.2.3.2(b)). The flood water flushes out K^+ from the upper horizons of the soil as it begins to flow through these horizons. During dry weather a reservoir of readily mobilised K^+ may be built up in these horizons by mineralisation of organic matter (Fig. 8.2.3.2(a)).

As a major nutrient, K^+ is retained within the soil and cycled through the vegetation efficiently. The effect was much more pronounced in the October storm because it occurred at the end of the growing season, when the annual litter fall provided an abundant supply of readily decomposable material.

It seems likely, therefore, that the concentration of K^+ in the stream can be related directly to the amount of flow passing vertically through, and horizontally along and over, the organic horizons of the soil. During storms, saturated flow may approach the surface in both soils, so the water will be in contact with organic matter for longer periods. Overland flow, too, will increase K^+ concentration by disturbing the most recently deposited organic matter. The effect of leaching is evident in a number of instances. For example, the storm of 29th December 1985 (Fig. 8.2.3.4) produced marked rises

in K^+ concentration. The first and smallest storm hydrograph produced the greatest concentration, though this is to be expected, as it was the first period of intense leaching after the snow period. Figure 8.2.3.2(a) shows the storm in July and how the K^+ was taken up during the summer by biological activity. The low values for December are not readily explainable, except that there has been a downward trend in concentration since the passing of the hydrograph of 6th November 1985.

The effect of dilution by storm hydrographs can be seen clearly in the December 1985 storm (Fig. 8.2.3.4). High concentrations of the major cations were recorded when most of the stream water in the channel came from the groundwater or baseflow, even under winter conditions in January 1986 (Fig. 8.2.3.4).

Markedly different patterns were exhibited by SO_4^{2-} during the two storms. They are not shown in Fig. 8.2.3.1(a) and (b) because some of the samples are thought to have suffered from interference from organic matter in the March storm. The trend of SO_4^{2-} concentration in the March storm appeared closely to follow that of Cl^-, rising on the rising limb of the flood and staying at high concentration during and after peak flow.

In the October storm, however, SO_4^{2-} concentration dropped sharply at the start of the flood rise, balancing an increase in Cl^- concentration (Fig. 8.2.3.1(a)). By peak flow it had recovered to a level slightly below its pre-storm concentration, and it remained at this level while the stream level fell. The drop in concentration was repeated at the onset of the second storm, and thereafter SO_4^{2-} concentration increased to above its pre-storm level. The reasons for this variation are unclear, and no firm conclusions can be reached.

However, dilution is also evident on the hourly samples during the passing of a storm hydrograph of 10th-24th April 1986 (Fig. 8.2.3.3(a) and (b)). The meltwater, which raises the hydrograph and consequently increases the SO_4^{2-} concentration, suggests that the store of SO_4^{2-} in the ground floor or the surface horizon is being removed by the meltwater over the ground (Fig. 8.2.3.5(a) and (b)).

2. Variation of pH

The increase in acidity during storm conditions reflects both the chemical and hydrological processes acting within the catchment area. During a storm, rainwater initially replaces soil storage water within the system. Further increases in rainfall may result in overland flow in the catchment as soil storage capacity is exceeded and the soil becomes saturated. Similarly, on both the brown earth and gley soils, once the stored soil water is completely replaced by recent precipitation and the soil is at field capacity, any further rain may move directly into the stream. Hydrogen ions replace exchangeable cations in the soil by the process of hydrolysis, so as soil water flow continues, fewer base metals become available for exchange, and the acidity of the soil water increases. At the same time, the velocity of the soil water movement increases and the water has less time to equilibriate with the soil. Similarly, during heavy rainfall in some parts of the catchment, the water may not even enter the soil, moving to the stream as overland flow acquiring dissolved organic acids from the upper horizon of the soil as it does so. The organic acids, and the high CO_2 levels in the soil atmosphere, increase the acidity of the water even further.

The pH values follow the trend of Ca^{2+}, Mg^{2+} and Na^+ concentrations. Their decrease on the rising limb is sharper than that of the cations, especially during the October 1985 and March 1986 storms (Fig. 8.2.3.6(a) and (b)).

3. Variation of nitrate and phosphate

The concentrations of NO_3^- show different trends in the two storms. During the March storm, NO_3^- concentrations are fairly steady at about 0.2 mg l^{-1} (Fig. 8.2.3.6(a) and (b)). At baseflow before the October storm, however, NO_3^- was 1.3 mg l^{-1}. The concentration fell rapidly to zero when the stream began to rise, but after the flood peak NO_3^- concentrations rose to 0.25 mg l^{-1} and remained fairly steady. Concentrations of PO_4^{3-} never exceed 1.0 mg l^{-1} (Fig. 8.2.3.6 (a) and (b) and Fig. 8.2.2.10(a) and (b)) and show no significant variation with the hydrograph.

4. <u>Variation of iron, manganese and colour</u>

Unlike all the species considered so far, these elements show a low level of concentration which does not exceed 0.01 mg l^{-1}. The stream water still has little colour at high flows, although turbidity is at a maximum. The colour of the stream becomes deep yellow due to partially decomposed organic material, peaty colloids and plant debris flushed from the organic surface horizons of the soil.

8.3 STATISTICAL RELATIONSHIPS BETWEEN SOLUTE CONCENTRATION AND DISCHARGE

8.3.1 Methods

The product moment correlation coefficients have been calculated for the concentration of each solute and discharge at the time of sampling for every weekly observation during the study period. In all cases concentration is the dependent (y) variable and discharge the independent (x) variable.   The discharge data have an approximately log-normal frequency distribution, and NO_3^- and SO_4^{2-}, which are positively correlated with discharge, are also positively skewed. The constituents that have an inverse relationship have a slightly negatively skewed frequency distribution.   The PO_4^{3-} concentrations have a bimodal frequency distribution, because PO_4^{3-} is removed by organic activity, producing lower concentrations in spring than would be expected if hydrologic factors were the only controls on concentration.

The amount of linear association between discharge and concentration has been ascertained by using the product moment correlation coefficient.   This has been computed first with both x and y untransformed, and second with x only logarithmically transformed.   This is to ascertain the appropriate regression equation for use in cases where a significant amount of correlation was found.   The equations are:

(i) $\quad y = bx + a$ $\hfill (1)$

(ii) $\quad y = b \log x + a$ $\hfill (2)$

(iii) $\quad \log y = b \log x + a$ $\hfill (3)$

Equation (2) is the one suggested by Douglas (1964) and Davis (1964), and (3) is the one derived by Hem (1970).   This can also be written as a power function:

$$y = a x^b \hfill (4)$$

In all these equations a and b are regression constants. The significance of the differences between the correlation coefficients has been assessed by comparing the differences of the figure z transformation of the coefficients to the standard error of their

difference (Moroney, 1956).

$$z = 1.15 \log_{10} \frac{1 + r}{1 - r} \qquad (5)$$

$$\text{standard error of difference} = \frac{1}{N_1 - 3} + \frac{1}{N_2 - 3} \qquad (6)$$

where r = correlation coefficient

N_1 = number of observations used in computing the first correlation coefficient

N_2 = number of observations used in computing the second correlation coefficient.

If the difference in two values is less than the standard error of the difference of the correlation coefficients, then there is no significant difference in the values of the coefficients. The calculation of standard errors does assume that the data are normally distributed. This is not always so for the concentration and discharge data collected in this study, though logarithmic transformations reduce the positive skew of discharge and of some of the concentrations. Moroney (1956) says that the procedure used here is safe for most practical purposes.

In no cases is there a significantly higher correlation coefficient between concentration and a measure of antecedent discharge than between concentration and discharge at the time of sample collection. The correlation coefficients were highest in most instances when discharge variables were logarithmically transformed. In most cases also there was little difference between using concentration either linearly or logarithmically transformed against discharge. For all seven sites the highest correlations for Mg^{2+} and discharge (at Site 3) are obtained when no transformations are used for both variables. These differences are again not significant when the difference in two transformations is compared with the differences of standard error, even though the difference in r values is 0.1. It thus seems from correlation analysis that it makes very little difference whether concentration is logarithmically transformed or not. The correlation coefficients of the logarithmically transformed and untransformed data for the seven sites are given in Table 8.3.1.1. The amount of explained variance is the square root

TABLE 8.3.1.1   CORRELATION COEFFICIENTS BETWEEN CONCENTRATION AND DISCHARGE, AND DISCHARGE STATISTICS

Correlation Coefficients

Discharge at Station	1		2		3		4		5		6		7	
Data of Transformation	Q	log Q	Q	log Q	Q	log Q	Q	log Q	Q	log Q	Q	log Q	Q	log Q
Conductivity	-0.284	-0.182*	-0.588	-0.640*	-0.532	-0.554*	-0.697	-0.681*	-0.654	-0.643*	-0.404	-0.429*	-0.263	-0.295*
Ca^{2+}	-0.441	-0.540	-0.098	-0.021	-0.584	-0.534	-0.595	-0.467	-0.642	-0.552	-0.567	-0.479	-0.083	-0.003
Mg^{2+}	-0.470	-0.596	-0.468	-0.408	-0.693	-0.650	-0.567	-0.529	-0.604	-0.524	-0.657	-0.581	-0.280	-0.235
Na^{+}	-0.225	-0.348	-0.333	-0.421	-0.201	-0.206	-0.456	-0.481	-0.300	-0.282	-0.057	-0.021	-0.226	-0.247
K^{+}	0.029	0.049	-0.257	-0.261	-0.218	-0.209	-0.184	-0.213	-0.122	-0.133	-0.071	-0.019	-0.188	-0.222
SO_4^{2-}	0.270	0.301	-0.317	-0.347	0.354	0.333	0.196	0.071	0.136	0.002	0.208	0.112	-0.072	-0.204
NO_3^{-}	0.101	0.175	0.391	0.325	0.294	0.383	-0.090	-0.041	0.153	0.123	0.253	0.274	-0.016	0.028
Cl^{-}	0.002	0.015	-0.546	-0.621	-0.163	-0.273	-0.084	-0.145	-0.220	-0.350	-0.125	-0.214	-0.031	-0.192

Discharge Statistics

	Q	log Q	Q	log Q	Q	log Q	Q	log Q	Q	log Q	Q	log Q	Q	log Q
Mean Q	17.4	2.53	8.50	1.849	8.640	2.065	27.04	3.16	17.16	2.618	14.87	2.58	3.88	1.204
Median Q	12.06	2.49	6.20	1.825	8.00	2.079	25.0	3.21	17.0	2.833	14.0	2.63	3.25	1.178
St. deviation Q	16.13	0.809	5.90	0.847	3.784	0.434	13.44	0.574	11.40	0.726	6.246	0.532	2.30	0.558
Minimum Q	1.25	0.228	1.00	0.00	3.00	1.09	5.00	1.609	2.00	0.693	1.50	0.405	1.00	0.00
Maximum Q	105.2	4.65	24.8	3.21	20.60	3.025	62.5	4.13	56.5	4.03	32.0	3.46	11.5	2.44

Dependent variable (y) = Concentration $y = b \log x + a$

Independent   " (x) = Discharge $* \log y = b \log x + a$

of the correlation coefficient and is expressed as a percentage of total explanation ($r = \pm 1.0$): this is an approximate figure, as it depends on the amount of error in the correlation coefficient.

It can be seen that Mg^{2+} has a highly significant amount of the variation in its concentration explained by discharge in all seven sites. The highest amount is $r = (-0.693)$ (70%) for Site 3. The amount for Ca^{2+}, which also has a direct relationship with discharge, varies from 54-64%. The only ion constituent that has a highly significant amount of variation explained in all sites is Mg^{2+}, although this amounts to only 28% for Site 7.

The best fit regression lines of conductivity against discharge have been constructed for Site 4, using equation (3) (both variables logarithmically transformed) (Fig. 8.3.1.1 and Table 8.3.1.2). It is difficult to compare trends in concentration of the different constituents.

It is interesting to speculate why the catchment (seven sites) does not show well-defined dilution patterns as described by Steele (1968), Ledbetter and Gloyna (1964), Gunnerson (1967), Johnson et al. (1969) and Hem (1970). Much of the work of the first three and that described by Hem is done in the western United States, where seasonal extremes of discharge are much greater and where intense evaporation is probably a significant factor in concentrating solutes. Steele's discharges (1968) range over five orders of magnitude, Edwards' discharges (1971) range over two orders, while in Macclesfield Forest it is over only two orders. Also important is the permeable and soluble nature of the catchments and their subdued relief. Overland flow was observed several times (November 1984, March 1985, March 1986). This was after heavy storm events or ice periods when the water melted and when the banks were overtopped and water was on the floodplain. The dilution models of Hem (1970) and Johnson et al. (1969) assumed that the diluting agent is the overland flow component of the hydrograph. The rapid runoff component in the Coombs Brook catchment is mostly by way of ditches in the soil, which is the most favourable zone for chemical reactions.

The testing of mixing models such as those derived to study
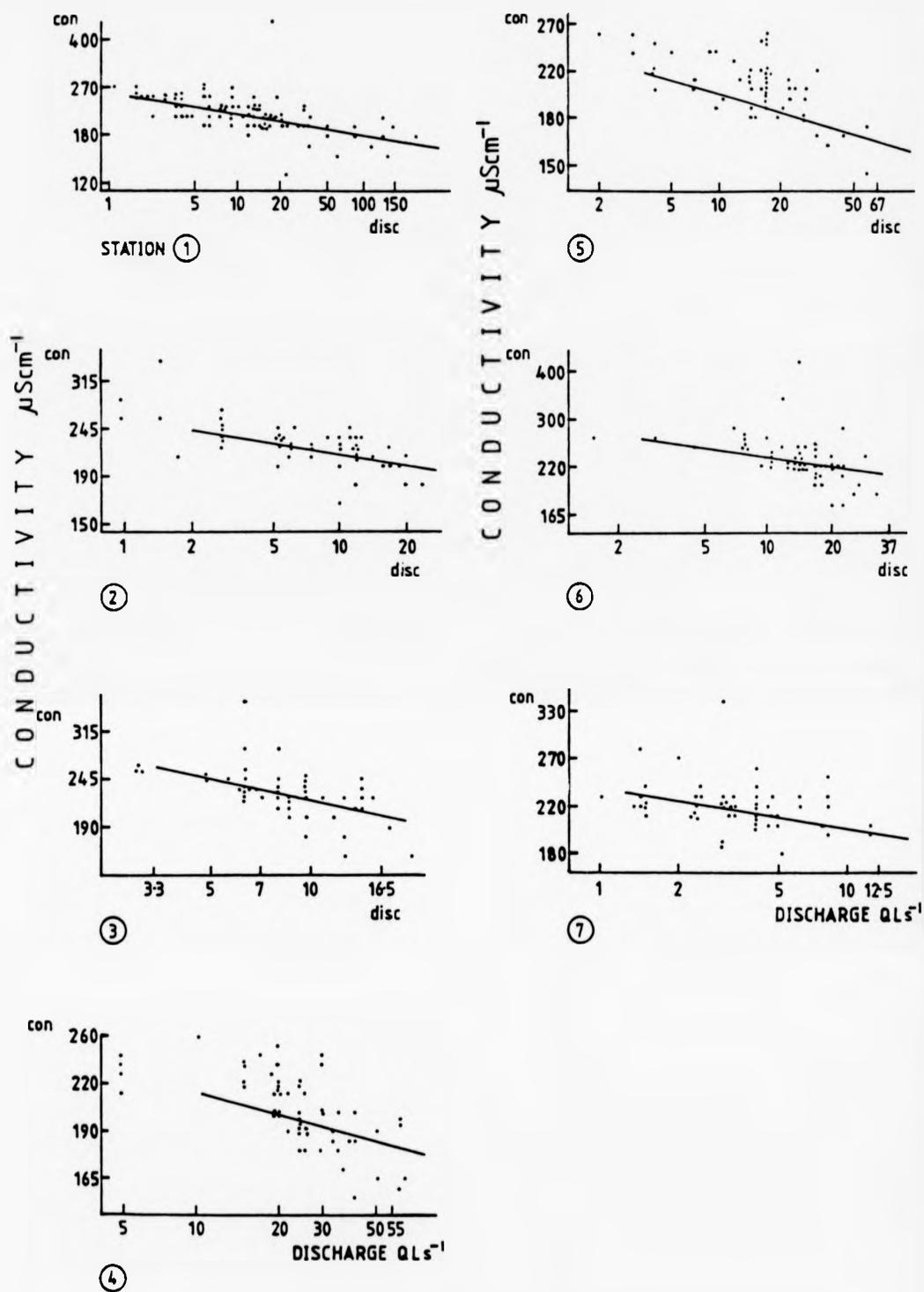
Fig.8·3·1·1. The relationships between conductivity and discharge for Coombs Brook. (see Table 8.3.2.1)

TABLE 8.3.1.2   REGRESSION ANALYSIS OF CONCENTRATION (mg 1^{-1})
WITH DISCHARGE ($1 \, s^{-1}$)

Site No.	Substance	Regression equation	Correlation	Level of significance of r
1	Ca^{2+}	$y = 26.7 \log x - 2.49$	$r = -0.540$	> 99.9%
	Mg^{2+}	$y = 11.2 \log x - 1.27$	$r = -0.596$	> 99.9%
	Na^+	$y = 8.67 \log x - 0.617$	$r = -0.348$	> 99.0%
	K^+	$y = 1.0 \log x + 0.217$	$r = 0.049$	n.s.
	SO_4^{2-}	$y = 20.1 \log x + 2.02$	$r = 0.301$	> 99.0%
	NO_3^-	$y = 8.32 \log x + 0.581$	$r = 0.175$	> 95.0%
	Cl^-	$y = 18.2 \log x + 0.063$	$r = 0.015$	n.s.
	Con.	$\log y = 5.54 \log x + 0.088$	$r = -0.182$	< 95.0%
2	Ca^{2+}	$y = 22.7 \log x - 0.069$	$r = -0.021$	n.s.
	Mg^{2+}	$y = 10.3 \log x - 0.643$	$r = -0.408$	> 99.9%
	Na^+	$y = 7.95 \log x - 0.636$	$r = -0.421$	> 99.9%
	K^+	$y = 1.83 \log x - 0.306$	$r = -0.261$	> 95.0%
	SO_4^{2-}	$y = 37.8 \log x - 2.51$	$r = -0.347$	> 99.0%
	NO_3^-	$y = 8.89 \log x - 1.20$	$r = 0.325$	> 95.0%
	Cl^-	$y = 24.9 \log x - 4.16$	$r = -0.621$	> 99.9%
	Con.	$\log y = 5.57 \log x - 0.082$	$r = -0.640$	> 99.9%
3	Ca^{2+}	$y = 30.0 \log x - 3.96$	$r = -0.534$	> 99.9%
	Mg^{2+}	$y = 15.7 \log x - 2.54$	$r = -0.650$	> 99.9%
	Na^+	$y = 8.52 \log x - 0.802$	$r = -0.206$	> 95.0%
	K^+	$y = 2.66 \log x - 0.575$	$r = -0.209$	> 95.0%
	SO_4^{2-}	$y = 16.3 \log x + 4.01$	$r = 0.333$	> 99.0%
	NO_3^-	$y = 5.38 \log x + 2.24$	$r = 0.383$	> 95.0%
	Cl^-	$y = 20.4 \log x - 2.42$	$r = -0.273$	> 90.0%
	Con.	$\log y = 5.77 \log x - 0.164$	$r = -0.554$	> 99.9%
4	Ca^{2+}	$y = 27.7 \log x - 2.37$	$r = -0.467$	> 99.9%
	Mg^{2+}	$y = 12.1 \log x - 1.34$	$r = -0.529$	> 99.9%
	Na^+	$y = 11.1 \log x - 1.11$	$r = -0.481$	> 99.9%
	K^+	$y = 3.08 \log x - 0.490$	$r = -0.213$	> 95.0%
	SO_4^{2-}	$y = 15.7 \log x + 0.94$	$r = 0.071$	n.s.
	NO_3^-	$y = 10.2 \log x - 0.25$	$r = -0.041$	n.s.
	Cl^-	$y = 22.8 \log x - 2.11$	$r = -0.145$	< 95.0%
	Con.	$\log y = 5.75 \log x - 0.137$	$r = -0.681$	> 99.9%

TABLE 8.3.1.2 (Continued)

Site No.	Substance	Regression equation	Correlation	Level of significance of r
5	Ca^{2+}	$y = 26.4 \log x - 2.44$	$r = -0.552$	> 99.9%
	Mg^{2+}	$y = 11.8 \log x - 1.19$	$r = -0.524$	> 99.9%
	Na^+	$y = 8.64 \log x - 0.551$	$r = -0.282$	> 95.0%
	K^+	$y = 2.29 \log x - 0.304$	$r = -0.133$	< 95.0%
	SO_4^{2-}	$y = 18.0 \log x + 0.02$	$r = 0.002$	n.s.
	NO_3^-	$y = 9.15 \log x + 0.364$	$r = 0.123$	< 95.0%
	Cl^-	$y = 20.9 \log x - 2.14$	$r = -0.350$	< 95.0%
	Con.	$\log y = 5.63 \log x - 0.115$	$r = -0.643$	> 99.9%
6	Ca^{2+}	$y = 30.4 \log x - 3.06$	$r = -0.479$	> 99.9%
	Mg^{2+}	$y = 15.5 \log x - 1.87$	$r = -0.581$	> 99.9%
	Na^+	$y = 7.57 \log x - 0.107$	$r = -0.021$	n.s.
	K^+	$y = 2.24 \log x - 0.121$	$r = -0.019$	n.s.
	SO_4^{2-}	$y = 16.4 \log x - 1.75$	$r = 0.112$	< 95.0%
	NO_3^-	$y = 6.20 \log x - 1.68$	$r = 0.274$	< 95.0%
	Cl^-	$y = 19.4 \log x - 1.65$	$r = -0.214$	> 90.0%
	Con.	$\log y = 5.75 \log x - 0.114$	$r = -0.429$	> 99.9%
7	Ca^{2+}	$y = 21.4 \log x - 0.013$	$r = -0.003$	n.s.
	Mg^{2+}	$y = 9.58 \log x - 0.446$	$r = -0.235$	> 95.0%
	Na^+	$y = 7.52 \log x - 0.566$	$r = -0.247$	> 95.0%
	K^+	$y = 1.92 \log x - 0.518$	$r = -0.222$	> 95.0%
	SO_4^{2-}	$y = 34.7 \log x - 4.08$	$r = -0.204$	< 90.0%
	NO_3^-	$y = 12.4 \log x + 0.102$	$r = 0.028$	n.s.
	Cl^-	$y = 18.1 \log x - 1.67$	$r = -0.192$	< 90.0%
	Con.	$\log y = 5.46 \log x - 0.0521$	$r = -0.295$	> 99.0%
	Ca^{2+}	$y = -3.0 + 2.44 \, pH$	$r = 0.257$	95.0%
	Mg^{2+}	$y = -4.27 + 1.70 \, pH$	$r = 0.439$	> 99.9%
	Ca^{2+}	$y = 6.74 + 1.72 \, Mg^{2+}$	$r = 0.701$	> 99.9%
	Na^+	$y = 7.13 + 0.116 \, K^+$	$r = 0.50$	> 99.9%

(Site No. 1)
pH $r = -0.399$ > 99.9%

TABLE 8.3.1.2 (SUMMARY)

(Continued) VARIABLES SIGNIFICANTLY CORRELATED WITH DISCHARGE AT THE SEVEN STATIONS

Station No.	Significance level	Positive correlations			Negative correlations			
		99.9%	99.0%	95.0%	99.9%	99.0%	95.0%	90.0%
1			SO_4^{2-}	NO_3^-	Ca^{2+}, Mg^{2+}, pH	Na^+	Cond.	
2				NO_3^-	$Mg^{2+}, Na^+, Cl^-,$ Cond.	SO_4^{2-}	K^+	
3			SO_4^{2-}	NO_3^-	$Ca^{2+}, Mg^{2+},$ Cond.		Na^+, K^+	Cl^-
4					$Ca^{2+}, Mg^{2+}, Na^+,$ Cond.		K^+, Cl^-	
5				NO_3^-, Cl^-	$Ca^{2+}, Mg^{2+},$ Cond.		Na^+, K^+	
6				SO_4^{2-}, NO_3^-	$Ca^{2+}, Mg^{2+},$ Cond.			Cl^-
7					Cond.		Mg^{2+}, Na^+, K^+	SO_4^{2-}, Cl^-

discharge-concentration relationships by Hall (1970, 1971) has not been attempted. These equations are not completely empirical, as their use involves assumptions concerning the nature of mixing components. Hall, however, finds most plots of concentration versus discharge on logarithmic paper produced a straight line. The trial and error fitting of the equations to data such as that obtained in this thesis produced similar fits for nearly all the models. Hall (1971) found that a model should be derived to suit a particular situation or an experiment designed to test a particular model. The complex nature of the inputs in the Macclesfield Forest catchment has not been measured in sufficient detail to make assumptions in mixing models such as Hall's. Simple logarithmic regression and correlation analysis has thus been used to see if there are any significant trends between discharge and concentration.

The problem of using multiple regression analysis is in obtaining truly independent variables. There is considerable evidence that for some constituents soil moisture content is an important factor. The understanding of discharge-concentration relationships and the leaching of the soil will be greatly aided by detailed (at least hourly) sampling through a series of periods of changing discharge at different times of the year. The work done on these events in this thesis is limited, as collections of samples of the rising and falling stage were made at only eight hourly intervals.

8.3.2   The Contrasting Results of Correlation and Regression Analysis

All species were tested for relationships between concentration and discharge using an equation of the form $y = b \log x + a$, described earlier. As the range of discharge was much greater than of the chemical variables, it was expressed logarithmically. Ten species showed statistically significant relationships, and the resulting regression equations are listed in Table 8.3.1.2: Ca^{2+}, Mg^{2+}, Na^+ and Cl^- concentrations and pH varied inversely (negative correlation), and NO_3^- and SO_4^{2-} concentrations varied directly with log discharge (positive correlation): PO_4^{3-}, Fe and Mn show no correlation between concentration and discharge. However, this relationship between concentration and discharge will be discussed in three different

groups as follows:

(a) Species with negative relationships.

(b) Species with positive relationships.

(c) Species with no apparent relationships.

The only constituents whose concentration is significantly diluted by discharge in all stations are Mg^{2+} and Ca^{2+}, though all the cation concentrations also had negative slope coefficients. On the other hand, a different behaviour was observed in the anion correlation in all sites. For example, there are significant increases of NO_3^- and SO_4^{2-} with discharge, but not in all sites. The spread of the constituent concentrations over seven sites or seven orders of magnitude makes it difficult to compare the rates of change in concentration. It can be seen that PO_4^{3-}, Fe and Mn have a small relative rate of concentration; it is enough to maintain the insignificant relation with discharge: PO_4^{3-} is slightly diluted in the catchment, and Na^+ and K^+ have an intermediate position.

Negative relationships of water quality with discharge

1. Calcium and magnesium

Both Ca^{2+} and Mg^{2+} concentrations show similar responses to changes in discharge and are diluted with increase in discharge. This was more clearly observed in Site 1 rather than the headwater sites 2-7. The same arguments that are used to explain the rise in hydrogen ion concentration can be used to explain the dilution of these two elements. The cation exchange capability of the soil decreases during a storm; the water has less time to equilibriate with the soil, and the runoff has less time to make contact with the soil.

Fisher et al. (1968) stated that "during periods of high rain infiltration into the soil, the chemical reaction that supplies ions to the soil water may not keep pace with the rate of soil water replacement". The lower concentrations of exchangeable Ca^{2+} and Mg^{2+} in the soil, and the effect of runoff causes the concentrations to be lower at the headwater. Although the flattening of the curves

at higher discharges at Sites 2, 4 and 7 may suggest the operation of an additional buffering mechanism, it is more likely to be caused by the relatively uniform chemical concentrations found in runoff.   As Gregory and Walling (1973) stated, at very high discharges the dilution effect becomes progressively less significant and concentrations are dominated by the near constant solute content of the storm runoff component.   The cations Ca^{2+} and Mg^{2+} are very similar chemically and are derived from carbonate minerals and other rock materials. Both of them behave in the same way, with rather imprecise negative relationships with discharge at all seven sites, but a positive relationship between each other.   This positive relationship of Ca^{2+} with Mg^{2+} reflects their chemical similarities (Fig. 8.3.2.2).   Despite showing little variability, with a coefficient of variability of -0.638, the Mg^{2+} concentrations are all negatively correlated with discharge (Fig. 8.3.2.1 and Table 8.3.1.2).

2. Sodium

The relationships between Na^+ concentrations and discharge are similar at all seven sites, exhibiting a slight dilution with increasing discharge, suggesting that the rate of supply of Na^+ is uniform throughout the basin.   The average concentration of Na^+ in rainfall is only 1.6 mg l^{-1}, despite the basin being approximately 50 km from the sea.   The most significant correlations for Na^+ concentrations and discharge for the whole sampling period were at Sites 1 and 4, with r values of -0.348 and -0.481 respectively.

3. Potassium

The only ion which should exhibit a positive correlation with discharge is K^+.   It is a major plant nutrient and therefore tends to be concentrated in the uppermost horizons of the soil, where it is recycled by the vegetation.   However, no meaningful correlations were obtained between the K^+ concentrations and discharge (Fig. 8.3.2.3), Site 1 showing no significant correlation (r = 0.049) with the headwater sites 2-7 showing negative correlation.   This may be explained by the effect of leaching which is evident at Site 1 in a number of instances during storm events (Section 8.2.3), but at Sites 2-7 the dilution processes which cause the negative correlation

are more evident.   The low levels and low variability of K^+ concentrations in the catchment (1.2 to 2.0 mg l^{-1}) may make the relationship between concentration and discharge difficult to recognise. Other suggestions are that much of the K^+ available for solution may be cycled through vegetation and cause a decrease in the amount of K^+ carried by a stream during the growing season.

However, the increase in K^+ with discharge at Site 1 may possibly be due to the solution of this ion from the leaves and clay carried in suspension.   The increase in K^+ content of the stream water may be attributed to the washing of leaves and organic matter from the ground flora.

The atmospheric supply of K^+ to the catchment is extremely small. Dilution of K^+ concentrations prevails during storm runoff at Stations 2 to 7, with a negligible role of release of K^+ from plant materials.

Positive relationships of water quality with discharge

1.   Chloride and sulphate

Unlike other relationships, the correlations between Cl^- and discharge are not significant at the 90% level for Site 1, but in the headwater sites (2-7) the correlation is negative (Table 8.3.1.2).

The concentrations of Cl^- and SO_4^{2-} in the stream water are thought to originate partly from precipitation and partly from rock and soil materials in the basin, since these materials contain some Cl^- and S^{2-} (Chapter 7).   The ions of SO_4^{2-} behave similarly to Cl^-, since there is a positive correlation at Sites 1, 3 and 6 and negative correlation at Sites 2 and 7, and no correlation at Sites 4 and 5. Also, SO_4^{2-} concentration appears to increase slightly with increasing discharge, as does Cl^- concentration, at Site 1.   Conversely, SO_4^{2-} and Cl^- are slightly diluted during high flows at some sites.   It is doubtful whether these trends are significant.   The importance of the high rate of runoff suggests that the Cl^- is more closely related to the discharge at high, rather than at low, rates of runoff;   this is witnessed by the wide scatter of points at low discharge rates in the discharge-Cl^- and SO_4^{2-} concentration relationship (Fig. 8.3.2.4). The variability of Cl^- and SO_4^{2-} at low discharge rates reflects the

operation of evaporation, pollution and atmospheric supply factors, in addition to experimental errors.

The supply of SO_4^{2-} from organic matter deposits during wet and cold conditions is probably due to the breakdown of organic sulphur compounds in leaves. The loss of SO_4^{2-} from the leaves suspended in streams is also evident in the catchment, particularly at Sites 1, 3 and 6, which have positive correlations of SO_4^{2-} with discharge. Some of the SO_4^{2-} entering the streams is derived from the leaching or washing out of SO_4^{2-} deposited as dry atmospheric fallout on leaves and other plant surfaces. Variations in SO_4^{2-} concentration may, in this way, be ascribed to the release of SO_4^{2-} stored on plants, on the forest floor, or the surface soil horizons. Concentrations of SO_4^{2-} may be lower in summer than in winter because of the possible precipitation, assimilation or conversion of SO_4^{2-} by stream bacteria or recycling processes.

2. Nitrate

The NO_3^- concentrations are significantly positively correlated with discharge (Fig. 8.3.2.5 and Table 8.3.1.2). Periods of high runoff result in the addition of much NO_3^- from the land. The summer concentrations may be reduced by uptake by plants. The close correlation of NO_3^- concentration with discharge (which should not be significantly affected by biological activity), indicates that the pattern is caused by leaching rather than by removal and storage of the nutrient by plants. Each period of high discharge results in an increase of NO_3^- concentrations. The NO_3^- is concentrated by biological activity in the surface horizons and is of only trace concentration in the bedrock. The NO_3^- concentration in winter time, through the periods when high loads of nitrogen were transported in the river, may contribute to or increase the NO_3^- concentration.

Cases with no apparent relationship between water quality and discharge

Concentrations of phosphorus, iron and manganese

Concentrations of PO_4^{3-}, Fe and Mn in Coombs Brook show no significant variation with discharge as the concentrations are lower than all the other species in the stream water (see Sections 8.2.2 and 8.2.3).
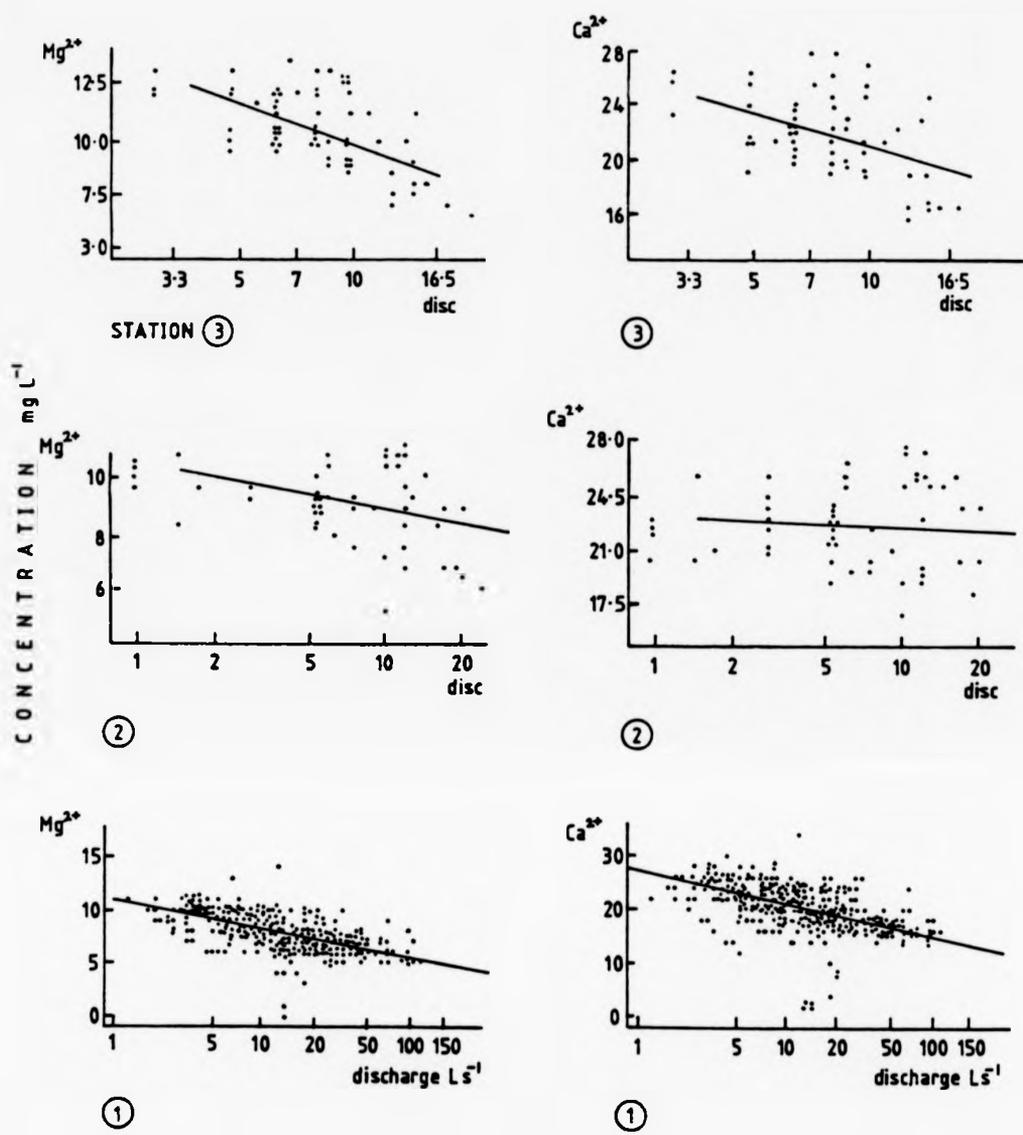
FIGURE 8.3.2.1

Relationship between stream discharge and Ca^{2+} and Mg^{2+} concentration during 1984-1986 (see Table 8.3.1.2)
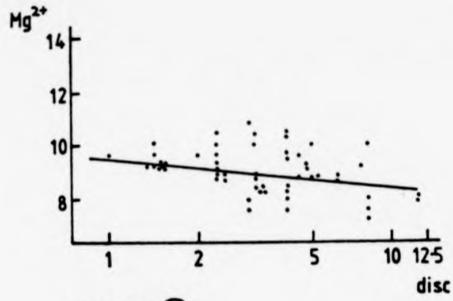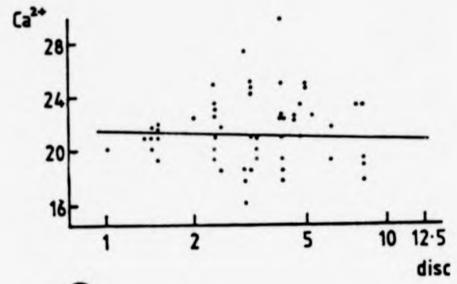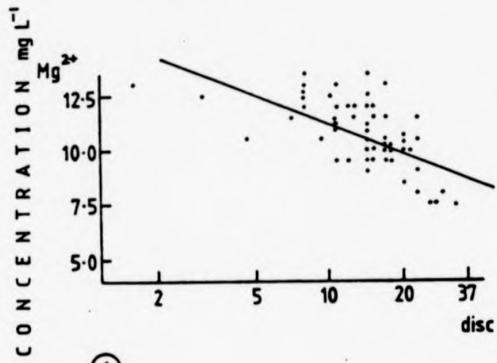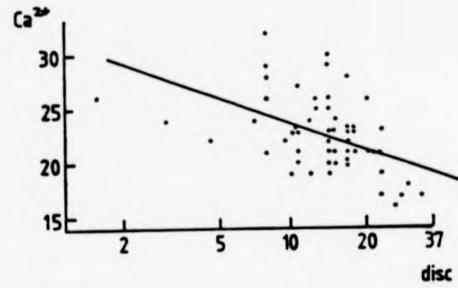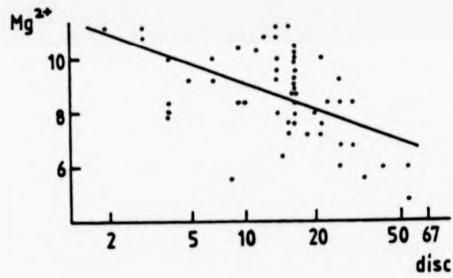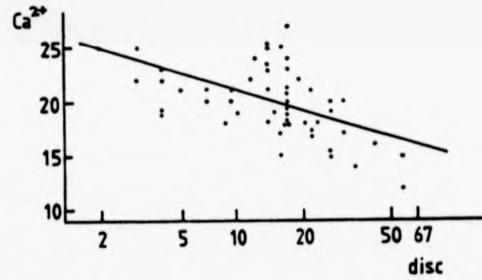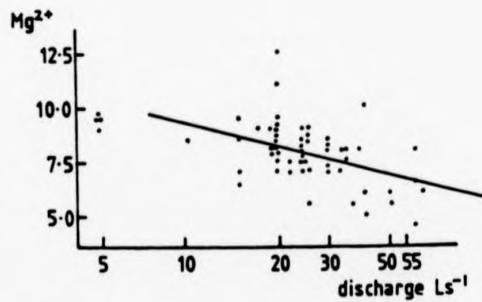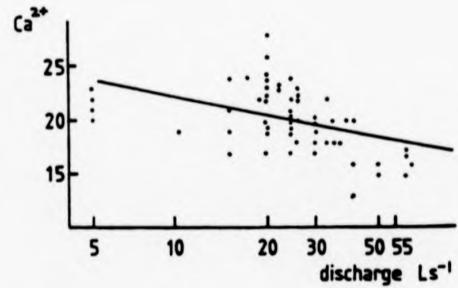
FIGURE 8.3.2.1 (Continued)
(see Table 8.3.1.2)
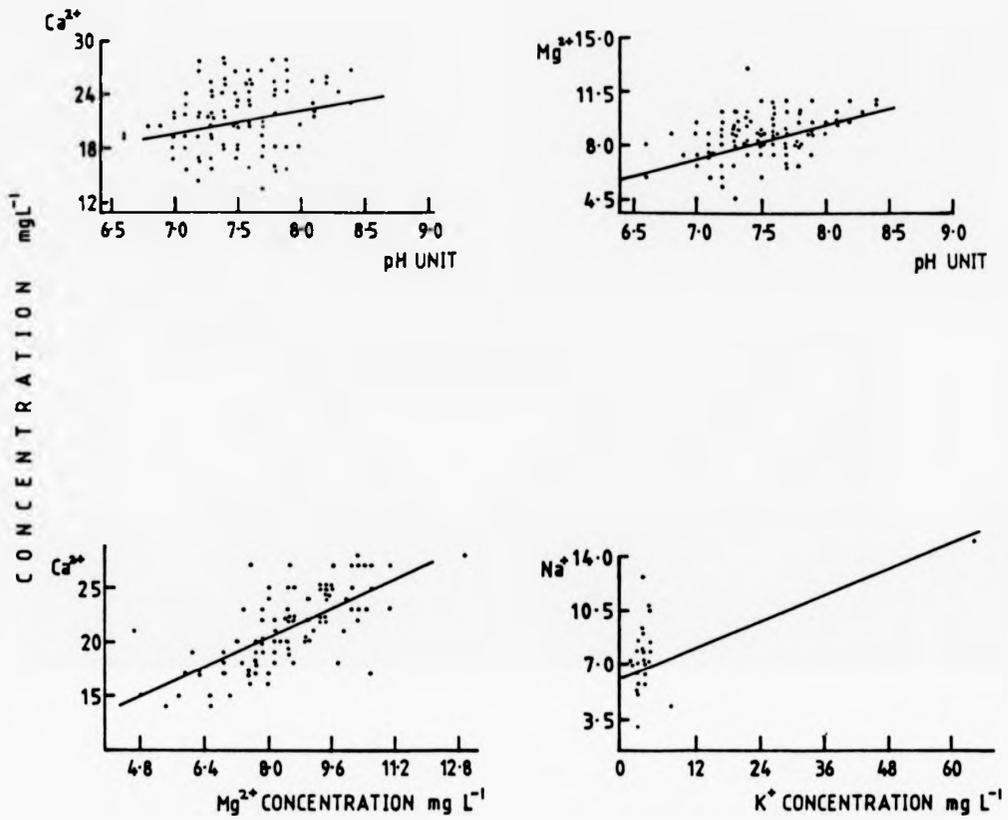
FIGURE 8.3.2.2

A positive relationship found between Ca^{2+}/Mg^{2+}, Na^+/K^+, Ca^{2+}/pH and Mg^{2+}/pH during 1984-86 (see Table 8.3.1.2)
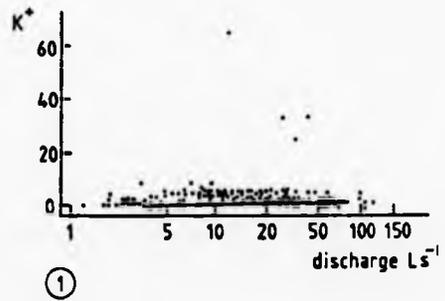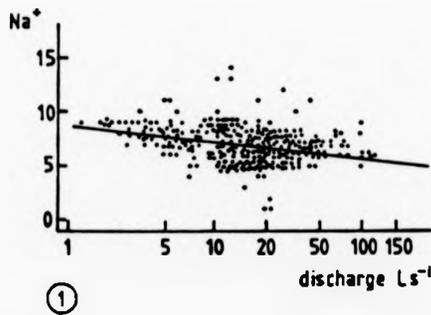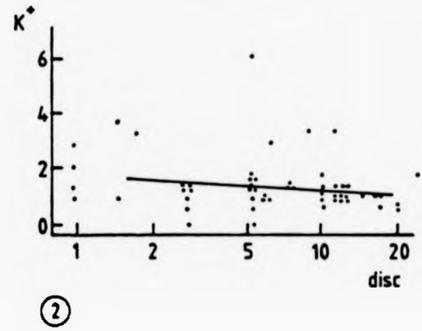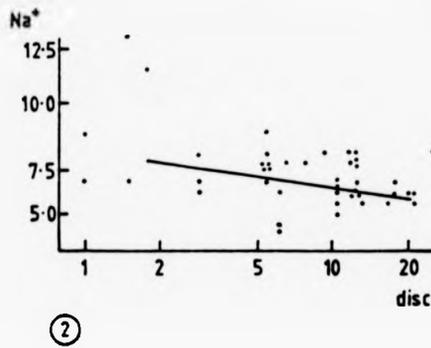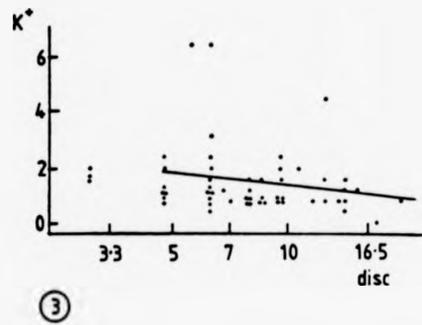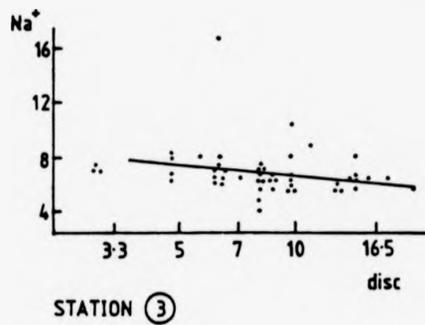
FIGURE 8.3.2.3

The relationship between Na^+ and K^+ concentrations and discharge
for Coombs Brook, at seven sites (see Table 8.3.1.2)
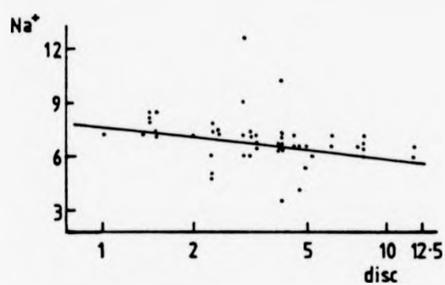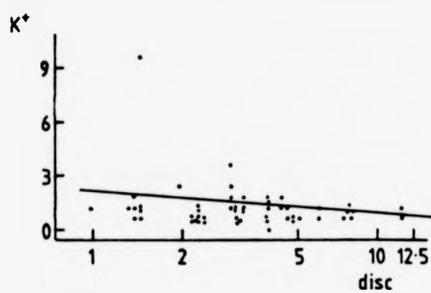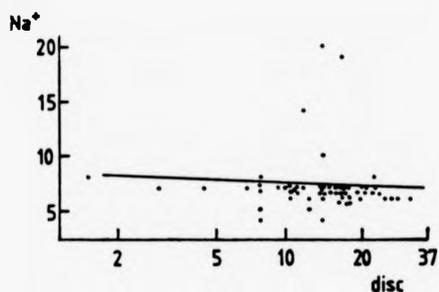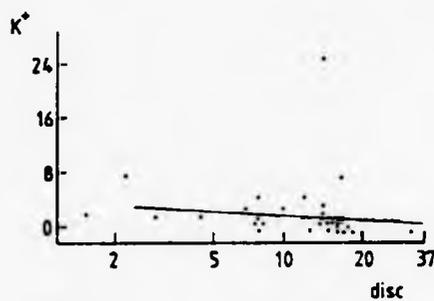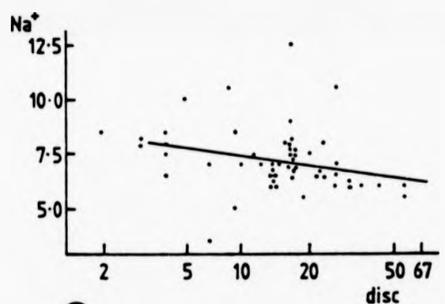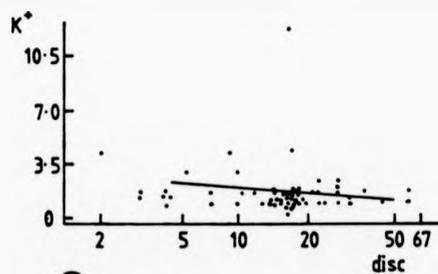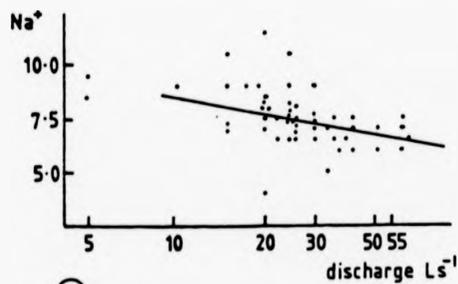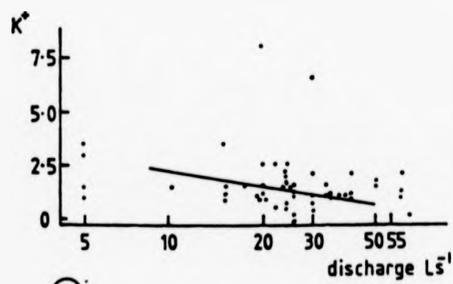
FIGURE 8.3.2.3 (Continued)

(see Table 8.3.1.2)
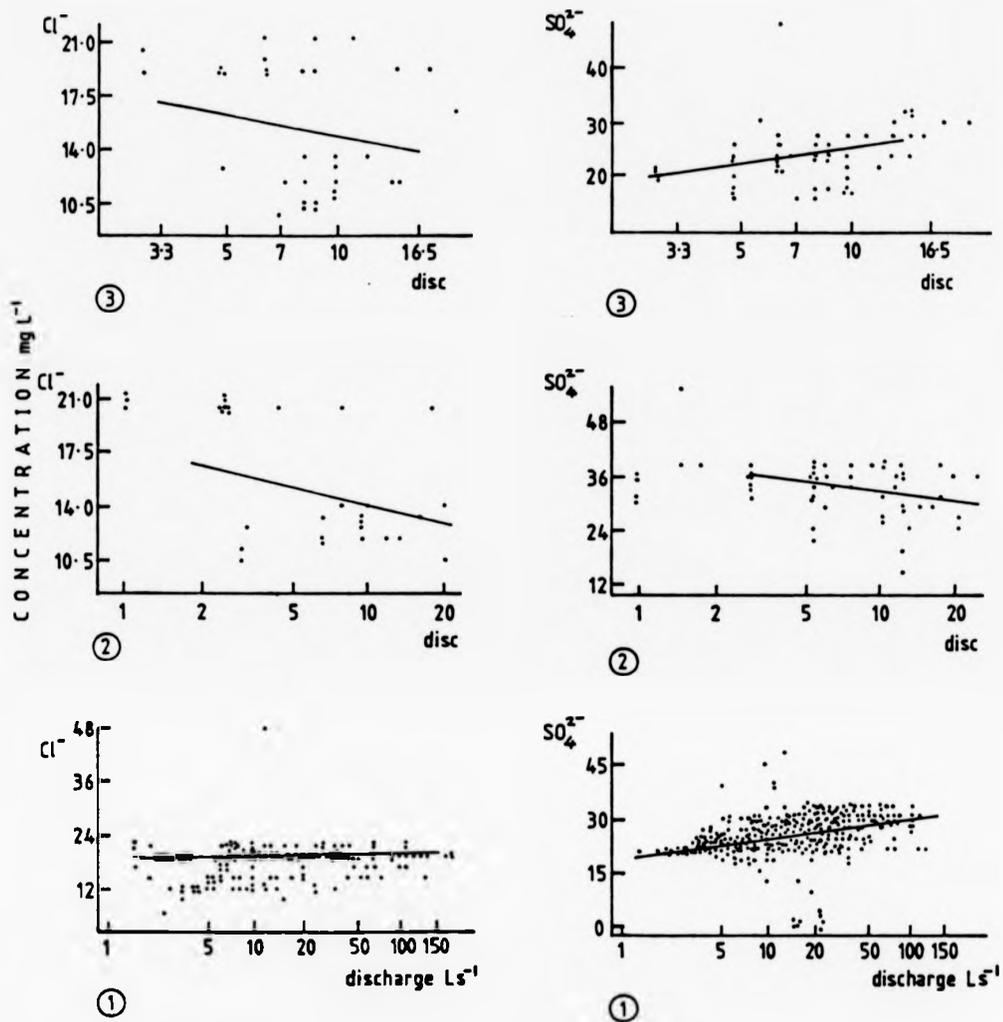
Fig. 8·3·2·4. The relationship between Cl^- and So_4^{2-} concentrations and discharge for the Coombs Brook at seven sites.
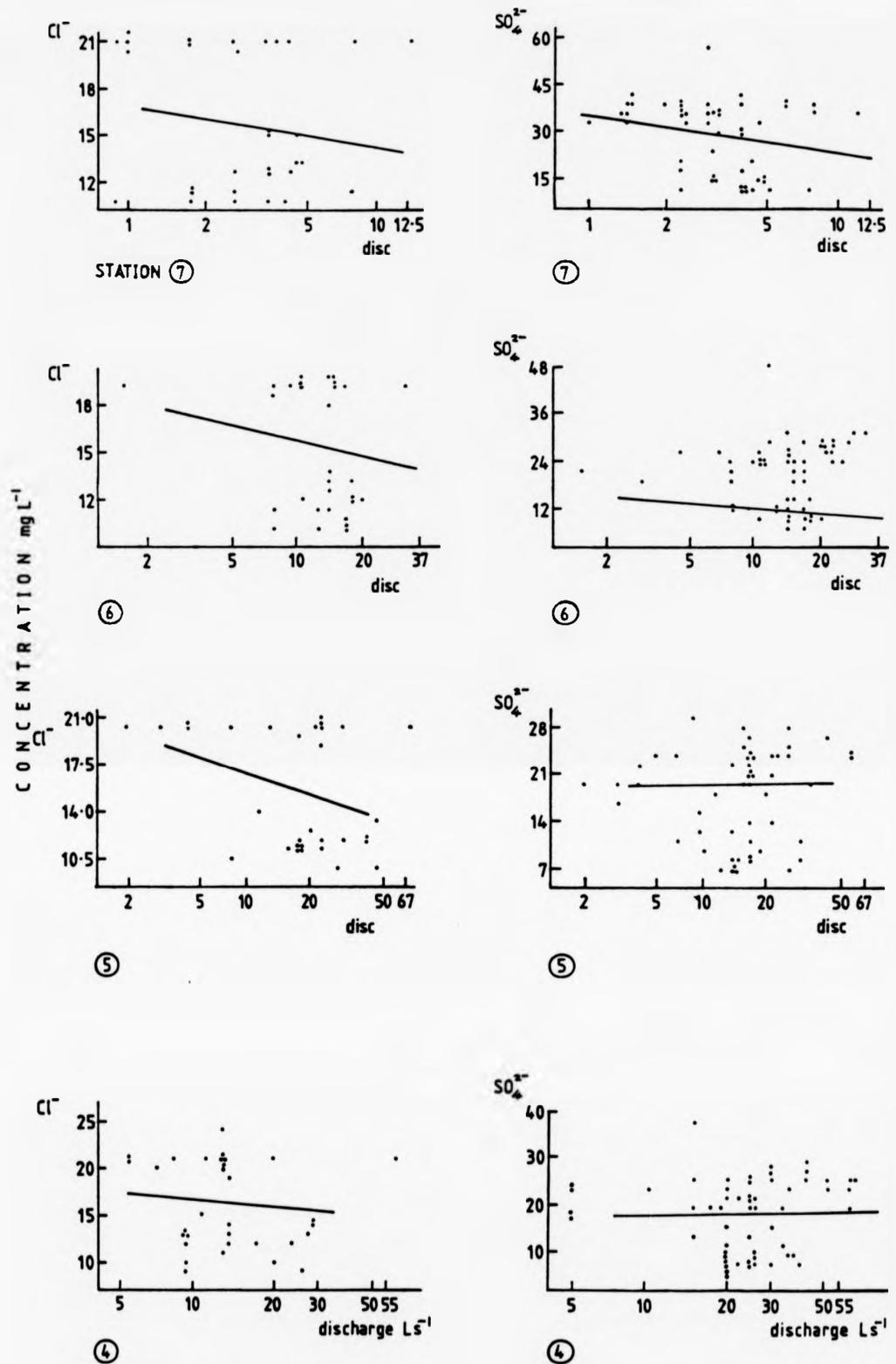
(see Table 8.3.1.2)

FIGURE 8.3.2.4 (Continued)
(see Table 8.3.1.2)
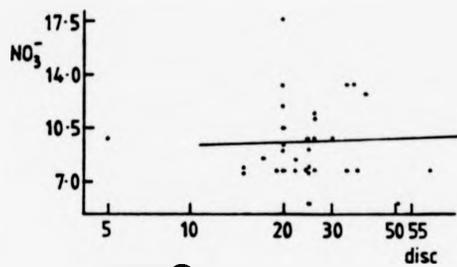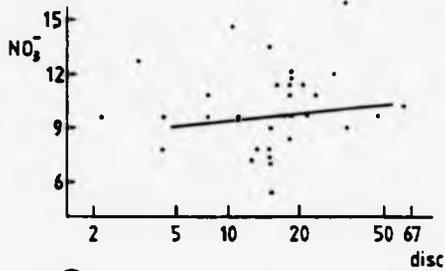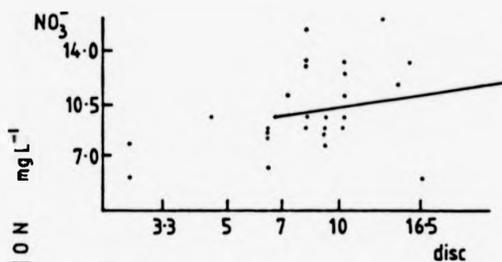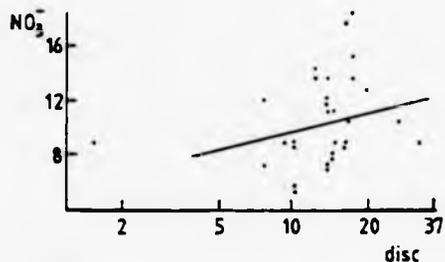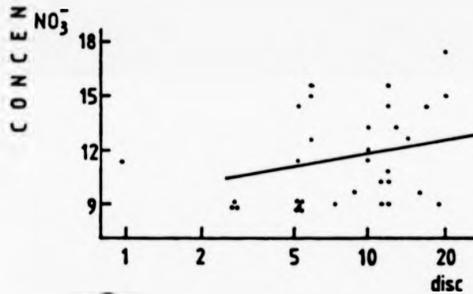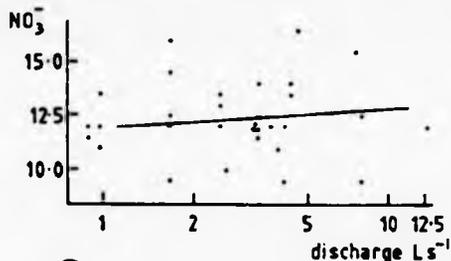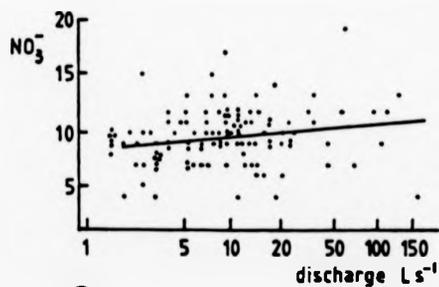
FIGURE 8.3.2.5

The relationship between the concentration of NO_3^- and stream discharge in Coombs Brook catchment (see Table 8.3.1.2)

8.3.3 Comparisons with the Results Obtained by Other Writers

The spatial distribution of mean concentrations of many determinations in Coombs Brook reflected changes in the rock, soil, the burnt areas of the catchment, soil _ water, and vegetation and their interactions (Chapter 7).   Johnson and Muir (1977) reported changes in the concentrations of major dissolved species related to changes in catchment geology of the Castlereagh River in New South Wales. Other workers have reported major discontinuities in river chemistry associated with geological changes but exaggerated by the presence of mine effluents rich in solids (Snow and Whitton, 1971; Hughes and Edwards, 1977).   Changes in concentrations of some solutes (SO_4^{2-}, NO_3^- and PO_4^{3-}) in the Coombs Brook which are not related to catchment geology, probably reflect interactions between and changes in organic matter, soil water and runoff.

The pattern in NO_3^- concentrations in Coombs Brook is similar to those recorded by Oborne et al. (1980) in the River Wye, and Toms et al. (1975) in the Great Ouse, with high concentrations in winter and low concentrations in summer.   Comparatively long-term increases in NO_3^- concentrations have been reported in the Rivers Lee and Thames (Scorer, 1974; Porter, 1977) and attributed principally to population increase.   Subsequently, high rainfall resulted in rapid and substantial increases in concentrations during the winter period.   Such changes were also reported in the River Exe (Walling and Foster, 1978), the River Wye (Oborne et al., 1980) and the River Chelmer (Slack, 1977), and have been attributed to the rapid breakdown and mineralisation of nitrogenous material accumulated within the soil during the long dry period.   Casey and Newton (1973) also reported that NO_3^- concentrations increased in Wraxall Brook after an increase in flow.

Negative correlations were found in this study between Ca^{2+}, Mg^{2+}, Na^+, K^+ and Cl^- and discharge, while Edwards (1973a) reported that Ca^{2+} concentrations increased with increasing flows, as did Na^+, K^+ and Mg^{2+} concentrations in certain rivers in Norfolk.   Likens et al. (1967) reported Ca^{2+} concentrations as being fairly constant over a wide range of discharges.   Gregory and Walling's results (1973) show that the dilution effect becomes less significant with respect

to constant solute content. These results correspond to Coombs Brook results for Ca^{2+} at Sites 2 and 7.

8.3.4 Factors Influencing Stream Water Quality in Coombs Brook

Introduction

Compared with the solute content of precipitation, stream water contains higher mean concentrations of all species except H^+ ions. The dominant constituents of the stream water are SO_4^{2-}, Ca^{2+}, Cl^-, NO_3^-, Mg^{2+} and Na^+ (Table 8.3.4.1). Compared with precipitation, SO_4^{2-}, NO_3^-, Cl^-, Na^+ and K^+ are more important, and Ca^{2+}, Mg^{2+}, PO_4^{3-}, Fe and Mn are less important. Stream water is alkaline (mean pH 7.5), whereas precipitation is acidic (mean pH 5.28). Clearly, major changes occur in the chemistry of water as it percolates through the soils of the catchment.

Results and discussion

The major processes affecting the chemistry of the stream water can be investigated in the same way as for precipitation, as described in Section 1.3 (Table 1.3.1).

Concentrations of calcium, magnesium, sodium, and pH

These elements vary with the hydrological conditions at the time of sampling, but a clear seasonal trend underlies this variation. The concentrations decrease from October to February as the soils become wetter with increased precipitation and decreased evapotranspiration, and baseflow is diluted by shallow sub-surface flow. Values are lowest in February and March, when stream flow is dominated by snow melt. During May, June and July concentrations increase greatly as the soil dries out and flow falls towards baseflow levels, and the concentrations remain high throughout the summer (Fig. 8.2.2.3).

Iron and manganese concentrations

These elements are leached from the upper organo-mineral horizons and precipitated lower down the profile (Plates 8.3.4.1(a) and (b)). The metals are thought to be transported mainly as complexes with organic matter (Petersen, 1976). During storms, water from the

TABLE 8.3.4.1   AVERAGE COMPOSITION OF PRECIPITATION AND STREAM
WATER DURING THE PERIOD MAY 1984 – APRIL 1986

Chemical species	Precipitation Site 1		Stream water Site 1	
	Mean $(mg\ l^{-1})$	Standard deviation	Mean $(mg\ l^{-1})$	Standard deviation
H^+	0.005	-	0.0003	-
pH	5.28	0.139	7.5	0.371
Conductivity	34.6	17.7	212.2	35.6
Ca^{2+}	0.88	1.32	20.4	3.72
Mg^{2+}	0.33	0.418	7.9	1.73
Na^+	1.6	2.83	7.1	1.43
K^+	1.01	1.42	1.5	3.58
SO_4^{2-}	3.0	15.6	25.2	5.4
Cl^-	2.0	0.03	18.3	3.2
NO_3^-	2.2	0.03	9.7	2.46
Mn	0.03	0.01	0.025	-
Fe	0.0	0.0	0.04	-
PO_4^{3-}	0.40	-	0.041	-

pH = pH unit
Conductivity = μScm^{-1} unit
Number of precipitation samples = 100
Number of stream water samples = 550

PLATE 8.3.4.1 (a)

PLATE 8.3.4.1 (b)

Iron podzols are found in the surface horizon in different locations.

near-surface organic and organo-mineral horizons contributes much of the stream water, and small quantities of these elements are flushed into the stream. At baseflow, however, water percolates to the lower horizons of the soil and some of the material is precipitated.

Nitrate concentrations

Concentrations of NO_3^- in stream water are low, despite the high concentrations of NO_3^- in precipitation. During the summer and autumn, plant nutrient demand is still high, but more organic nitrogen is mineralised within the soil so that concentrations increase but are extremely erratic. In winter there is little demand, so that any NO_3^- derived from precipitation or from mineralisation in autumn is leached into the stream.

Phosphate, sulphate, potassium and chloride concentrations

The concentrations of these species are not significantly correlated with discharge. The concentrations of PO_4^{3-} are always low in both precipitation and stream water. The K^+ is released more slowly than the other cations present in the silicate minerals of the soils. Some of the K^+ which is released is taken up by plant roots and some is incorporated into the lattice of hydrous mica in the clay fraction of the soils. For these reasons the concentrations of K^+ in stream water are low and vary independently of the other cations.

Although Cl^- and SO_4^{2-} are derived from atmospheric inputs, their concentrations in precipitation are controlled by different sources, so that their patterns of seasonal variation are quite different. Another cause of their different behaviour is the incorporation of S^{2-} into organic matter and its subsequent mineralisation. Estimates of geochemical balances show that inputs in precipitation account for 19.1 kg ha^{-1} y^{-1} of the Cl^-, while annual Cl^- outputs are 8.4 kg ha^{-1} y^{-1}; likewise, annual SO_4^{2-} inputs are 28.6 kg ha^{-1} y^{-1} and outputs are 12.8 kg ha^{-1} y^{-1}. In addition, vegetation can absorb gaseous SO_2, which would also contribute to the different behaviour of Cl^- and SO_4^{2-}.

These findings reveal that the composition of the stream water is governed by processes operating in the soil. The most important

factor, as shown by the variance value, represents cation exchange processes which affect Ca^{2+}, Mg^{2+}, Na^+ and pH. The second factor is related to the formation podzols and affects Fe and Mn. The third factor represents the controlling influence of plants and organisms in the soil for NO_3^- concentrations in the stream. Even species such as SO_4^{2-} and Cl^- are controlled by soil factors during their passage through the profiles rather than by their pattern of variation in precipitation.

The variation of concentrations of the chemical species during storm events or rising and falling stages and the weekly samples (Section 8.3.4) supports the grouping of the species produced by the above factors.

The Ca^{2+}, Mg^{2+}, Na^+ and pH variables all show a similar pattern during storms; a lag effect followed by a drop in concentration. The size of the drop in concentration and the rate of recovery after the drop vary according to the sources and properties of the species. This pattern confirms that the behaviour of the above elements is an indicator of the properties of stored soil water, or baseflow, in the stream.

The interpretation of Fe and Mn as an indicator of water from the upper soil horizons contributing directly to stream flow is borne out by the small flushes of these elements during the storms. However, the soils above Sites 4 and 5 show different characteristics. In extreme cases, Fe podzols may be found (Plate 8.3.4.1(a) and (b)). Again, Fe and Mn patterns vary somewhat because of the individual properties of each element.

The behaviour of NO_3^-, its lack of correlation with discharge, and its slight seasonal variation, is confirmed by the storm data. The remaining ions, SO_4^{2-}, Cl^-, K^+, and PO_4^{3-}, all show independent patterns of variation of concentration during storms, although Cl^- and K^+ show some similarities to Ca^{2+}, Mg^{2+} Na^+, and pH and SO_4^{2-} show similarities to NO_3^-.

These patterns show how the dynamic of nutrient chemicals varies in stream water, and how the chemistry of streams is controlled by hydrological conditions. The general patterns are determined by the

relatively permanent properties of the area: maritime climate; acid,
bedrock; soils subject to continual leaching; and land use as forest.
The specific patterns in any one storm are affected by more variable
properties: antecedent soil moisture conditions; intensity and
duration of precipitation; and season, temperature and biotic
activity.   Thus, while the weekly data, and the storm data, enable
prediction of the general patterns of stream chemistry in Coombs
Brook, variation in these specific factors is so great that prediction
of the specific patterns during any short period - a storm or a week -
cannot be made with any accuracy.

Surface runoff was not observed to be of major importance in
Coombs Brook during the study year.   Thus, nearly all precipitation
flows through the soil before reaching the stream.   Stream water
appears to be a mixture of two different 'types': water from the
lower, mineral soil horizons with high concentrations of cations, and
water from the organic and organo-mineral upper soil horizons, with
lower concentrations of these species but high concentrations of
organic matter and associated metals.   Stream water during storms is
thought to originate in a fairly small 'contributing area' around the
stream net, by the expansion of the drainage net through intermittent
and ephemeral channels and pipes in the soil (Gregory and Walling,
1973; Kirkby, 1969).   Thus, even the water from the upper soil
horizons may have been in contact with the soil for some time, moving
slowly downslope towards the stream net (Kirkby, 1969).   The patterns
of variation in concentration of chemical species thus depend on how
rapidly this water is flushed into the stream and the extent of mixing
between it and the deeper soil water, which depend on the specific
hydrological conditions during each storm.

8.4 CONTRASTS BETWEEN STATIONS AND THE DYNAMICS OF THE TRANSFER OF NUTRIENTS THROUGH THE CATCHMENT

The Coombs Brook forest ecosystem is characterised by qualitative and quantitative chemical changes in water from rain and snowmelt as it passes through the system. Water enters the system as a dilute solution of sulphuric and nitric acid (pH 4.0 to 5.28), but leaves the system containing primarily neutral SO_4^{2-} and NO_3^- (pH 6.5 to 8.4). The stream water chemistry is dominated by Ca^{2+} and SO_4^{2-}, but Na^+ and Mg^{2+} are also relatively important cations on an equivalent basis, SO_4^{2-} being more abundant than the next most abundant anion, NO_3^-, in stream water. Cations and anions in stream water are quite well balanced over the two-year span (Chapter 9).

As water is lost from the system by evapotranspiration, chemicals in solution tend to be concentrated into a smaller volume of water, and are based upon an average annual evapotranspiration loss of approximately 40% (Chapter 9). However, the concentration factor is not straightforward at all times in all sites, for not only do concentrations in stream water change, but the proportions of ionic or dissolved species change as well, indicating important internal chemical and biological reactions. In any case, an additional quantity of dissolved salts is acquired by the water from inside the catchment boundaries.

In general, the measured stream water concentrations of most dissolved substances vary within a narrow range (Table 8.4.1), even though discharge of water may fluctuate over four orders of magnitude during an annual cycle. This is particularly true for Mg^{2+}, SO_4^{2-}, Cl^- and Ca^{2+} concentrations. Concentrations of Na^+ may be diluted up to threefold during periods of high stream-flow, whereas NO_3^- concentrations are increased with increased discharge. Biotic activity within the ecosystem plays an important role in determining these relationships for NO_3^- in stream water: K^+ and NO_3^- are quite sensitive indicators of biological activity; therefore stream-water concentrations for these two nutrients are markedly reduced during periods of plant growth and increased during periods of vegetation dormancy, although the K^+ concentration shows a disturbance pattern in the catchment sites.

TABLE 8.4.1   AVERAGE OF LOWEST RECORDED CONCENTRATION
               TO HIGHEST RECORDED CONCENTRATION $(mg\ 1^{-1})\ast$
               = HIGHEST/LOWEST $(mg\ 1^{-1})$

	1	2	3	4	5	6	7
Ca^{2+}	28.9	2.01	2.54	2.05	2.26	2.27	2.4
Mg^{2+}	72.5	2.4	3.12	2.69	2.44	3.0	2.7
Na^+	145.0	3.0	7.68	3.00	5.16	5.0	4.5
K^+	65.2	11.6	6.58	910.0	766.6	25.5	37.4
SO_4^{2-}	48.8	3.9	3.14	5.35	4.5	5.9	4.7
NO_3^-	4.29	2.0	3.5	3.07	3.48	3.5	2.8
Cl^-	5.1	2.05	2.3	2.56	2.08	2.0	2.07
PO_4^{3-}	20.6	5.3	5.1	2.6	2.5	3.8	2.8
Con.	82.8	2.04	2.24	3.06	1.87	2.41	1.86
Disc.	83.6	24.8	6.8	12.5	28.2	21.3	11.5

$\ast$
highest value
lowest value

Although the concentration of most ions in stream water varies little from time to time, the annual concentration of NO_3^- has been generally increasing during the period 1984-86. For example, the average concentration of NO_3^- in stream water was 5.0 mg l^{-1} during 1984-85, and 9.7 mg l^{-1} during 1985-86, the same as S^{2-}, Cl^- and SO_4^{2-} behaviour which shows an increase in concentration during short terms. An explanation for this change in the NO_3^-, S^{2-}, SO_4^{2-} and Cl^- concentration is primarily circumstantial and there are several possibilities. The snow cover formed very late in the winter of 1985-86, and for the first time in 10 years widespread freezing of the soil was observed (North West Water personnel, personal communication). Various workers have reported that the freezing and thawing of soils promotes nitrification and the mobilisation of NO_3^- to drainage waters (Arefyeva and Kolesnikof, 1964; references cited in McGarity and Rajaratnam, 1973). Therefore, freezing and thawing of the Coombs Brook soils may have induced nitrification and the subsequent loss of relatively large amounts of NO_3^- and SO_4^{2-} in stream water. However, we have no explanation for the slow rate of NO_3^- observed during 1984-1985. But it might have been expected that if soil frost enhanced nitrification, the NO_3^- would have been flushed rapidly from the system and in subsequent years NO_3^- concentrations in stream water would have returned to 'normal'. It may be that part of the increased NO_3^- concentration in stream water in 1985-86 is related in some manner to the increasing concentration of NO_3^- in precipitation. A final complicating factor is that some sites in the forest show a larger response for NO_3^- concentrations in stream water than others, for example, the amount of NO_3^- concentration in stream water in Site 2 which was affected by the high rate of organic matter.

The highest loads recorded for Site 1 were for July, when the discharge at the time of sampling was 12.1 l s^{-1}. These loads amounted to 34.7 mg l^{-1} Ca^{2+}, 14.5 mg l^{-1} Mg^{2+}, 14.5 mg l^{-1} Na^+, 65.0 mg l^{-1} K^+, 48.8 mg l^{-1} SO_4^{2-}, 18.9 mg l^{-1} NO_3^-, and 46.9 mg l^{-1} Cl^-. Some peak solute concentrations were recorded at the lowest discharge and others at the highest discharge. For example, Ca^{2+} and Mg^{2+} have the highest concentration recorded in the lowest discharge. This was not so clear for the other elements because of the different sources of these loads, but in general the highest concentrations of major

cations were recorded at all sites at low discharges (Section 8.3.2 and Fig. 8.2.2.1).

The various levels of correlation between solute concentrations and discharge and their levels of significance may be explained in terms of contrasts between tributaries or, at some sites, problems of obtaining accurate discharge measurements. Generally, the major cations are significantly negatively correlated with discharge. The major exceptions to this are the Ca^{2+} concentrations at Stations 2 and 7 and the Na^+ concentration at Station 6. The problems at Stations 2 and 7, which are both on the smallest tributary studied, are possibly due to the inaccuracy of the discharge measurements in depths of water of less than 7 cm. Concentrations of Na^+ at Station 6 and at Station 3, where it is positively correlated with discharge, again show one tributary behaving differently from the rest of the catchment. Here, measurement errors are less likely, and some greater local mobility of Na^+ has to be envisaged as the cause of the unusual behaviour.

At Stations 1 and 6, K^+ is not significantly correlated with discharge. This may arise from the seasonal biotic controls on its mobility which give rise to wide contrasts in K^+ concentration at given discharges at different times of the year. For many runoff events K^+ is low, despite the effects of leaching (Section 8.3.2 and Fig. 8.2.2.5).

The anions SO_4^{2-}, NO_3^- and Cl^- are the only species which have any significant positive correlations with discharge, whereas conductivity, Ca^{2+} and Mg^{2+} concentrations are commonly highly significantly negatively correlated with discharge. The behaviour of SO_4^{2-}, NO_3^- and Cl^- shows different patterns at different sites. This can be explained in terms of the local sources and the leaching processes of these species in each tributary of the catchment. In addition to the differences in the relative mobility of SO_4^{2-} and Cl^- from site to site, the various types of trees and soils in the catchment and some analytical errors could partly explain this behaviour. At Sites 2 and 7, which are on the same small tributary, SO_4^{2-} only has negative correlations, probably as a result of some local source (Fig. 8.2.2.7).

At Sites 2, 3, 6 and 7, Cl^- also shows highly negative correlations,

and at Site 5 highly positive correlations, while at Site 1 it is not significantly correlated. This probably is related to local processes affecting the mobility of Cl^- rather than to any analytical errors. Anion behaviour generally shows unstable patterns, indicating the complexity of interactions between the soils, waters and organic matter affecting the mobility of different substances in the catchment.

8.5 CONCLUSIONS

The effect of increases in stream discharge in the Coombs Brook on the 10 constituents analysed can be divided into three classes:

1. Concentrations of NO_3^- and SO_4^{2-} nearly always increase with increasing discharge, in particular at Site 1.

2. As discharge increases, Ca^{2+}, Mg^{2+} and Na^+ are usually diluted. The same behaviour is shown by K^+ and Cl^-. Significant negative correlations with discharge are shown by Ca^{2+} (99.9%). It is hypothesised that Ca^{2+} is derived from the solution of $CaCO_3$.

3. A negligible amount of concentration, and insignificant correlation with discharge at all sites in the catchment, is nearly always shown by Fe, Mn and PO_4^{3-}.

These relationships are tentatively explained by a combination of the solubility of minerals dissolved and their location in the vertical profile of the catchment deposits. The leaching effect of the hydrographs of November and December 1984 may be exaggerated due to the preceding long period of low flows, but it was not quite clear for November and December 1985.

Thus, a general picture of the chemical evolution of water within the catchment can be built up from the soil and water data. Because of the variation in soil properties (Chapter 7), precipitation, diluted and dominated by Na^+ and H^+ among the cations, percolates into the soil and reacts with the cation exchange complex. This is richer in Ca^{2+}, Mg^{2+} and K^+ than precipitation, so the soil solution is enriched in these ions. The water slowly percolates downwards through the soil. Some water is lost by evapotranspiration, and cations are cycled through the vegetation. In response to further inputs of precipitation, the water is flushed into the underlying organo-mineral horizons. Large amounts of the Mg^{2+}, Ca^{2+} and K^+ released are taken up by roots and recycled within the soil, producing the observed distribution of exchangeable cations of the organic horizons.

Finally, contrast variation and dynamic movement of species in all sites in the Coombs Brook area have been studied. The individual analysis for all sites has revealed that Site 3 was the only site which showed that the rate of movement of the ions was significantly high for all species involved. Similarly, for the remaining sites the rate of ion movement was significantly high, with the few exceptions as described in each site (see Section 8.4).

CHAPTER   NINE

THE   WATER   AND   HYDROGEOCHEMICAL   BUDGETS

Introduction

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CHAPTER   NINE

THE   WATER   AND   HYDROGEOCHEMICAL   BUDGETS

INTRODUCTION

The preceding chapters have shown that much information on the biogeochemical and hydrological processes operating in a catchment may be obtained from a study of the chemistry of precipitation, stream water, soils and bedrock.   If the total amounts of elements entering and leaving the ecosystem can be calculated, it may be possible to quantify some of these processes.

Theoretically, then, the difference between annual input (I) and output (O) for a given chemical constituent tells whether that constituent is being accumulated within the ecosystem, $I > O$;   is being lost from the system, $I < O$;   or is quantitatively passing through the system, $I = O$.

Calculations of these inputs and outputs for Coombs Brook for the period 1st April 1984 to 30th March 1986 are presented in the following sections.   The errors involved in the calculation and the influence of a variety of possible sources of input and output are discussed. A hydrological, hydrochemical and geochemical balance is drawn up, and the results compared with those in the other studies.

The flux of chemicals within and through the Coombs Brook system may be simplified to input from precipitation (meteorologic vector), input from bedrock (geologic vector), and the output to that in drainage waters (hydrochemical vector).

9.1 THE HYDROLOGICAL BUDGET

The 800 ha Coombs Brook catchment received a total precipitation of 870.1 mm in the 1984-85 water year and 1038.2 mm in the 1985-86 water year, whilst stream flow at Station 1 was 379363 m^3 and 467886 m^3 respectively. From these figures it is possible to estimate the volume of water lost through evapotranspiration and storage (Table 9.1.1 and Fig. 9.1.1).

The water budget equation would thus take the normal form:

$$\text{Input} = \text{output} \pm \Delta \text{ storage} \qquad (1)$$
$$p = Q + Et \pm \Delta S \qquad (2)$$
$$p = R + (P - R) \qquad (3)$$

Over a year, it is conventionally assumed that storage is the same at the beginning and end of the year. Thus, neglecting the storage term, the water balance for Coombs Brook in each of the two study years is (following equation 3):

1984-85   696080 m^3 = 379363 m^3 ± 316717 m^3

1985-86   830560 m^3 = 467886 m^3 ± 362674 m^3

thus: in 1984-85 Runoff = 54.5%, Evapotranspiration and change
in storage = 45.5%

in 1985-86 Runoff = 56.5%, Evapotranspiration and change
in storage = 43.7%

Although the monthly data for rainfall and runoff generally show a predictable relationship (Table 9.1.1), there were four periods with unexpected results. For example, in February 1985, more water was discharged by the stream than fell as precipitation, thus evapotranspiration and change in storage has a negative value, because a heavy snowpack which built up in late January 1985 thawed, producing much runoff in early February.

The results for April, May, June, July, August and September 1984 show large apparent losses during these months, because of high temperatures during the summer, and subsequent high evaporation. This period was the hottest of the whole study period.

TABLE 9.1.1 WATER BALANCE FOR THE CATCHMENT IN TERMS OF
              PRECIPITATION (P), STREAM DISCHARGE (R),
              EVAPOTRANSPIRATION AND STORAGE (F)

Year	Month	P	R	$E = P-R$	Loss as % input $(E/P\%)$	Stream discharge as % $(R/P\%)$
		(all figures m^3)				
1984	April	11200	4759	6441	58	42
	May	41120	10874	30246	74	26
	June	60880	16863	44017	72	28
	July	27120	9280	17840	66	33
	August	49440	8994	40446	82	18
	September	136160	33710	102450	75	25
	October	77360	52167	25193	32	68
	November	128080	123046	5034	4	96
	December	49840	29944	19896	40	60
1985	January	50800	38966	11834	23	77
	February	*6720	23484	-16764	-249	-349
	March	57280	27276	30004	52	48
	April	88560	52207	36353	41	59
	May	51120	29486	21634	42	58
	June	75680	32739	42941	57	43
	July	58800	14637	44163	75	25
	August	74240	35992	38248	51	49
	September	38400	29867	8533	22	78
	October	58240	35805	22435	38	62
	November	72800	35368	37432	51	49
	December	94240	66221	28019	29	71
1986	January	91920	63331	28589	31	69
	February	44800	19635	25165	56	44
	March	81760	52598	29162	35	65
Total	1984-85	696080	379363	316717	46	54
	1985-86	830560	467886	362674	44	56

*Snow
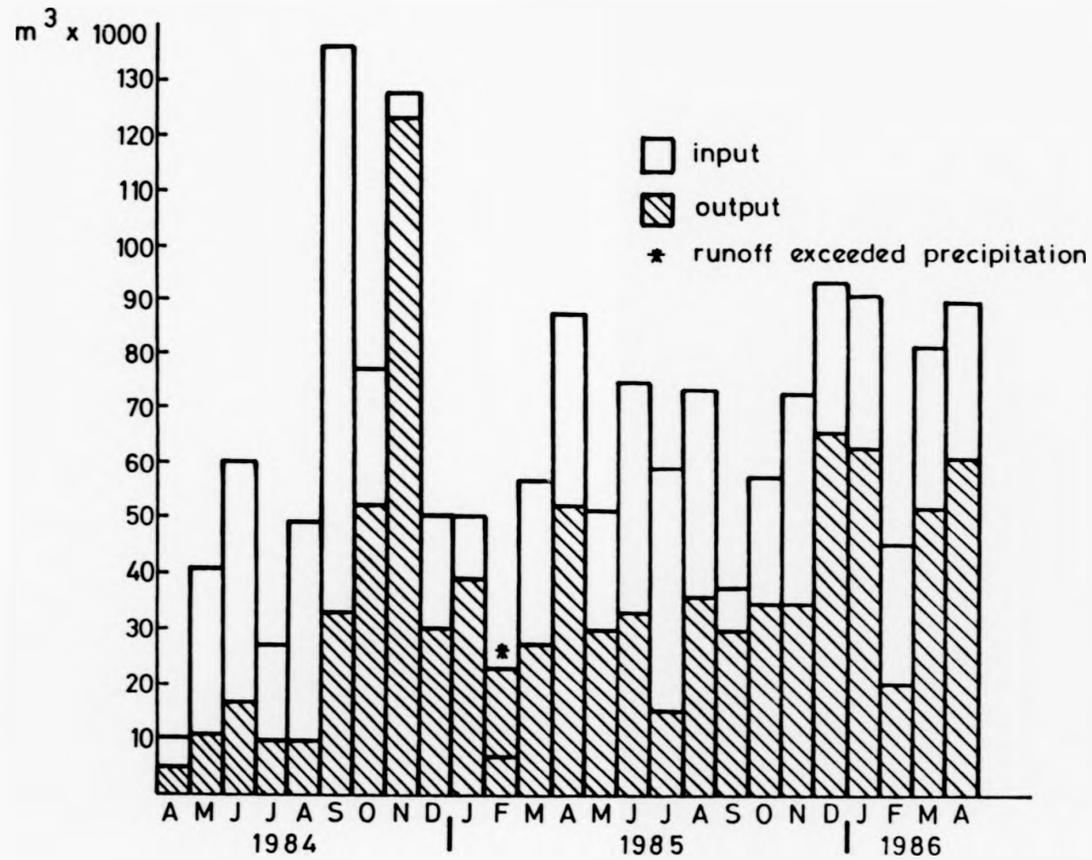
FIGURE 9.1.1   Monthly input and output for Coombs Brook catchment during 1984-1986

The apparently small evapotranspiration losses in November 1984 were due to heavy precipitation at the beginning of the month when 50 mm fell on November 2nd and rainfall was heavy for seven days. Most of this intense rain in a cold month ran off quickly to streams, leaving little to be lost by evapotranspiration. From March 1985 to March 1986, losses by evapotranspiration were generally high, except in September and December 1985, when heavy storms accounted for over 60% of the total rainfall, producing high discharges and little addition to the catchment storage.

The proportion of water input lost by evapotranspiration, 45.5% and 43.7% in the two successive years, shows remarkable consistency. The pattern of storms and snowfalls, rather than seasonal temperatures, influence the volume of runoff, storms in excess of 4 mm per day being most important. While evapotranspiration accounts for most of the loss of water each month, there will also be some water retained in catchment storage. In some cases such stored water is returned to the atmosphere by evapotranspiration in a later month. Losses (or gains) due to underflow are often assumed to be negligible. In this catchment some water may move at depth beneath the glacial deposits, but the quantities, unknown, are likely to be small.

Other small catchment water budget studies, such as Hubbard Brook (Likens et al., 1967), Pondwater Branch (Cleaves et al., 1970) and the Cottonwood and Sage Hen catchment (Marchend, 1971) are assumed to have been made in watertight catchments. However, Cleaves et al. (1970) took into account the change in groundwater storage of water, using an observation well. All these catchments are in areas thought to be unaffected by man.

The main limitation with these and the budgets calculated in this thesis is that they cover a period of only two years. Sampling over four years in the Hubbard Brook shows that total runoff, and therefore solute losses, vary greatly from year to year.

9.2   THE HYDROGEOCHEMICAL BUDGET APPROACH

9.2.1   Precipitation Inputs

Only seven uncontaminated samples of precipitation were obtained
for major cation and anion chemical analysis (Chapter 7).   Individual
storm inputs of solutes therefore cannot be assessed.   Budget calcu-
lations are therefore based on mean concentrations.   The shortcomings
of this method are recognised, for the solute content of precipitation
can vary not only from storm to storm, but also through a storm
(Carroll, 1962).   However, there is no alternative to taking mean
values with such a small number of samples.

Total inputs from precipitation were derived from multiplying
precipitation depth by catchment area and by mean concentration
(Table 9.2.1.1).   The inputs of each chemical species were calculated
on a weekly basis by multiplying the concentration of each species by
the volume of precipitation for the catchment area and adding them
together for each month.   These monthly inputs were then summed to
give the total annual input (Table 9.2.1.1).

The chemistry of the precipitation reflects diverse oceanic and
terrestrial sources (Section 1.3.1): Cl^- is generally greater than
Na^+ in precipitation, indicating some non-oceanic sources (Junge and
Werby, 1958) and some Cl^- may be held in the catchment for considerable
periods, being carried out in stream water in a later year (Fisher et
al., 1968).

9.2.2   Stream Outputs

Chemical outputs from the catchment at Station 1 are calculated
from the discharge record.   Continuous discharge records are not
available for the other sites upstream.   The weekly discharge is mul-
tiplied by weekly chemical concentration, then summed to monthly, to
give total values for chemical annual loads discharged out of the
catchment (Table 9.2.1.1).

Table 9.2.1.1 is included to give the total input and output of
elements in solution during the study period.   The output of the Ca^{2+}

TABLE 9.2.1.1   QUANTITY OF THE INPUT AND OUTPUT, ANNUAL AND TOTAL NET LOSS AND GAIN, FOR COOMBS BROOK CATCHMENT, MACCLESFIELD

	Ca^{2+}	Mg^{2+}	Na^+	K^+	SO_4^{2-}	PO_4^{3-}	NO_3^-	Cl^-	S^{2-}	Total
Input (kg/ha^{-1}) 1984–85	7.6	2.1	12.2	8.78	26.1	3.4	19.1	17.4	8.0	
Output (kg/ha^{-1}) 1984–85	10.1	4.0	3.5	0.967	11.49	0.189	4.69	7.53	3.5	
Net gain (+) or loss (−) kg/ha^{-1}	−2.5	−1.9	+8.7	+7.8	+14.6	+3.3	+14.4	+9.9	+4.5	
Input (kg/ha^{-1}) 1985–86	9.1	2.49	14.5	10.48	31.1	4.15	22.8	20.76	10.0	
Output (kg/ha^{-1}) 1985–86	12.5	4.9	4.32	1.19	14.17	0.233	5.79	9.29	4.4	
Net gain (+) or loss (−) kg/ha^{-1}	−3.4	−2.4	+10.2	+9.3	+16.19	+3.9	+17.0	+11.5	+5.6	
Total input $(kg/ha\ y^{-2})$ 1984–86	16.7	4.59	26.7	19.26	57.2	7.55	41.9	38.1	18.0	230.0
Total output $(kg/ha\ y^{-2})$ 1984–86	22.6	8.9	7.82	2.157	25.66	0.422	10.48	16.82	7.9	102.8
Net removal of material $(kg/ha\ y^{-2})$	−5.9	−4.31	+18.8	+17.1	+31.54	+7.128	+31.42	+21.28	+10.1	127.2
Difference as % of input	35.3	93.8	70.4	88.7	55.1	94.4	74.9	55.8	56.1	55.3
% of total input	7.2	2.0	11.6	8.37	24.86	3.2	18.2	16.5	7.8	100
% of total output	21.9	8.6	7.6	2.09	24.96	0.40	10.2	16.3	7.6	100

and Mg^{2+} concentration in solution exceeds the input. This must reflect solution of these elements from the rock and soil of the catchment. The sandstones in the catchment could release a considerable amount of Ca^{2+} and Mg^{2+} but a small amount of Na^+, K^+, SO_4^{2-}, PO_4^{3-}, NO_3^- and Cl^-. A considerable proportion (about 70%, 88%, 55%, 94%, 75% and 56% respectively) of the input of the latter elements does not pass out of the catchment in solution. Uptake of such nutrients as PO_4^{3-} in solution by a catchment system is to be expected. Allen (1964) showed that the litter and upper layers of the soils from Moor House National Nature Reserve can adsorb and hold considerable quantities of added nutrients, including PO_4^{3-}, living plants of the catchment playing an important part in this process. The retention of precipitation solutes by the soil must be quantified. Therefore the rate of increase in nutrient uptake by the vegetation and litter must be quantified in the catchment. The vegetation samples taken at Coombs Brook provide information on the rates of nutrient accumulation which were collected during the study period (Section 7.2).

9.2.3 Annual Variation

From the annual budget for April 1984 to March 1986 for precipitation input and stream water output, we are now able to estimate with some accuracy mean annual budgets for most of the major ions (Table 9.2.1.1). Over the two year period, there has been considerable variation; in general, however, a net loss of Ca^{2+} and Mg^{2+} has occurred from the catchment area each year. The study period averages suggest that there has been a small net gain in NO_3^-, Cl^-, PO_4^{3-}, SO_4^{2-}, K^+ and Na^+ in both years (Table 9.2.1.1).

There are two separate considerations in evaluating annual input-output budgets:

(1) the direction of the net change, whether input is greater or lesser than output; and

(2) the magnitude of the net change, i.e. the difference in amount between input and output.

These parameters may vary from year to year for the individual chemical

elements.   For some ions, data from a single annual cycle (n=1) are
sufficient to establish the direction of net change;   for other ions,
data from several years (n>1) are necessary.   Similarly, a variable
number of years is required to characterise the magnitude of net
change with meaningful confidence limits.   The two years of study at
Coombs Brook make it difficult to form generalisations about the
annual budgets for the various ions.   However, the direction of net
change for budgets of precipitation input minus stream water output
for Ca^{2+}, Mg^{2+}, Na^+ and SO_4^{2-} was probably predictable (Table 9.2.1.1).
For these ions the direction of the budget is not in doubt, but the
magnitude may be.   For K^+, NO_3^-, and Cl^- the two years of observation
are unlikely to give reliable results for both net change and magnitude.

9.2.4   Seasonal Variation

Much of the biogeochemical activity in the Coombs Brook system
reflects the seasonal, climatic and organic processes.   Normally, a
snowpack may occur for a period at any time between mid-November and
April.   The deciduous trees start to produce leaves during May, and
the major leaf fall occurs in early October.   Some organisms of the
ecosystem are adapted to make full use of the environmental conditions
in the transition periods between seasons (Muller and Bormann, 1976).

To investigate seasonal changes, the year was divided into four
periods, summer conditions being assumed to operate from June to
September, autumn from October to November, winter from December to
February, and spring from March to May.   Although these periods are
arbitrary, they correspond well with biological activity in the Coombs
Brook catchment.   Although the concentrations of various ions in pre-
cipitation are highly variable from storm to storm and week to week,
some seasonal trends emerge.   The total ionic concentration of winter
precipitation in Coombs Brook is almost one-half that of other seasons
of the year (Table 9.2.4.1).   This is reflected in the concentration
of all ions, except K^+, Na^+ and NO_3^-.   Winter concentrations of the
latter three ions are either equal to or exceed those in other seasons.
A peak in concentration for Cl^-, Na^+, K^+, and Mg^{2+} occurs in the
winter (Table 9.2.4.1).   This annual sinusoidal pattern for many of
the elements may result in part from the origin of air masses and in

TABLE 9.2.4.1   AVERAGE CONCENTRATIONS IN BULK PRECIPITATION DURING
                 DIFFERENT SEASONAL PERIODS FOR THE COOMBS BROOK
                 CATCHMENT ($mg/1^{-1}$) DURING TWO YEARS (1984-1986)

	Summer June-Sept.	Autumn Oct.-Nov.	Winter Dec.-Feb.	Spring March-May
Ca^{2+}	0.573	0.622	1.679	0.819
Mg^{2+}	0.208	0.237	0.524	0.340
Na^+	2.226	1.252	2.3	1.78
K^+	1.27	0.779	1.531	1.347
SO_4^{2-}	7.47	1.67	5.019	6.525
PO_4^{3-}	0.42	0.423	0.074	0.062
NO_3^-	4.07	4.4	4.9	4.8
Cl^-	5.5	3.4	6.7	4.5
S^{2-}	2.46	0.55	1.66	2.14

TABLE 9.2.4.2   AVERAGE CONCENTRATIONS IN STREAM WATER DURING
                 DIFFERENT SEASONAL PERIODS FOR THE COOMBS BROOK
                 CATCHMENT ($mg/1^{-1}$) DURING TWO YEARS (1984-1986)

	Summer	Autumn	Winter	Spring
Ca^{2+}	23.9	19.3	20.5	21.3
Mg^{2+}	8.6	8.3	8.5	8.25
Na^+	7.86	7.17	6.9	7.55
K^+	1.29	1.23	2.2	1.42
SO_4^{2-}	23.3	24.7	26.1	26.3
PO_4^{3-}	0.49	0.39	0.48	0.40
NO_3^-	9.5	8.49	10.9	10.0
Cl^-	18.2	14.72	15.3	15.8
S^{2-}	7.5	7.97	8.41	8.53

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Cl^-	5.5	3.4	6.7	4.5
S^{2-}	2.46	0.55	1.66	2.14

TABLE 9.2.4.2   AVERAGE CONCENTRATIONS IN STREAM WATER DURING
DIFFERENT SEASONAL PERIODS FOR THE COOMBS BROOK
CATCHMENT $(mg/1^{-1})$ DURING TWO YEARS (1984-1986)

	Summer	Autumn	Winter	Spring
Ca^{2+}	23.9	19.3	20.5	21.3
Mg^{2+}	8.6	8.3	8.5	8.25
Na^+	7.86	7.17	6.9	7.55
K^+	1.29	1.23	2.2	1.42
SO_4^{2-}	23.3	24.7	26.1	26.3
PO_4^{3-}	0.49	0.39	0.48	0.40
NO_3^-	9.5	8.49	10.9	10.0
Cl^-	18.2	14.72	15.3	15.8
S^{2-}	7.5	7.97	8.41	8.53

part from differences in aerosol scavenging efficiency between rain-
drops and snowflakes.   Herman and Gorham (1957) have suggested from
their studies in Nova Scotia that snowflakes may be less efficient
than raindrops in removing materials from the atmosphere.   Concen-
trations of NO_3^- in precipitation are relatively similar during all
seasons (Table 9.2.4.1).   The relatively high concentrations of Na^+
and Cl^- in winter rains may reflect a larger influence of marine
aerosols at this time in western England.

Concentrations of various ions in stream water vary less season-
ally than in precipitation (Table 9.2.4.2), being slightly higher in
the summer, because of higher temperatures, more intense biological
activity and greater transpiration.   In general, NO_3^- concentrations
in stream water begin to rise in the autumn when there is a reduction
in biological activity, and attain a maximum concentration in the
winter or early spring.   The United States Geological Survey Water
Resources data and Hubbard Brook Experimental Forest data show a
similar pattern for rivers and streams throughout New England and New
York State.   This pattern has also been observed in the surface waters
of many freshwater lakes where NO_3^- concentrations reach maximum levels
in winter and early spring probably as a result of increased nitrifi-
cation during the winter.

At Coombs Brook, NO_3^- concentrations increase markedly with in-
creased stream flow.   However, this may be a fortuitous relationship,
since the late winter-early spring period of maximum stream flow is
potentially also a time for relatively high nitrification in the soil.
Even though there may be no casual relationship between high NO_3^- con-
centration and increased stream flow during this time, the incidence
of high NO_3^- coincides with the period of high discharge.

The seasonal pattern of average precipitation input and stream
water output (Table 9.2.4.3) is similar to the monthly flux (Figs.
9.2.5.1, 9.2.5.2, 9.2.5.3 and 9.2.5.4).   Input was greatest during
spring and autumn 1984-85, and summer and spring 1985-86.   It was
lowest during winter and summer 1984-85, and autumn and winter 1985-86.
Such a pattern is not uniform for each year because of the sharp rise
and fall in some elements in different seasons (for example, Cl^-, NO_3^-,
and SO_4^{2-} species), but the rest of the elements have similar behaviour

TABLE 9.2.4.3   AVERAGE OF SEASONAL, ANNUAL AND NET REMOVAL IN THE CATCHMENT AREA (in kg ha^{-1} y^{-1})

		Ca^{2+}	Mg^{2+}	Na^+	K^+	SO_4^{2-}	PO_4^{3-}	NO_3^-	Cl^-	S^{2-}	Total	% of yearly total
Input 1984-85	Summer	0.53	0.12	0.82	0.94	2.56	0.34	1.88	1.70	0.75	9.6	17.1
	Autumn	0.78	0.37	1.95	0.71	3.85	0.51	2.82	2.57	1.1	14.6	25.9
	Winter	0.37	0.28	0.86	1.05	3.78	0.03	3.06	1.70	1.25	12.4	22.1
	Spring	1.30	0.43	1.39	0.54	5.25	0.07	6.86	2.1	1.69	19.6	34.8
	Total	2.98	1.2	5.02	3.24	15.4	0.95	14.6	8.1	4.8	56.2	100.0
Input 1985-86	Summer	0.50	0.16	2.61	1.99	6.07	1.05	3.14	7.5	2.01	25.0	40.0
	Autumn	0.52	0.13	0.92	0.77	1.45	0.55	3.6	2.65	0.47	11.1	15.0
	Winter	0.81	0.32	1.89	0.52	2.33	0.08	2.63	3.56	0.77	12.9	17.5
	Spring	0.31	0.27	2.01	2.13	6.81	0.28	3.82	6.8	2.27	24.7	33.5
	Total	2.14	0.88	7.43	5.41	16.6	1.96	13.2	20.5	5.5	73.7	100.0
Average for 2 years		2.56	1.04	6.2	4.3	16.0	1.4	14.0	14.3	5.1	65.0	–
Output 1984-85	Summer	0.68	0.21	0.17	0.02	0.48	0.008	0.21	0.34	0.15	2.26	11.2
	Autumn	1.97	0.84	0.73	0.13	2.46	0.04	1.08	1.74	0.7	9.69	48.0
	Winter	0.87	0.40	0.21	0.06	0.86	0.01	0.39	0.48	0.23	3.51	17.4
	Spring	1.47	0.58	0.311	0.04	0.97	0.017	0.47	0.57	0.30	4.73	23.4
	Total	4.99	2.03	1.4	0.25	4.77	0.075	2.15	3.13	1.38	20.2	100.0
Output 1985-86	Summer	0.78	0.30	0.20	0.03	0.84	0.013	0.32	0.73	0.23	3.44	15.3
	Autumn	0.92	0.39	0.33	0.05	1.19	0.09	0.32	0.60	0.48	4.37	19.4
	Winter	1.28	0.47	0.50	0.61	1.82	0.02	0.66	1.16	0.53	7.1	31.5
	Spring	1.31	0.53	0.58	0.13	2.2	0.02	0.77	1.33	0.69	7.6	33.8
	Total	4.29	1.69	1.61	0.82	6.1	0.143	2.07	3.82	1.93	22.5	100.0
Average for 2 years		4.6	1.86	1.5	0.53	5.4	0.109	2.1	3.4	1.65	21.3	–
Average of net removal		-2.04	-0.82	+4.7	+3.77	+10.6	+1.29	+11.9	+10.9	+3.45	+43.7	–
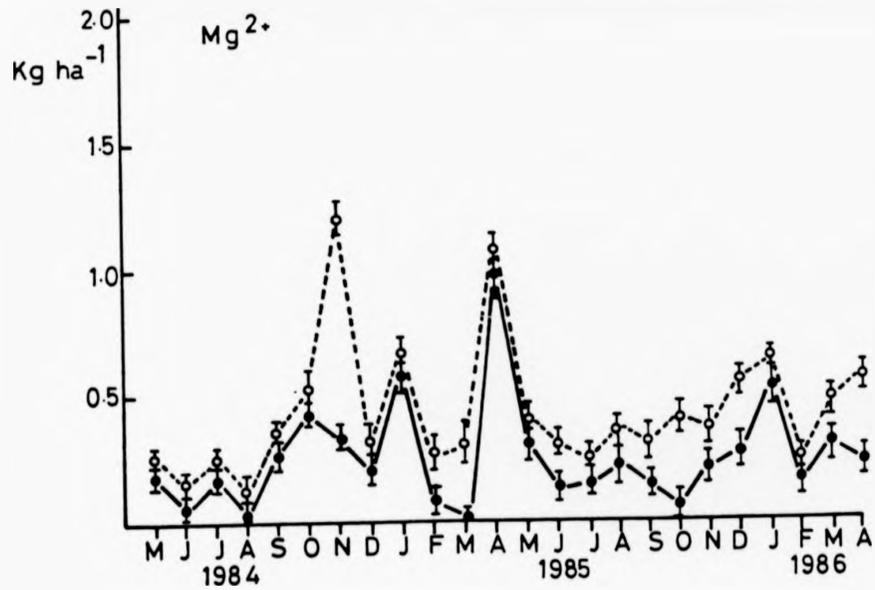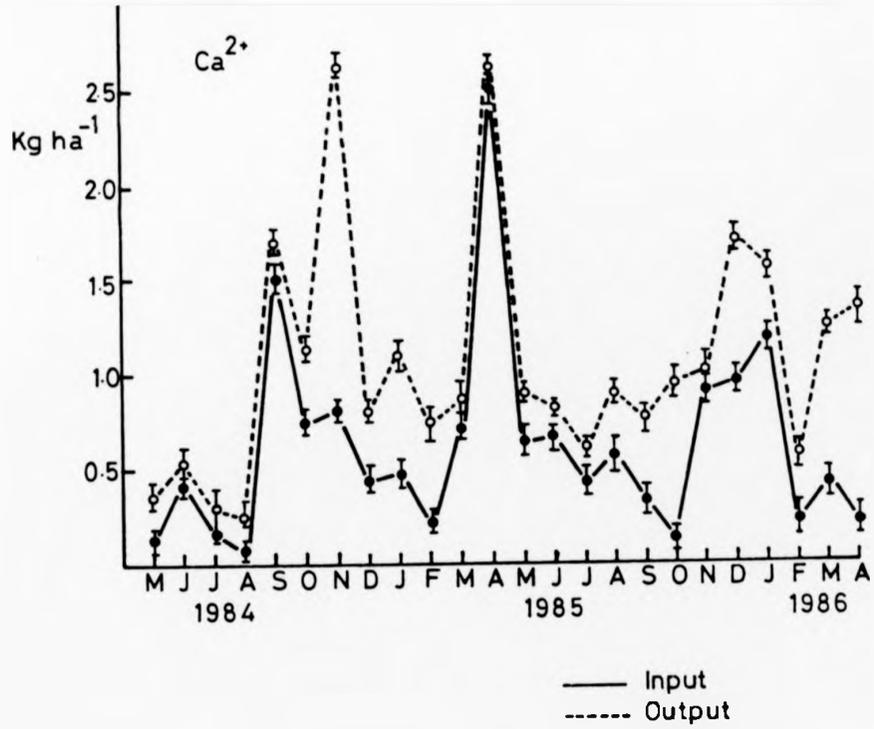
FIGURE 9.2.5.1

Monthly flux of Ca^{2+} and Mg^{2+} for Coombs Brook catchment
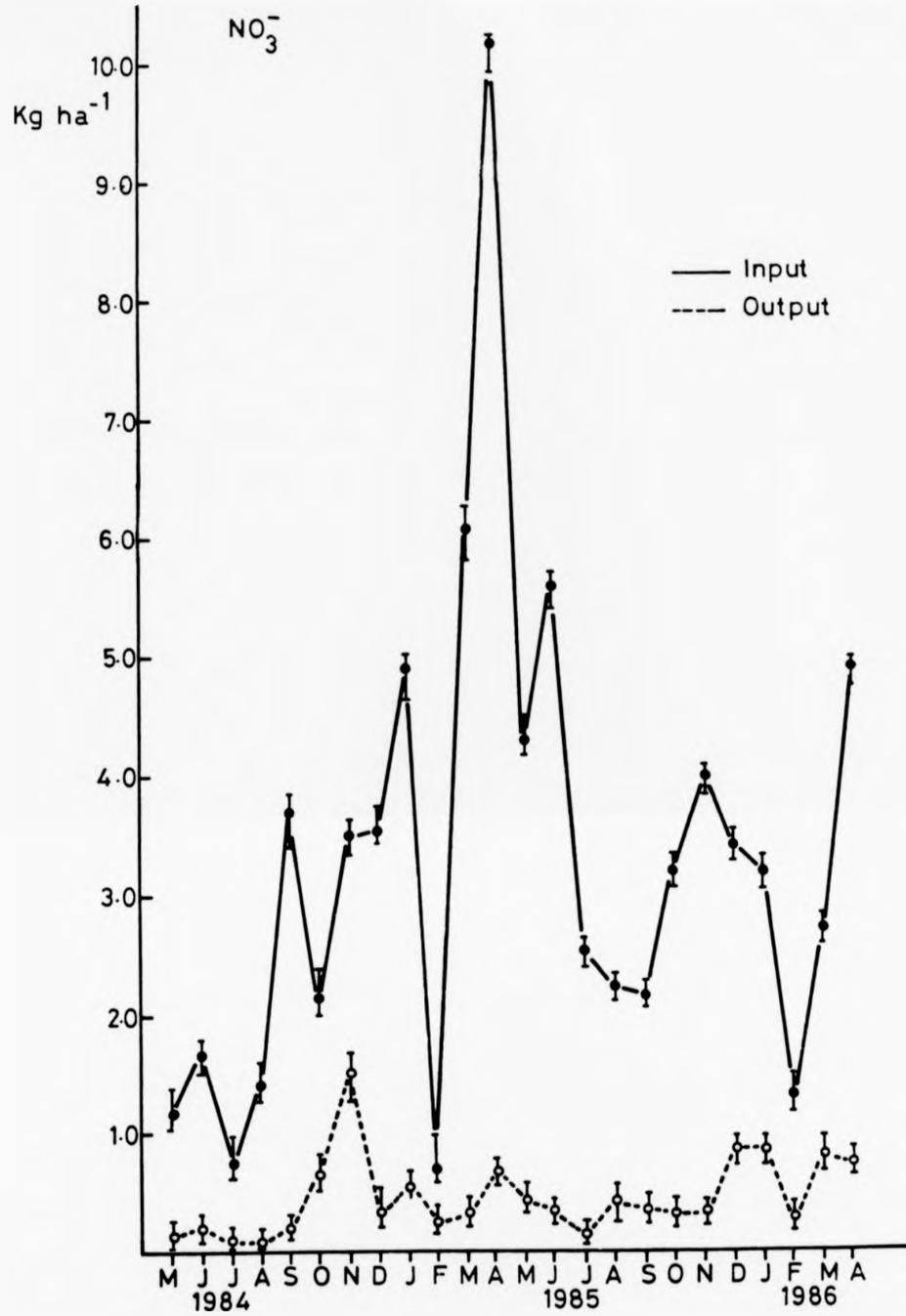
FIGURE 9.2.5.2

Monthly flux of NO_3^- for Coombs Brook catchment
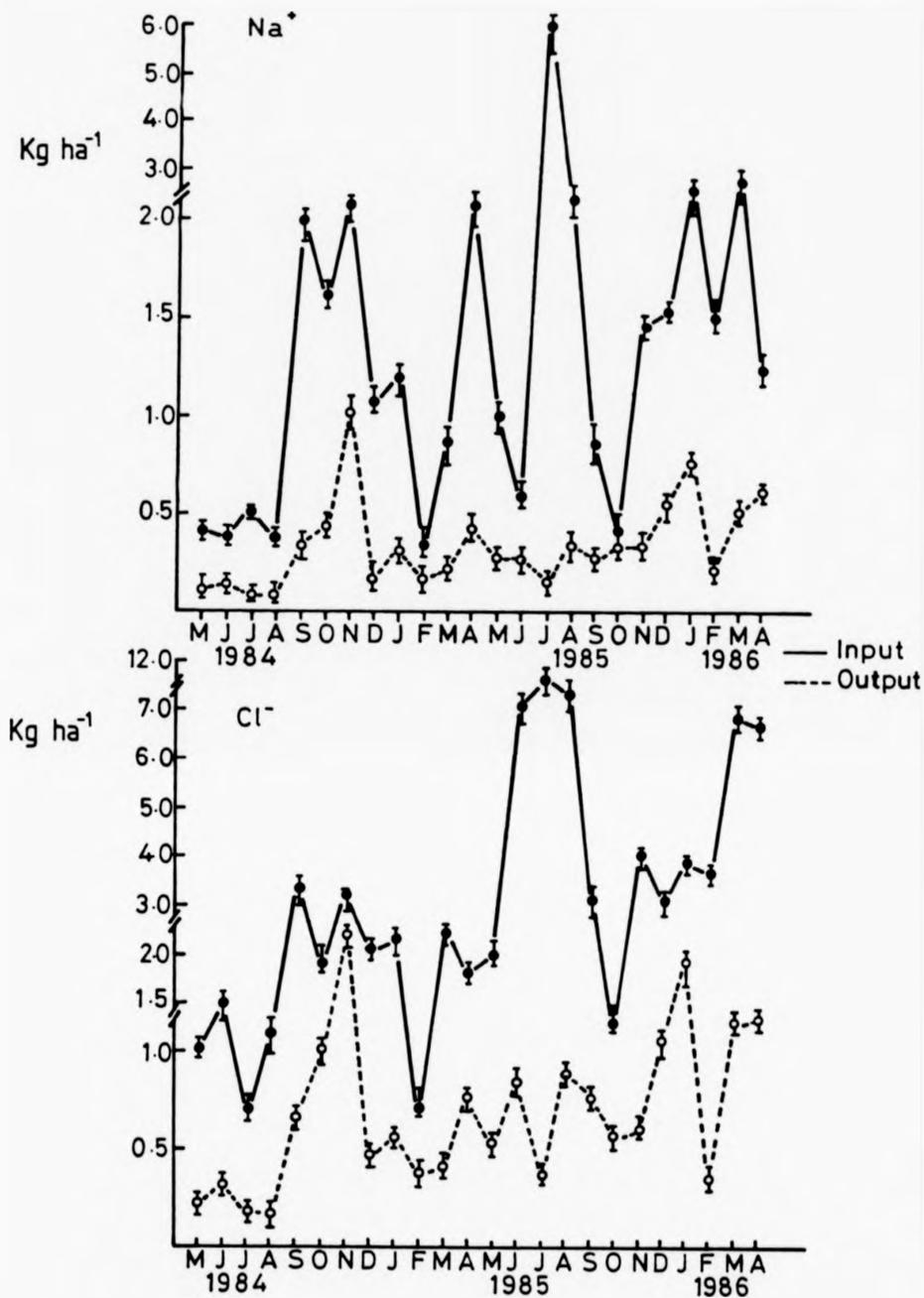
FIGURE 9.2.5.3

Monthly flux of Na^+ and Cl^- for Coombs Brook catchment
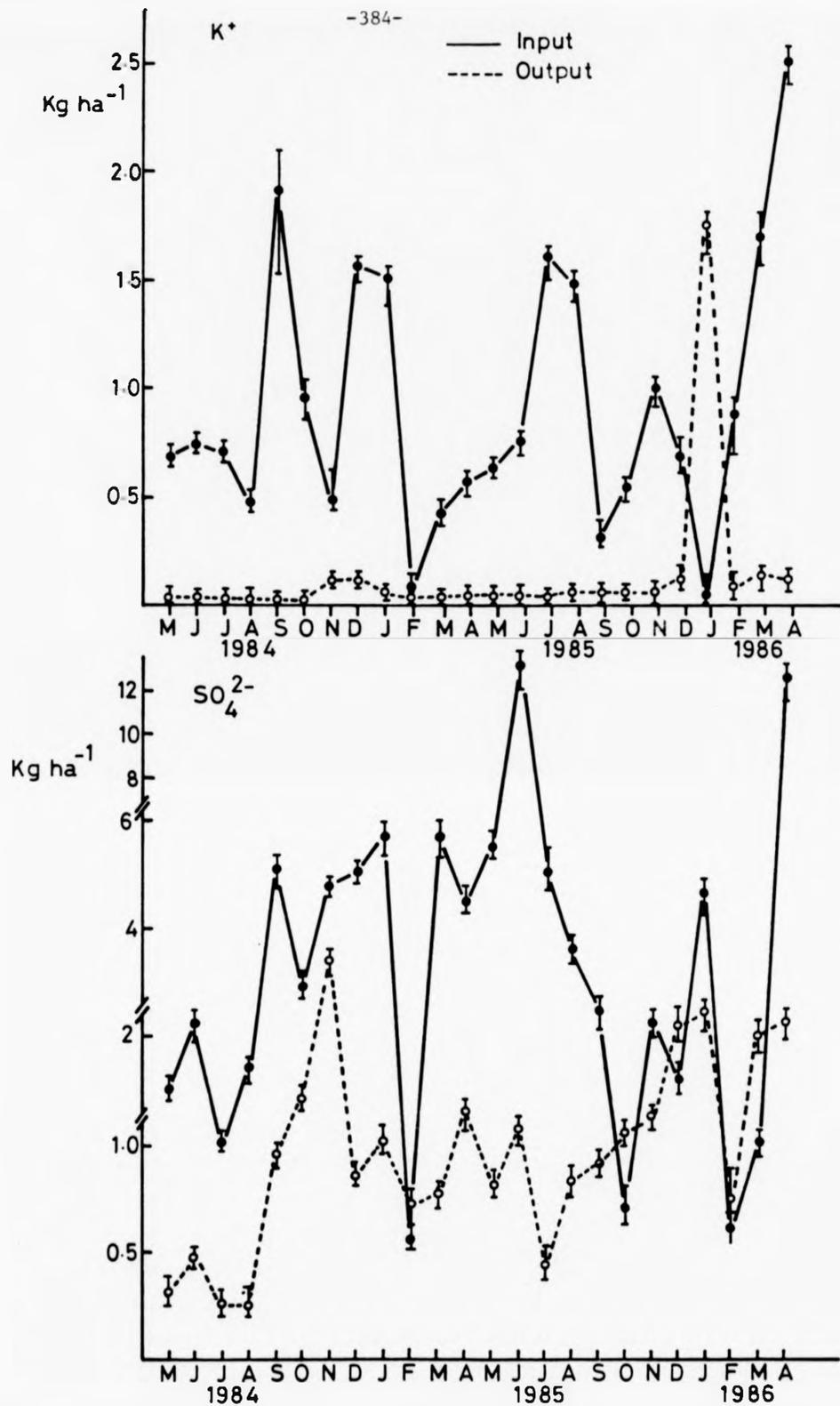
FIGURE 9.2.5.4   Monthly flux of SO_4^{2-} and K^+ for Coombs Brook catchment

during the four seasons.   Thus, while major cations vary little, the major anions vary considerably in different seasons of the year, probably as the nature of their sources changes: Cl^-, SO_4^{2-}, and NO_3^- comprise about 68-70% of the dissolved substances in precipitation (Table 9.2.4.3), resulting in a lack of balance between the cation and anion contents of precipitation.   The total anion content is three times greater than the cation.   Inputs of Na^+, K^+, and, to a lesser extent, Ca^{2+} and Mg^{2+}, are greater than would be expected from precipitation amounts in the autumn.   However, winter precipitation is less enriched with solutes relative to the annual average.   While precipitation brings lower amounts of all dissolved substances than would be expected in winter, such inputs vary greatly at all seasons (Table 9.2.4.3).

About 48% of the annual solute load was discharged in the 1984 autumn, and 20% in the 1985 autumn.   Only 11-15% of the annual load was removed in the summers of 1984 and 1985.   However, 17% and 32% was discharged in the two winters respectively, and 23% and 34% in the spring seasons.   It seems that winter and spring behaved similarly during the study period.

The output of dissolved substances is clearly dominated by SO_4^{2-}, with Ca^{2+}, Mg^{2+}, SO_4^{2-}, Cl^- and Na^+ losses from the stream water reflecting the amount of water discharged.   Losses of PO_4^{3-} bear little relationship to the amount of stream-flow.   Likewise, output of NO_3^- during summer and autumn is less than expected and in winter and spring is more than expected on the basis of water loss.   Outputs of K^+ are variable, but the reduction of K^+ in summer indicates an obvious drop in stream water output assumed to be from biologic utilisation within the forest ecosystem (Table 9.2.4.3).

9.2.5 Monthly Variation

A greater insight into the chemical budget of this catchment forest ecosystem can be gained by looking at the nutrient budgets on a monthly scale.   Three patterns of input-output emerge:

(a) those in which output exceeds input in every month;

(b)   those in which input exceeds output in every month;   and

(c)   those in which there is a transition from input dominance
      to output dominance on a monthly basis.

These patterns are not related to chemical sources.   For example,
Ca^{2+} and K^+ are both mainly derived from sedimentary rocks, yet they
exhibit different patterns; SO_4^{2-} and NO_3^-, however, both from atmos-
pheric sources, exhibit two different patterns, reflecting complex
interactions involving the effects of biologic activity and annual
variations in weather.

(a)   Output consistently greater than input

Solutes whose outputs exceed the inputs in each month of the
study period are exemplified by Ca^{2+} and Mg^{2+} (Fig. 9.2.5.1).   Over
the two years, despite variations in monthly gains and losses, losses
always exceed inputs.

(b)   Input consistently greater than output

Concentration of NO_3^- is characterised by monthly gains that con-
sistently exceed losses in a term of study (Fig. 9.2.5.2).   Monthly
losses of NO_3^- are relatively constant and low, but inputs are highly
variable, being relatively high in autumn and winter: Na^+ and Cl^-
have patterns similar to NO_3^-, with losses consistently exceeding gains
each month (Fig. 9.2.5.3).

(c)   Transition patterns

Gains of K^+ exceeded losses from May 1984 until April 1986, except
during January 1986 when loss exceeded the gain (Fig. 9.2.5.4).   This
is of great interest, as it was suggested earlier that the K^+ budget
(particularly K^+ in stream water) is particularly sensitive to seasonal
biologic control within the ecosystem, especially the onset of vegeta-
tion growth in spring and the maximum litter fall in autumn.

The monthly pattern for SO_4^{2-} is generally similar to that of K^+
(Fig. 9.2.5.4).   The monthly gains of SO_4^{2-} had a rather unsymmetrical
pattern, with a peak in June, April and January and low in February.

9.3 OTHER SOURCES OF INPUT AND OUTPUT

Using the results from Sections 9.1 and 9.2, a list of inputs in precipitation, outputs in stream water, and the balance between them can be drawn up for all species (Table 9.1.1). Inputs and outputs of chemical species from other sources will be considered in the light of these data, in this section. Approximately 95% confidence limits are given for each species. These relate to errors in estimating the concentrations of chemical species, and make no allowance for errors in calculating the inputs and outputs of water.

9.3.1 Discussion

Following the approach of Bormann and Likens (1967) and Likens et al. (1977), I have considered meteorologic input and geologic output as the major factors in biogeochemical cycling of elements through the catchment. It is necessary, however, to assess the importance of other sources of input and output, and their significance for measuring meteorologic input and geologic output in relation to the aims of this project. Significant inputs may also occur through the dry deposition of oceanic aerosols or gases on vegetation (Chapter 7). White et al. (1971) have shown that less than 50% of the salts arriving at a rain gauge at Liverpool University were associated with rain; the rest arrived as a dry deposit and were washed into the gauge by subsequent precipitation. In view of its maritime climate, dry deposition of oceanic aerosols would be expected to be important in Macclesfield Forest, in common with other forest catchments in Britain (Roberts and James, 1970; White et al., 1971). Thus, the amounts of salts supplied to the catchment have to be estimated indirectly (by the method described later), using throughfall data described in Chapter 7. This can be achieved for a number of elements.

1. Nitrate

During the two year period 1984-1986, 41.9 kg ha^{-1} of NO_3^- were added in bulk precipitation and 10.48 kg ha^{-1} were lost in stream water from the catchment area. These short-term data show that more NO_3^- has been added to these catchments in precipitation than has been lost in stream water. This amount (which was about 30 kg ha^{-1} y^{-2}),

in addition to the amount supplied by throughfall (which was about 46 kg ha^{-1} y^{-2}) (Table 9.3.1.1), although substantial, cannot account for N$_2$ accumulating within the ecosystem in living and dead biomass: NO$_3^-$ is incorporated in this biomass and thereby is stored at a rate of about 76 kg ha^{-1} y^{-2} in these forest ecosystems, or absorbed and recycled.

2. Sulphur

This also may exist as a gas or as an aerosol in the atmosphere. About 18.0 kg ha^{-1} y^{-2} were added in bulk precipitation and about 7.7 kg ha^{-1} y^{-2} lost in stream water from the catchment. But the throughfall accumulation of S^{2-} shows that about 66 kg ha^{-1} y^{-2} of S^{2-} must be accumulated during the two study years from the vegetation in addition to 18.0 kg ha^{-1} y^{-2} of S^{2-} from bulk precipitation (Table 9.3.1.1).

3. Chloride

The relatively high concentrations of Cl$^-$ in throughfall and stream flow (Table 9.3.1.1)suggest that Cl$^-$ is released from, or washed off, vegetation surfaces. Possibly small amounts of impacted aerosols containing Cl$^-$ accumulate on vegetation surfaces. Any net output over the year must be assigned to dry deposition, as negligible amounts of Cl$^-$ accumulate in the soil or result from weathering processes.

Precipitation of Na$^+$ and Mg^{2+} are, like Cl$^-$, dominantly of oceanic origin. Thus, a similar percentage of their total input probably also arrives as dry deposit. Thus, the approximate amounts of Na$^+$ and Mg^{2+} dry deposited during the study period can be calculated by the following method. The values for Na$^+$ and Mg^{2+} can be checked by the use of the Na$^+$/Cl$^-$ and Na$^+$/Mg^{2+} ratios of precipitation. These ratios show high variation and, assuming that the ratios are identical in dry deposition (Claridge, 1970), the amounts of dry deposit are found by multiplying the net output of Cl$^-$ by the Na$^+$/Cl$^-$ ratio to obtain the amount of Na$^+$ dry deposit, and dividing this by the Na$^+$/Mg^{2+} ratio to obtain the amount of Mg^{2+} dry deposit.

Some Ca^{2+}, K$^+$, and SO$_4^{2-}$ will also be dry deposited as aerosols. However, the ratios of these species to Na$^+$ and Cl$^-$ in precipitation cannot be used to assess dry deposition. Some species come from

TABLE 9.3.1.1   THE BALANCE OF SOLUTE AT COOMBS BROOK FOR THE STUDY PERIOD 1984-86 $(kg\ ha\ y^{-2})$

	Ca^{2+}	Mg^{2+}	Na^+	K^+	SO_4^{2-}	PO_4^{3-}	NO_3^-	Cl^-	S^{2-}
Net input from precipitation	16.7	4.5	26.6	19.1	57.2	7.5	41.9	38.1	18.8
Net throughfall and stemflow	65.3	12.9	26.2	41.3	221.5	-3.8	46.8	171.8	66.9
Stream water output	22.5	8.9	7.8	2.15	25.6	0.184	10.4	16.8	7.7

sources other than oceanic spray; Ca^{2+}, K^+ and some of the SO_4^{2-} appear to have a terrigenous origin, whereas the rest of the SO_4^{2-}, NO_3^- and H^+ appear to have an industrial origin. The ability of vegetation to absorb gaseous SO_2 is well known (Fowler and Unsworth, 1974). For the sake of an example, it may be assumed that approximately half of the excess SO_4^{2-} in the geochemical balance is balanced by absorption of gaseous SO_2 by vegetation, and half by dry deposition of aerosols of $CaSO_4$.

Turning to sources of output, the geological output will all appear in the stream as the bedrock is practically impermeable, but not all forms of it have been measured. The chemistry of suspended sediments which consist mainly of organic material, quartz and silicate minerals, was not measured in this project, which was concerned with chemical rather than physical elements.

An open 2 ha area around Site 5 (Plate 2.2.4) has been used for burning the heather and for pine seedlings, on a random basis. The burning may have added material to the atmosphere as smoke, gas and windblown ash. However, unless the burning gets out of hand and the ash is removed by wind erosion, the Ca^{2+}, Mg^{2+}, K^+ and PO_4^{3-} are mainly converted to soluble ash. This will be leached into the soil by precipitation, and may ultimately appear as geological output in the stream. However, these elements may be taken up by roots or organic matter, and retained in the soil (Allen, 1964). The length of the rotation of burning at Macclesfield Forest is greater than ten years ago (personal communication), so the potential losses from this source could be small.

Thus, in addition to the inputs and outputs measured in this project, there are a number of other sources of input and output of chemical species to the catchment. The most significant appear to be the dry deposition of Na^+, Mg^{2+}, Cl^-, Ca^{2+} and SO_4^{2-}, the output of suspended sediment and organic matter in the stream, and possibly other elements in smoke produced by heather and stock burning.

9.4   COMPARISON WITH BUDGET CALCULATIONS FOR OTHER CATCHMENTS

Introduction

Having examined the input and output budget, we can now proceed
to compare the balances in the study area with those of other catch-
ments.   Many workers in the last 30 years have studied the hydrolo-
gic cycle within individual catchments in varying degrees of detail.
The aims of such studies have varied greatly, from the assessment of
the cycling of nutrients in vegetation, to the weathering reactions,
and the effects of different systems of land use.   Common to most is
a 'balance sheet' of inputs and outputs, which permits net gains or
losses from the catchment to be estimated.

Inputs and outputs of elements to a catchment may be either bio-
logic, meteorologic or geologic.   However, by measuring meteorologic
input (gases, aerosols, and dissolved solids in precipitation) and
geologic output (dissolved and particulate matter in the stream), and
the biologic factor, an almost complete balance can be erected for
the catchment.   This is difficult for elements, such as N_2 and S^{2-},
with a major gaseous phase, but for elements existing dominantly in
the solid state or aqueous solution, this approach can distinguish the
elements removed from the catchment in solution from those involved in
internal cycling within the ecosystem.   The Coombs Brook catchment
complies with these requirements, being forested and having largely
impermeable bedrock.

9.4.1   Examples of Hydrogeochemical Balance for Small Catchments

Probably the most thorough and long-running small catchment study
is that conducted on seven small forested catchments at Hubbard Brook
Experimental Forest in the White Mountains of New Hampshire since 1963
by Likens, Bormann, Pierce, Eaton and Johnson (1977).   As well as
monitoring the amount and chemical composition of precipitation and
river water, they have investigated the storage of elements by vege-
tation within the catchment, the mineralogy of the soils and bedrock,
and the weathering processes operating.

The Hubbard Brook catchment has a cool humid continental climate,

but industrial pollution is a major influence on precipitation chemistry which is a mixture of dilute H_2SO_4 and HNO_3. The stream water consists of a near-neutral solution of SO_4^{2-} and NO_3^-, the H^+ having been used up in ion exchange and hydrolysis reactions which have released the cations. The vegetation is aggrading deciduous northern hardwood forest, and the soils are mature podzols developed on glacial till which overlies impermeable schists and gneisses. Annual balances show a net loss of Ca^{2+}, Mg^{2+}, K^+, Na^+ and SO_4^{2-}, and a net gain of NH_4^+, H^+ and PO_4^{3-}. The long-term inputs and outputs of NO_3^- and Cl^- are nearly equal. For most elements the direction of change in the budget was discernible from only a few years' data, but for K^+, Cl^- and NO_3^- these data give unreliable results for both direction and magnitude of change.

Weathering reactions are caused not only by H^+ in precipitation, but also by H^+ generated within the soil by oxidation of NH_3 and decomposition of organic matter. As there is little change in concentration with discharge, total output is proportional to total discharge, and is least in the driest year and greatest in the wettest year.

In a stand of hard beech at Silver Stream, near Wellington, New Zealand, Miller (1968) measured Ca^{2+}, Mg^{2+}, K^+, Na^+, PO_4^{3-}, S^{2-} and Cl^- in litter, leaf drip, rainfall, vegetation and soil for several years, and produced a tentative balance sheet for the cycling of nutrients within the trees and the site as a whole. He found that considerable quantities of nutrients were taken up by the trees, but only about 10% was retained in the long term. The rest was returned to the soil in the annual litter fall and by leaching of nutrients from the leaves by rainwater. There were large overall losses of Ca^{2+}, Mg^{2+}, K^+, Na^+ and S^{2-} from the site, small losses of N_2 and PO_4^{3-}, and the Cl^- budget was balanced. Comparison with the Hubbard Brook study illustrates how different forests differ in the rate at which they immobilise nutrients, and how this will vary with the age of the trees.

Crisp (1966) produced a nutrient balance for an area of moorland used for sheep pasture at Rough Sike in the northern Pennines, England. This is an 83 ha catchment with blanket bog vegetation and peat soils, eroding in places, underlain by glacial drift and bands of limestone, shale and sandstone. Over a year, measurements were made of the

N_2, PO_4^{3-}, Ca^{2+}, K^+ and Na^+ content of precipitation and stream water. The results show that only dissolved material in the stream and eroded peat carried in suspension by the stream are of major importance for the output of elements from the ecosystem. This is an important finding because, in moorland catchments, such as Rough Sike, biological inputs and outputs, i.e. movement of animals into and out of the catchment, are certainly not random, as they are in undisturbed forested ecosystems such as Hubbard Brook. However, the removal of nutrients in livestock is so small relative to other sources that it can safely be ignored. This conclusion is backed by the data of Robertson and Davies (1965), who showed that for heather moorland areas of low productivity, the loss of nutrients in sheep sold off the catchment was negligible compared to the amount of nutrients cycled within the vegetation.

Returning to Rough Sike, dissolved material in the stream was the main source of output for K^+, Ca^{2+} and Na^+, but eroding peat was the dominant factor for output of N_2 and contributed over 50% of the output of PO_4^{3-}, 20% for K^+, and nearly 10% for Ca^{2+}.

Crisp's (1966) study was concerned mainly with nutrient element, so we cannot tell whether the large net output of Na^+ which he found originated from mineral weathering or by dry deposition of oceanic aerosols associated with Cl^-. Some light is shed on this by a detailed chemical study by White, Starkey and Saunders (1971) of the west Sleddale catchment, in the nearby Lake District. This is a larger catchment (1214 ha^{-1}) but, like Rough Sike, it is a moorland area used for sheep pasture. The underlying geology is andesite. A balance was constructed for Cl^-, $SO_4^{2-} - S^{2-}$, $Na^+ - K^+$, Mg^{2+}, Ca^{2+}, $NO_3^- - N_2$ and SiO_2.

Comparison of inputs in precipitation and outputs in stream water over a period of 24 months revealed large net losses of all constituents. This indicated that considerable amounts of Cl^-, SO_4^{2-}, Na^+ and other cations had arrived as a dry deposit on vegetation, either as aerosols or gases.

Thus, in maritime areas, measurements of the chemistry of precipitation may represent only a fraction of the input of certain elements,

compared with continental areas such as Hubbard Brook, where the near
balance of Cl^- budget indicates a minimal amount of dry deposition.
However, the annual Cl^- budget at Hubbard Brook showed a great deal
of variability from year to year, the true trend only becoming appar-
ent after several years.

The data from precipitation, river water and soil water collected
by White et al. (1971) assessed the relative importance of rain, dry
deposition and chemical weathering as sources of the different elements.
They estimated that weathering accounted for 100% of the SiO_2, 55-67%
of the Ca^2, 40-50% of the Mg^{2+}, less than 20% of the Na^+, an unknown
amount of the K^+, and negligible amounts of the Cl^-, NO_3^- and SO_4^{2-} in
river water.   This contrasts with Hubbard Brook, where chemical
weathering is the major source of Ca^{2+}, Mg^{2+}, Na^+, K^+ and SiO_2.

Roberts and James (1970) studied the headwaters of the rivers
Wye and Severn in mid-Wales.   These are two adjacent valleys, both
underlain by shale and with similar inputs of water and dissolved
solids in precipitation, but contrasting systems of land use.   The
Wye Valley consists of grassy upland sheep pasture, and the Severn of
coniferous forest.   The authors measured Na^+, K^+, Mg^{2+}, Ca^{2+} and Cl^-
in precipitation and river water.   They found that:

(a)   The difference in land use between the catchments led to
      differences in the river chemistry.

(b)   The Severn water had significantly higher concentrations
      of Na^+ and Cl^- but lower concentrations of Ca^{2+} and Mg^{2+}.

(c)   Concentrations of K^+ were the same in both rivers.

(d)   The temperature of the river water also varied between
      the catchments, the forested Severn catchment showing a
      smaller range of river temperature than the grassland Wye
      catchment.

Nutrient balances were prepared for a total of 24 weeks over a
period of 18 months.   These revealed a large net export of all species
from both catchments.   Since the rocks and soils contain no Cl^-
minerals, the excess Na^+ and Cl^- were assigned to dry deposition of

aerosols. The Na^+/Cl^- ratios in precipitation and river water indicated that the source of both these elements was the sea. This dominance of river water chemistry by oceanic salts seems to be a feature of upland areas with acid, infertile soils in areas with a maritime climate.

Edwards (1971, 1973a,b) studied unpolluted upland catchments in four lowland, arable agricultural catchments in Norfolk, England. This area is underlain by chalk and calcareous drift, so the concentrations of most dissolved solids are greater than in the upland rivers previously considered. Edwards produced solute budgets for 1970. He showed that rainfall was a significant source of input for K^+, Mg^{2+}, Na^+, Cl^- and SO_4^{2-}. Sewage contributed less than 15% of the input of all constituents except PO_4^{3-}, although several towns and villages are situated within the catchments. The concentration of Ca^{2+} is derived mainly from a solution of calcite and gypsum in the soils and bedrock. This process also supplies the HCO_3^- and much of the SO_4^{2-} in the river waters: SiO_2, which is present in concentrations similar to those in the small upland rivers, comes mainly from weathering of SiO_4^{2-} minerals; NO_3^- is derived from a number of sources, including leaching of fertilisers, and sewage and other effluents. Nevertheless, studies like Edwards' can reveal much about the factors controlling river water quality, even in such areas.

The study of Pound Branch, Maryland, by Birker, Godfrey and Cleaves (Bricker et al., 1968; Cleaves et al., 1970), is an example of studies made in small catchments. The catchment is underlain by a deep mantle of weathered rock, with the water table at depth. The authors allowed for this by repeatedly measuring the chemistry of groundwater and observing changes in its level in a nearby well. They also determined the chemistry of soil water and stemflow as well as precipitation and runoff, and by coupling this with a thorough investigation of the primary and secondary mineralogy of the soils and bedrock, they were able to produce a detailed geochemical balance for the catchment (Cleaves et al., 1970) and to trace the chemical evolution of the water as it percolated through the catchment (Bricker et al., 1968).

The small catchment at Taita, New Zealand, studied by Claridge (1975a,b) was underlain by deeply weathered greywacke, with the water

table 38m below the ground surface. He measured Cl^-, Na^+, K^+, Ca^{2+}, Mg^{2+} and SO_4^{2-} in precipitation and runoff. As in most recent studies, where runoff is sampled weekly, an automatic discharge-weighted sampler was used. As the stream was flashy, this ensured that it was sampled under all conditions of flow. Balances were drawn up for four years. They showed that the net gain or less of elements was directly proportional to precipitation; in dry years, a net gain of all elements was recorded, but in years with near average precipitation, a net loss of all elements occurred. Like the Hubbard Brook study, this study indicates how the balance may be affected by weather conditions in the short term, and that the results of one or two years' work must be interpreted with caution.

From this review it appears that slightly different processes affect the water quality in different areas, although in areas with maritime climates it may be very difficult to separate a component of stream flow derived from weathering, as the Wet Sleddale study showed (White et al., 1971). The simple approximation of subtracting precipitation chemistry from river water chemistry works only in continental areas, where precipitation is very dilute relative to river water and dry deposition of oceanic aerosols is negligible. This approach can only be applied in areas where soils have developed directly on bedrock. In areas of glacial drift, for example, the clay mineralogy may be inherited from a previous period of soil formation under different conditions, and not be in equilibrium with present-day conditions (Douglas, 1972).

This summary illustrates the variety of approaches that have been applied to the problem of producing geochemical balances. Some of the main findings have been mentioned, as well as many of the problems which still need discussion in this field. However, this list is thought to cover most of the aspects relevant to the present project. It is clear that an inter-disciplinary approach is necessary if most of the processes controlling gains and losses of elements are to be identified. Thus, by far the most successful study in this field has been that at Hubbard Brook, where the combined efforts of several workers in different disciplines, investigating various attributes of the ecosystem over a number of years, have resulted in very detailed knowledge of the biogeochemistry of the area, and its response to

changes in land use.

9.4.2 Comparison of Coombs Brook Findings with Other Hydrogeochemical Budgets

A comparison of the annual net balance for 13 chemical species in Coombs Brook with balances from 10 other small catchments is given in Table 9.4.2.1. These catchments have been discussed in Section 9.4.1.

Apart from the Severn and Wye balances, which are given in kg ha^{-1} for a total of 24 weeks, all the figures are in kg ha^{-1} y^{-1}. The figures for Coombs Brook, Glendye, Narrator, Upper Wye, Wales (1986), West Sleddale, the Severn and Wye (1970) and Taita are derived from input in precipitation minus output in stream water. The data from Hubbard Brook include particulate as well as dissolved outputs in stream water. The Rough Sike data include output in eroding peat in the river, drift of fauna in and on the stream, and sale of sheep and wool, as well as dissolved output in stream water and input in precipitation. The Yare data include input from sewage and precipitation and dissolved output in river water.

All the British studies reveal large net outputs of Cl^- and SO_4^{2-}, confirming the importance of dry deposition of oceanic aerosols in areas with a maritime climate. Hubbard Brook, with a continental climate, shows a small net input of Cl^-, but a net output of SO_4^{2-}. Oceanic aerosols are of less importance at Hubbard Brook, but dry deposition of gaseous SO_2, derived from industrial pollution, appears to be just as important as in the British Isles.

There is a net gain of Ca^{2+}, Mg^{2+}, Na^+ and K^+ in all catchments, except for Narrator, Taita, and Macclesfield (in the case of Na^+ and K^+ only), but the relative amounts of the different cations vary with bedrock and land use. The ions of K^+ are always exported in smaller amounts than the other cations, and Mg^{2+} is always smaller than Ca^{2+} and Na^+ but greater than K^+. In maritime catchments with acid bedrock - Glendye, Severn, and Wye - the output of Na^+ is greater than that of Ca^{2+}, largely because of the additional input of Na^+ as a dry deposit with Cl^-. In a continental environment with acid bedrock (Hubbard Brook), the output of Ca^{2+} is more than double that of Na^+.

TABLE 9.4.2.1 GEOCHEMICAL BALANCE (kg ha^{-1}) FOR SEVERAL SMALL CATCHMENTS

	Catchment	Geology	Vegetation	Ca^{2+}	Mg^{2+}	Na^+	K^+	Cl^-	SO_4^{2-}	H^+	HCO_3^-	SiO_2	PO_4^{3-}	NH_4^+	NO_3^-	Al
	Coombs Brook, Macclesfield	Sandstone	Forest	$^-3.0$	$^-2.2$	$^+9.4$	$^+8.5$	$^+10.6$	$^+15.8$	n.d.	n.d.	n.d.	$^+3.5$	n.d.	$^+15.7$	n.d.
1	Glendye, Grampian Mountains	Granite	Heather moor	$^-19.6$	$^-7.6$	$^-29.3$	$^-3.25$	$^-31.7$	$^-7.6$	$^+0.75$	$^-48.0$	$^-82.4$	$^-0.02$	$^-1.21$	$^+10.7$	$^-1.77$
2	Hubbard Brook, New Hampshire	Schist	Forest	$^-11.6$	$^-2.55$	$^-5.64$	$^-0.99$	$^+2.02$	$^-5.11$	$^+0.87$	$^-7.64$	$^-38.4$	$^+0.035$	$^+1.98$	$^+0.59$	$^-1.87$
3	Rough Sike, Pennines	Sandstone, shale limestone	Blanket bog	$^-49.7$	n.d.	$^-20.01$	$^-7.97$	n.d.	n.d.	n.d.	n.d.	n.d.	$^-0.24$	$^-9.48$		n.d.
4	West Sleddale, Lake District	Andesite	Heather grassland	$^-26.9$	$^-11.4$	$^-20.5$	$^-3.9$	$^-23.4$	$^+14.0$	n.d.	n.d.	$^-28.9$	n.d.	n.d.	$^+1.9$	n.d.
5	Upper Severn, mid-Wales	Shale	Forest	$^-5.7$	$^-3.6$	$^-12.2$	$^-0.46$	$^-18.0$	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
	Upper Wye, mid-Wales	Shale	Grassland	$^-9.3$	$^-4.4$	$^-11.8$	$^-0.48$	$^-17.1$	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.

TABLE 9.4.2.1 (Continued)

	Catchment	Geology	Vegetation	Ca^{2+}	Mg^{2+}	Na^+	K^+	Cl^-	SO_4^{2-}	H^+	HCO_3^-	SiO_2	PO_4^{3-}	NH_4^+	NO_3^-	Al
6	Yare, Norfolk (East Anglia)	Chalky boulder clay	Arable crop land	-284.9	-9.48	-50.1	-5.1	-58.6	-49.1	n.d.	-678.0	-20.8	0	n.d.	-12.3	n.d.
7	Taita, New Zealand	Greywacke	Forest	+1.32	+1.85	+15.2	+1.28	+38.0	-0.57	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
8	Upper Wye, Wales	Shale	Grassland	-18.9	-7.4	-5.3	-1.2	-41.0	-13.4	+0.6	-64.0	-23.9	n.d.	+7.9	+1.4	n.d.
9	Narrator basin, Dartmoor S.W.England	Granite	Forest & grassland	+11.3	+2.3	+6.7	+3.1	0.0	n.d.	-1.00	n.d.	+92.6	n.d.	n.d.	n.d.	n.d.

Source: 1 Reid (1981)
         2 Likens et al. (1977)
         3 Crisp (1966)

         4 White et al. (1971)
         5 Roberts and James (1970)
         6 Edwards (1971)

         7 Claridge (1975b)
         8 Reynolds, Hornung and Stevens (1987)
         9 Williams, Ternan and Kent (1986)

Where bedrock is intermediate in composition, as in the andesite at West Sleddale, the output of Ca^{2+} exceeds that of Na^{+}, and where it is calcareous in part, as at Rough Sike, Ca^{2+} output is more than double that of Na^{+}, despite the importance of dry deposition in both areas. These examples illustrate the major effects that geology, particularly the presence of minerals and other elements, and land use, can have on the chemical composition of streams, as shown by the Macclesfield and Glendye, or Severn and Wye balances.

The Taita catchment in New Zealand has a different hydrological regime from the other catchments. Most of the discharge occurs during short period but very intense storms, when the soils are thoroughly leached of mobile constituents. It is very near the sea and receives very large quantities of oceanic salts in precipitation and by dry deposition. The figures in Table 9.4.2.1 are average values for four years which were considerably drier than the long-term average. Net inputs of all cyclic salts except SO_4^{2-} are found, but in years with more normal precipitation there are indications that the balances would show outputs of most species (Claridge, 1975b). The difference in the balance suggests that the large difference in net output between Coombs Brook and the other rivers is largely related to the differences in runoff between the catchments.

The net output of Ca^{2+} and Mg^{2+} is similar in Coombs Brook and Upper Severn, mid-Wales, but Na^{+} and K^{+} is similar to Taita, New Zealand, and Narrator, south-west England, which have more input than output. The net output of NO_3^{-} in Coombs Brook is similar to that in Glendye, Hubbard Brook and Upper Wye.

Net input and output of PO_4^{3-} is very small in all catchments. However, when total PO_4^{3-} is measured and factors such as peat erosion are taken into account, as in the Rough Sike study, a significant net output is found. The ions of NH_4^{+} also show fairly small net gains or losses, but NO_3^{-} always shows an overall input in Coombs Brook, Upland Glendye, Hubbard Brook, West Sleddale, and Upper Wye, if output in peat erosion is not considered. The net input is much greater in Coombs Brook than for the other catchments, however. By contrast, the Yare catchment shows a large net output of NO_3^{-}, due to leaching of fertilisers and to the much greater bacterial activity in the soils of this

arable, lowland area.   When total N_2 is considered, there is a large
net loss from the Rough Sike catchment due to eroding peat.   This
factor will probably be of less importance in other catchments such
as Hubbard Brook, Upper Wye, Glendye, Wet Sleddale and Coombs Brook.

These examples illustrate the effects of climate, hydrology,
geology and land use on the geochemical balances of various chemical
species in small catchments.   These factors must be taken into account
when calculating and interpreting such balances.

CHAPTER TEN

CONCLUSIONS

10.1   Representativeness of the Coombs Brook Study Period

10.2   Appraisal and Hypotheses

        10.2.1 Geomorphic hypotheses

        10.2.2 Hydrologic hypotheses

10.3   Suggestions for Further Research

        10.3.1 Geomorphic suggestions

        10.3.2 Hydrologic suggestions

CHAPTER TEN

CONCLUSIONS

In this concluding chapter, the most important findings and com-
ments on the hydrologic and geomorphic processes in Coombs Brook are
discussed separately.   The value of small catchment studies for in-
vestigating erosional processes and stream water chemistry, and for
establishing sediment and nutrient budgets is discussed briefly and
some possible avenues for further research are indicated.

10.1   REPRESENTATIVENESS OF THE COOMBS BROOK STUDY PERIOD

The climate being a strong driving force behind many geomorphic
and hydrologic processes, it is clearly important in a process-study
of this kind to demonstrate how representative the climatic character-
istics of the study period are.   Conclusions regarding the relative
significance of different processes could be biased if the period of
monitoring was climatologically unusual in some respects.   This exer-
cise may be done by comparing the climatic records obtained at local
meteorological stations for the study period with longer-term averages.

The nearest place to the Coombs Brook bank erosion sites where
climatic data are collected is Station 1, which has been discussed in
previous chapters.   Only two years of record, beginning on 1st May
1984, are available, but these cover the whole study period.   The first
year of record had 56 frost days, the second 70 (Table 10.1.1).

To get a more accurate indication of days of ground frost, as
opposed to freezing temperatures in the Stevenson Screen, the number of
air frost days was multiplied by 1.5, as field experience indicated
that ground frost occurred about one-and-a-half times as frequently as
air frost.   Although this was just an approximation, it probably
represents field conditions reasonably well.

TABLE 10.1.1   COMPARISON OF FROST FREQUENCIES IN COOMBS BROOK
DURING THE STUDY PERIOD

	Period	Number of air frost days	Number of ground frost days
1.	May - April 1984-85	56	84
2.	May - April 1985-86	70	105
	Total	126	189

When the data from Station 1 are compared with those for the previous ten years at the Langley Station (Table 10.1.2), about 250m further down-valley, the frequency of the air frosts seems a little greater.   This may reflect the difference in altitude between the two sites.   In the two study years, the air frosts are more concentrated in the January - April period than in earlier years.   Prolonged periods of frost, such as in December 1980, January 1984 and February 1986, are possibly highly significant for erosion by frost action.   The February 1986 period was the longest in the whole 12 year period (Table 10.1.2).

Langley data may also be used to compare rainfall between the study period and the 1974-1984 period (Table 10.1.3).   Of the two study years when bank erosion was monitored, 1984-85 had slightly less precipitation than the average for 1974-84 (Table 10.1.4), while in 1985-86, over 120 mm more than the average fell.   Of the two winters studied, when bank erosion was particularly active, 1985 was drier than average, except for April, while 1986 was wetter, except for the cold, dry, frosty February period.

TABLE 10.1.2   COMPARISON OF DAY OF AIR FROST IN EACH MONTH FROM 1974 TO 1986,
THE STUDY PERIOD AND THE PREVIOUS TEN YEARS

	1974-75	75-76	76-77	77-78	78-79	79-80	80-81	81-82	82-83	83-84	84-85	85-86
Oct.	02	–	–	–	–	–	03	–	02	–	–	–
Nov.	–	08	06	10	05	10	02	04	05	02	–	06
Dec.	–	06	17	04	15	12	22	11	06	05	–	07
Jan.	–	06	15	12	27	12	15	05	13	27	21	16
Feb.	05	08	04	16	21	18	06	20	11	13	18	28
March	10	11	03	04	11	03	02	04	06	11	13	13
April	06	03	04	06	–	02	02	04	–	02	04	–
May	–	–	–	–	–	–	–	–	–	–	–	–
Total days	23	42	49	52	79	52	37	52	49	43	56	70

TABLE 10.1.3   ANNUAL RAINFALL AND NUMBER OF STORM EVENTS IN
                MACCLESFIELD FOREST IN THE TEN YEARS PRIOR TO
                THE STUDY PERIOD AND IN THE 1984-86 STUDY PERIOD

	Date	Annual rainfall (mm)	Number of storm events
1	1974-75	1095.2	30
2	1975-76	747.0	19
3	1976-77	1083.3	34
4	1977-78	854.3	18
5	1978-79	1066.2	37
6	1979-80	1103.7	31
7	1980-81	1222.1	42
8	1981-82	1029.3	30
9	1982-83	1143.7	28
10	1983-84	1006.8	30
11	1984-85	871.0	38
12	1985-86	1039.0	30

Source: 1974-84   Langley
          1984-86   Station 1

TABLE 10.1.4   COMPARISON OF MONTHLY AND ANNUAL RAINFALL AVERAGES IN THE
                 STUDY PERIOD WITH THOSE DURING THE PERIOD 1974-1984

Period	Number of years	Mean annual rainfall (mm)	Monthly averages (1974-84) and totals (1984-86) (mm)				
			Jan.	Feb.	March	April	May
1974-84	10	913	108.0	69.7	94.0	66.0	68.5
1984-85	1	871	63.5	8.4	71.6	110.7	63.9
1985-86	1	1039	114.9	56.0	102.2	111.5	96.2

10.2 APPRAISAL AND HYPOTHESES

The objectives of this thesis were to study the geomorphic and hydrologic processes in a number of ways or stages (Section 1.4). The aims could be summarised as follows:

1. To study the geomorphic and hydrologic processes in the catchment area.

2. To establish the budgets of both sediments and solutes.

3. To identify sources of solutes and sediments in the catchment area.

4. To study at-a-station variations in sediments and solutes.

5. To relate variations in material carried (sediments and solutes) to hydrometeorological factors.

6. To study bank erosion, which is an important, if not dominant, aspect of sediment supply, by:

    (a) determining the seasonal and spatial variations in the sediment supplied by bank erosion;

    (b) analysing the relative contributions of the stream-bank processes to catchment sediment output: and

    (c) quantifying the relative contributions of non-channel sediment sources.

A number of hypotheses about the geomorphic and hydrologic processes were studied:

I Geomorphic hypotheses

1. That the bulk of sediment is supplied from defined discrete sources, or from critical parts of the catchment, and the bank erosion and channel processes are dominant sources of particulate matter (Sections 5.1 and 5.2).

2. That the frost action plays a vital role as an agent of bank erosion (Section 5.3).

3. That sediment yield varies in space, seasonally, and within storms (Chapters 5 and 6).

II Hydrologic hypotheses

1. That the solute content of precipitation varies within narrow limits (Section 7.1.2).

2. That the cations and anions in precipitation originate from a variety of sources (Section 7.1.3).

3. That the stream water quality intimately reflects the over-all structure and operation of the catchment ecosystem. Broadly, the dissolved solids loads reflect vegetation type, soil-soil water, and bedrock conditions (Chapters 7 and 8).

4. That the stream water quality varies in space, seasonally, and during storm events (Chapter 8).

5. That the relationships between concentration and discharge and input and output will show different patterns of variation.

Findings relating to both aims and hypotheses are discussed before further research requirements are suggested.

10.2.1 Geomorphic Hypotheses

One of the main aims of this stage is to identify processes and sources of sediment and to construct a sediment budget for the study area, special emphasis being given to the contribution of stream bank erosion.

1. With reference to the first hypothesis, six processes were found to be active in stream bank erosion (Section 5.1); the activity of each of these processes was restricted to a particular part of the bank and to specific hydrometeorological conditions (Section 5.1).

    (a) The rate of lateral corrasion exhibited wide variations both in time and space, due to the complex interactions between hydrometeorological factors and bank erosion

resistance. Temporal variations in recession rate are mainly influenced by the magnitude of discharge. The mean soil loss by bank scour in the study period amounted to 13.0 kg per metre of bank length (Section 5.1.1).

(b) Subsoil fall plays a distinct role in stream bank erosion, as is manifest by the development of undercuts up to 70 cm in depth and a continuous supply of sediment. The rate of soil loss from these undercuts is largely dependent upon the characteristics of the subsoil, especially with respect to its structure and stability, and on the severity of frost conditions. The average soil loss amounted to about 10 kg per two years per 30 cm width (Section 5.1.2).

(c) Soil creep processes exhibited a maximum intensity on the fine textured soils of the banks of the catchment formation. The mean rate of sediment supply to the river by soil creep was 15g per 30 cm width per year (Section 5.1.3).

(d) Measurements of overland flow on stream banks show that this flow action consists of a rather complex set of processes. It was shown that overland flow acts primarily as a transport medium for material detached by other processes active on the stream banks and that detachment by flow action alone is of very limited importance (Section 5.1.4).

(e) The mean mass failures processes occurred on the stream banks as flow-slides and, more often, shallow landslides. The occurrence of both types was restricted to periods with frequent rainfall or rapid snowmelt. However, the cause of triggering the failures was different. While flow-slide took place due to the addition of water by overland flow or seepage, landslides were caused by undercutting due to stream flow action (Section 5.1.5).

(f) Splash erosion in the Coombs Brook catchment was measured. Exposure of soil by tree fall created about 20% of the sites affected by splash erosion. Half of these tree

fall sites were within 25m of the stream channel on the steep lower slopes. Direct input of material by splash to the stream channels is probably relatively small (Section 5.1.6).

Also with regard to the first hypothesis, there are other sediment processes which occur on valley slopes. These processes may be distinguished as being active in the various source areas on the valley slopes, including the role of rills and gullies in the catchment and leaf transport (Sections 5.2, 5.2.1 and 5.2.2).

2. The second hypothesis illustrates the vital role played by frost in the preparation of material for removal following freeze-thaw processes such as needle ice formation. The aggregate-debris zone is important because it represents the temporary accumulation of material directly eroded by the action on the sedimentary units above. Needle ice was observed to have both direct and indirect effects on bank erosion. Four principal routes were identified by which sediment encapsulated within needle ice was introduced to the stream (Section 5.3). Clearly, frost has a vital role in bank erosion.

3. Regarding the hypothesis that sediment yield varies in space seasonally, the activity of erosion processes was restricted to a particular part of the bank and to specific hydro-meteorological conditions. Maximum rates of lateral corrasion and splash erosion were generally encountered during wet periods, while the highest rates of subsoil fall were measured during frost periods. High rates of soil creep could largely be attributed to the effect of biological activity (in summer) and, to a lesser extent, to the effect of frost action (in winter). The spatial trend in sediment supply from the stream banks showed a general increase with increasing size of the catchment area. However, the highest rates of bank recession were encountered in the upstream part of the main channel. These were due to various indirect effects of distinct breaks in the longitudinal profile, especially related to the presence of organic debris dams.

Splash detachment and subsequent transport of detached material by overland flow appeared to be the dominant mechanism of soil erosion on the valley slopes, contributing 35% to total sediment supply.

Studying the sediments at-a-station variations, it was found that suspended sediment concentration discharge relationships for Sites 2-7 varied, with weak correlations and regressions with a broad scatter (Section 6.4 and Table 6.4.1.1). The type of response of sediment concentration is apparently random.

The suspended sediment-discharge relationships for the catchment show many of the characteristics previously noted: a wide scatter of points on the plot which may in part be related to seasonal, hysteretic and exhaustion effects.

Suspended sediment concentrations were determined during storm events for the catchment area, and both storm hydrographs and hysteresis loops were produced for 45 storms. The behaviour of suspended sediment concentrations was extremely variable, and some different types of response were recognised. The free availability of suspendable material appears to be an important limiting control on sediment concentration, and this appears to be related to different responses, such as soil moisture conditions, the activity of bank erosion, and bank collapse. The most striking result is the complexity of sediment behaviour during storms, up to four different types of response occurring in the catchment over the two-year period. There is no simple relationship between suspended sediment concentration and discharge, and any relationship which might exist is variable through time and space. The behaviour of sediment is not solely dependent on discharge, but is related to other factors which produce seasonal and spatial variations. Geomorphic hypothesis 3 is therefore confirmed.

To summarise, the first stage of the hypothesis is valid, with some qualifications:

1. Within the study period, strong seasonal contrasts in bank
    erosion rate could be identified, with most material being
    removed between the months of November and April, and espec-
    ially during March 1986 (Chapter 5). This is in accordance
    with the findings of other bank erosion workers in humid
    temperate environments (e.g. Hill, 1973; Lawler, 1984, 1986).

2. The results of frost action (Section 5.3) showed that at the
    Coombs Brook study sites, indices of frost consistently
    emerged as the variables most strongly active, and probably
    explain most of the mean and maximum bank erosion rates.

    In contrast, the results of frost action controlling the
    rate of bank erosion at the Coombs Brook sites are similar
    to the findings of Lawler (1984, 1986), Blacknell (1981),
    Hill (1973), Leopold (1973), and McGreal and Gardiner (1977),
    who all suggested that periods of bank material preparation
    by ice-crystal growth were necessary precursors to substantial
    erosion by following stage-rise events or heavy storm events.

3. There is no simple single constant relationship between dis-
    charge and suspended sediment concentration. The free avail-
    ability of suspendable material during different conditions
    (wet and dry) appears to be an important limiting control on
    sediment concentration, and this appears to be related to the
    soil moisture conditions and the rainfall intensity and run-
    off condition. This is in accordance with the findings of
    other workers (Olive et al., 1984).

4. Erosion pins were used for different purposes at different
    parts of the study area, and at different accuracies (Table
    3.6.1). Rates of erosion varied according to site from 32
    to 40 mm per month for the standard year, April 1985 - March
    1986, adopted for inter-site comparisons, although the range
    of values dropped to 20-24 mm/month when all data were con-
    sidered (Section 5.1.1).

    The conclusions of this stage could be weakened if the experimen-
tal measurements (Table 3.6.1) were subject to gross errors.   For
example, if erosion pins had been heaved out of the bank.   This would

result in an overestimation of bank erosion. Nevertheless, it was considered appropriate to use different techniques in this study.

10.2.2 Hydrologic Hypotheses

The second aim of this project was to identify sources, processes and budgets of the solutes. The main findings were:

1. With regard to the first hypothesis, that the solute content of precipitation varies within narrow limits: in terms of a small catchment area, the results show slightly variable trends in concentrations. The chemistry of bulk precipitation at two sites in the catchment showed that the relative contributions of cations were similar, with $Na^+ > K^+ > Ca^{2+} > Mg^{2+}$, while anions measured at both sites were ranked $SO_4^{2-} > NO_3^- Cl^- > PO_4^{3-}$ (Table 7.1.2.2). No significant variation between gauges was found. The variation in the amount of precipitation between Sites 1 and 2 does not exceed 50 mm per year. This indicates that the composition of precipitation varies little across the catchment, and that it is determined by the air mass producing precipitation rather than by local variations in topography.

2. With regard to the second hypothesis, that cations and anions in precipitation originate from a variety of sources, including oceanic spray, terrestrial dust and gaseous pollutants: the precipitation chemistry is controlled by three major influences.

   (1) Industrial pollution (from Manchester and Sheffield) and the burning of fossil fuels. This is the major source of SO_4^{2-} and NO_3^- through emissions of gaseous nitrogen and sulphur oxides.

   (2) Oceanic spray. This is thought to account for the Na^+, Mg^{2+} and Cl^-. It shows seasonal variation, being dominant in early winter and of much less importance in summer

   (3) Terrestrial dust, which is considered to be the major source of Ca^{2+}, K^+, Fe, Mn and PO_4^{3-}.

3. Stream water quality reflects the overall structure and operation of the catchment ecosystem. Throughfall and stemflow results indicate:

(1) The chemical composition of the water that reaches the forest floor differs greatly from that of the incident precipitation (Table 7.2.1.1).

(2) Throughfall and stemflow are greatly enriched in Ca^{2+} (about 10 times), Mg^{2+} (five times), Na^+ (three times), K^+ (five times), SO_4^{2-} (seven times), NO_3^- (four times), and Cl^- (eight times) (Table 7.2.1.2).

(3) There are various sources for the dissolved substances in throughfall and stemflow. Some nutrients are contained in the incident precipitation; some of the nutrients may have impacted aerosols that are washed off by the incident precipitation; and nutrients with a normal gaseous phase, which were incorporated directly on or into the plant and then removed from tissues by incident precipitation.

(4) Some elements were removed to a greater degree from one species than from another (Table 7.2.2.1).

(5) Tables 7.2.2.1 and 7.2.4.1 show that the chemical content of fresh leaves is higher than in senescent leaf. This explains how much each species is able to leach elements by rainfall.

(6) The leaching of elements from the forest canopy by precipitation is dependent on a number of factors. First, an element must be present, indicating either a biological requirement or a non-selective uptake of the element by the plant. For example, elements which are present in large amounts in the fresh leaves are leached in larger absolute amounts (Table 7.2.4.1 and Fig. 7.2.2.2).

Regarding soil-soil water, the results show:

(1) The increase in the $\dfrac{Ca^{2+} + Mg^{2+}}{Na^+ + K^+}$ from 2.75 at 20 cm depth and 2.96 at 50 cm to 5.94 at 90 cm depth indicates

the greater amount of Ca^{2+} + Mg^{2+} in the lower parts of the profiles.

(2) The soil-soil water analysis shows that the cations can be divided into two groups: Ca^{2+} and Mg^{2+} are the most mobile, while Na^+ and K^+ have moderate mobility. Of the first group, Mg^{2+} appears to be slightly more mobile than Ca^{2+}; K^+ is generally less mobile than Na^+ in all the horizons. This will reflect the contribution of each element to stream water.

(3) The pH of the soil water lay between 7.0 and 3.7. At the lowest pH values, the soil water is more acid than both precipitation and stream water. However, the down-profile reduction in acidity is a major control of the pH of drainage waters entering the stream.

(4) The cationic composition of the soil waters lies along the same line of variation as stream water. This may indicate that the composition of soil water and stream water varies in the same way and is probably controlled by the same processes.

(5) Since the soil water is the dominant source of the stream water during dry periods, the results show higher concentrations of major cations in stream water during such periods, because the chemical composition of waters passing through soil and rock materials mainly involve relatively high concentrations of cation exchange reactions with soil and rock.

Regarding bedrock contributions to stream water chemistry, the results indicate enrichment in rock water samples, with Ca^{2+}, Mg^{2+}, Na^+ and K^+ as the most significant cations in the samples. Concentrations of Ca^{2+} and Mg^{2+} increase greatly in soil, rock, and stream water, probably as a result of the high levels of both ions on exchange sites within the soil and rock. The interpretation of such results relies on a combination of hydrological, pedological and biogeochemical factors. This indicates the locus of solutional erosion within the catchment system.

4. Regarding the fourth hypothesis, which is that stream water
    quality varies in space, seasonally, and during storm events,
    the main findings were:

    (1) The variation of solute concentration with time and
        space.
        The results show variation in solute concentration with
        time and space, because the catchment processes which
        generate stream-flow and its dissolved content are
        dynamic rather than static in nature (Section 8.2).
        The time series plots of solute concentration reveal
        that the annual patterns of solute behaviour vary bet-
        ween stations and according to the ion under considera-
        tion.
        Seasonal fluctuations of Ca^{2+} and Mg^{2+} are more strongly
        affected by the random impacts of storm events.
        The variation of each of the following species can be
        seen in Section 8.2.2.   Marked seasonal changes in
        the concentration of some determinants were observed,
        particularly at Station 1, where concentrations were
        often substantially higher than at sites in the head-
        water stations, 2-7. For example, NO_3^- concentration
        showed little pattern of change, Cl^- and SO_4^{2-} showed
        rapid fluctuations, particularly in Site 1, and concen-
        tration of PO_4^{3-} fluctuated over a small range and was
        low.

    (2) In terms of variation in the chemical composition of
        stream water during storms (Section 8.2.3), concentrations
        of Ca^{2+}, Mg^{2+} and Na^+ remained steady during the first
        part of the rising limb of the hydrograph, then fell
        rapidly to a minimum value a few hours after peak flow;
        thereafter they slowly rose to the pre-storm levels.
        Concentrations of other species did not vary markedly
        during the storms. The lag effect at the start of the
        storm is caused by the expulsion of stored soil water
        from the lower, mineral horizons. This is then replaced
        by water from the upper organo-mineral and organic soil
        horizons. This water continues to dominate river flow

for some time after peak discharge, as these horizons drain. The precise patterns found during a storm depend upon a number of seasonal and hydrologic factors, and cannot be quantitatively predicted. Clearly, this agrees with the hypothesis that the dissolved solids loads reflect bedrock and soil types as well as vegetation conditions.

5. All species were tested for relationship between concentration and discharge (Section 8.3.2) (hypothesis 5). The results show three different groups:

    (a) Species with negative relationship (Ca^{2+}, Mg^{2+}, Na^{+}, and K^{+}).

    (b) Species with positive relationship of water quality with discharge (Cl^{-}, SO_4^{2-} and NO_3^{-}).

    (c) Cases with no apparent relationship between water quality and discharge (PO_4^{3-}, Fe and Mn).

The results show various levels of correlation between solute concentrations and discharge and their levels of significance may be explained in terms of contrasts between tributaries or, at some sites, problems of obtaining accurate discharge measurements. The major cations are significantly negatively correlated with discharge, with some exceptions (for example, the Ca^{2+} concentrations at Sites 2 and 7 and the Na^{+} concentration at Site 6).
The anions SO_4^{2-}, NO_3^{-} and Cl^{-} are the only species which have any significant positive correlations with discharge, whereas conductivity, Ca^{2+}, Mg^{2+} concentrations are commonly highly significantly negatively correlated with discharge (Section 8.4).

The sediment and solute budgets: a major objective of the study

1. Sediment budgets

The sediment budget of the catchment was divided into three main parts:

- sediment transfer from the stream bank (Section 5.1),

- sediment transfer from valley slopes (Section 5.2), and

- sediment output from the drainage basin (Section 5.4).

The stream banks contributed 65% to the total supply of sediment, with lateral corrasion and subsoil fall being the main bank processes, contributing 36% and 18% respectively. Bank failures, rainsplash erosion and soil creep transferred 7.3%, 1.3%, and 0.6% respectively.

Splash detachment and subsequent transport of detached material by overland flow appeared to be the dominant mechanism of soil erosion on the valley slopes, contributing 35% to total sediment supply.

Sediment transfer out of the drainage basin dominantly occurred as suspended load (92%), while bedload contributed only 8% approximately. Both transport modes showed highest output rates during wet periods. Grain size analysis of the sediment supplied by the various stream bank and valley slope processes revealed that bedload was largely caused by lateral corrasion, subsoil fall and bank failures. On the other hand, hillslope processes were the main contributor to suspended load (Table 5.4.1 and Fig. 5.4.1.1).

2. Nutrient budgets

The nutrient budgets on a monthly scale show three different patterns of input-output:

(a) those in which output exceeds input in every month (Ca^{2+} and Mg^{2+}),

(b) those in which input exceeds output in every month (NO_3^-, Na^+ and Cl^-), and

(c) transition patterns (K^+ and SO_4^{2-}).

These results exhibit a complex interaction involving the effects of stream water chemistry and annual variations of input.

Calculations of the inputs of chemical species in precipitation and output in stream water for the year 1st May 1984 to the end of April

1986 reveal a net output of two species only, which are Ca^{2+} and Mg^{2+}. The net outputs of Ca^{2+} (5.9 kg ha^{-1} y^{-2}) and Mg^{2+} (4.31 kg ha^{-1} y^{-2}) are both large.   The net inputs of Na^{+} (26.7 kg ha^{-1} y^{-2}), K^{+} (19.26 kg ha^{-1} y^{-2}), SO_4^{2-} (57.2 kg ha^{-1} y^{-2}), PO_4^{3-} (7.55 kg ha^{-1} y^{-2}), NO_3^{-} (41.9 kg ha^{-1} y^{-2}), and Cl^{-} (38.1 kg ha^{-1} y^{-2}), are fairly large and more than offset the small amounts of output which are 7.82 kg ha^{-1} y^{-2} of Na^{+}, 2.157 kg ha^{-1} y^{-2} of K^{+}, 25.66 kg ha^{-1} y^{-2} of SO_4^{2-}, 0.422 kg hg^{-1} y^{-2} of PO_4^{3-}, 10.48 kg ha^{-1} y^{-2} of NO_3^{-}, and 16.82 kg ha^{-1} y^{-2} of Cl^{-}.   The high values for Ca^{2+} and Mg^{2+} indicate the importance of the sources of these cations in the bedrock glacial deposits and the soil.

10.3   SUGGESTIONS FOR FURTHER RESEARCH

10.3.1   Geomorphic Suggestions

This stage underlined the need for further research into a number
of related issues, outlined in the hope that some points will be
explored further.

- First, it would be useful for work at the Coombs Brook sites to
  be continued and extended, as the observation periods of this
  kind of study require a great deal of time.   For example, Kesel
  and Baumann's (1981) monitoring of a Mississippi site extended
  over ten years.   The observations should be intensified during
  the most critical periods as identified in this study.   These
  might be characteristic in winter peak of erosion, and the times
  of melting of needle ice, usually between December and March
  (Chapters 5 and 6).

- Second, because flood period sediment transport is so important,
  it would be useful to measure sediment concentrations in more
  detail during specific flood events.   This would enable more
  accurate predictive equations to be developed and lead to a more
  accurate estimation of the sediment discharge.

- Third, spatial investigation of sediment transport in the small
  tributaries (rills and gullies) of Coombs Brook might verify
  several of the assumptions made in this thesis about the sediment
  supply of the stream tributaries.

- Fourth, the erosion pin measurements used in this research have
  been made over a short period of time and, as the pins are still
  in location, it would be useful to continue taking readings from
  them for several more years to get a better indication of long-
  term changes and to examine more closely the effects of storm
  events.   It would be useful to extend this kind of measurement
  to other localities.

- Fifth, the role of needle ice in stream bank erosion may help to
  explain the mechanisms by which sediment is incorporated into the
  ice volume, and to establish simple relationships between climatic

factors, needle ice morphology and sediment transport. This could be achieved by using environmental cabinets (e.g. Cooke, 1979).

- Sixth, because of the sediment concentration in the catchment related to the availability of suspendable material condition, there is a requirement for an integrated examination of soil erodibility in the catchment.

10.3.2 Hydrologic Suggestions

Studying the stream water chemistry in a forest area such as Coombs Brook is apart from the complex subject of hillslope hydrology, and would repay further investigation.

1. The soil water samples obtained in this project gave interesting results (Chapter 7), and a more extensive programme, including the sampling of different horizons with the soil at several points on a slope, and sampling soils from different types within the catchment, might help to elucidate these problems. The sampling could be allied with measurements of the flow of water through the soil on a slope by physical soil techniques (Atkinson, 1978).

   The field data from such a project could be backed up by carefully controlled leaching experiments in the laboratory. Samples of field moist organic horizons could be leached with artificial rainwater at a rate similar to natural precipitation (e.g. 2 mm h^{-1}) until a set amount (e.g. 50 mm) had been added. The leachate rate from this horizon could then be passed through a sample of the underlying organo-mineral horizon, again in field-moist conditions, and then through a sample of the lower, mineral horizon. The temperature of the soil could be carefully controlled and the experiment repeated over a range of temperatures. At each stage the leachate would be measured and analysed. This information would help to elucidate the progressive changes in water chemistry as it percolates through the soil. The use of a Blasma machine or an atomic absorption spectrometer would be of great advantage, as a number of elements could be determined

on a very small volume of samples.

2. Another aspect of the intrasystem mechanics of the ecosystem
    that requires further investigation is the uptake and immobili-
    sation of elements by vegetation. As Robertson and Davies's
    (1965) data show (Table 10.3.2.1) considerable quantities of
    certain elements are held in the vegetation and organic soil
    phases of the ecosystem. Some information on this could be
    provided by more extensive data on the chemistry of soil water
    from different horizons. More detailed data on the quantities
    of nutrients held in different phases of the soil ecosystem
    could also be of value. An example of this approach is the work
    of Chapman (1967, 1970) in the Poole Basin, Dorset. He measured
    the quantities of Na^+, K^+, Ca^{2+}, Mg^{2+}, N_2, PO_4^{3-}, organic carbon
    and dry matter in vegetation, roots, soil organic matter and
    the mineral soil in heather stands of various ages on podzolised
    soils.

    Such data could be interpreted more easily if more information
    on the pathways followed by elements through the soil was
    available. This could be gained by experiments with radioactive
    tracers. Suitable isotopes are available for several elements,
    particularly Ca^{2+}, K^+ and PO_4^{3-}. These tracers could be added
    to the soil surface in simulated rainwater, and their progress
    through the soil monitored. Riekerk (1971) describes this pro-
    cedure for a forest soil. It would also be of great interest
    to release labelled cations in the organo-mineral horizon, and
    to see to what extent they are taken up by deep roots and to
    what extent flushed out of the soil.

3. The results of this project show the concentration of Na^+ is
    by far the dominant cation in precipitation, yet it is less
    important relative to the other cations in stream water and is
    not retained on the exchange complex to any extent, or probably
    in vegetation. This seems to suggest a considerable input of
    the other cations by weathering, and their relocation within the
    soil. Deep roots could take up K^+, Ca^{2+} and Mg^{2+} from the soil
    solution and bring them to the surface. Once they are within
    the surface horizons, they would be efficiently retained there

TABLE 10.3.2.1   QUANTITIES (kg ha^{-1}) OF CATIONS IN DIFFERENT PHASES OF THE ECOSYSTEM, GLENDYE, SCOTLAND

	Location	Na$^+$	K$^+$	Ca^{2+}	Mg^{2+}
1.	Heather vegetation plus litter	n.d.	40	34	13
2.	Peat (top 17.5 cm)	n.d.	194	619	366
3.	Moder (13.6 cm)	23400	81880	2000	710
	Annual input (ppt + dry deposition)	44.9	2.39	11.29	5.45
	Annual output due to weathering	10.06	3.25	14.7	5.29

After Robertson and Davies (1965)

by the main body of plant roots. This system is not fully understood, and requires further investigation.

4. The hydrological and geochemical balances give a general idea of the net gains or losses of elements from the catchment forest. Balances for Coombs Brook could be compared with balances for a forested catchment underlain by granite or other rocks (Chapter 9), to ascertain the effects of different systems of land use or different geology on the losses of elements in river water within a region. If more specific information on factors such as uptake of elements by vegetation, hydrological processes, or other such internal aspects of the ecosystem is desired, then much more detailed studies are necessary. The best example of this is the Hubbard Brook study (Likens et al., 1977). Such studies, however, require a considerable input of resources, equipment and personnel over a period of several years, and a broad-minded, interdisciplinary approach by the researchers, if they are to achieve their full potential.

From the work described in this thesis, further work on the effects of soil leaching on stream chemistry is required: for example, sampling on a frequent time interval of a series of storm hydrographs at different conditions of soil moisture. The rising stage of a hydrograph is frequently over by the time arrangements can be made for the collection of samples. As emphasised by Williams (1971), the composition of water draining the soil can change very quickly, and much still needs to be known about the processes of leaching of nutrients.

A number of small instrumented catchments have been set up for the North West Water Authority. The Coombs Brook project is part of this programme, and there is a need for other catchments in the Macclesfield Forest to be sampled regularly for both dissolved and particulate load.

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APPENDIX 1

SOIL AND SEDIMENT RESULTS

1.1   Profile Description of the Forest Soil within the Coombs Brook
       Catchment

1.2   Grain Size and Chemistry Analysis

1.3   General Characteristics of the Bank Material Properties and
       Channel Form of the Eight Measurement Sites

APPENDIX 2

CHEMISTRY OF SEDIMENT

2.1   The Concentration of Leachable Elements in Sediment (in ppm)

2.2   The Concentration of Leachable Elements in Dry Suspended
       Sediment (in ppm)

APPENDIX 1

SOIL   AND   SEDIMENT   RESULTS

1.1 Profile Description of the Forest Soil within the Coombs Brook Catchment

Profile: 1
Angle of slope   30°
Altitude: 260m
Parent material: Gley soil

Horizon   0 - 5 cm   Mainly pine needles, 1.5 cm in depth; the O
                         layer, which was the organic humus layer,
                         reached a depth of 4 cm; abrupt irregular
                         boundary.

A   5 - 15 cm   A clay loam texture, friable (10 YR 4/1);
                         dark grey in colour, with some faint, fine
                         mottling; some rusty mottling along root
                         channels, commonly yellowish red (5 YR) in
                         colour; clear wavy boundary.

B   15 - 45 cm   Greyish brown (10 YR 5/2), clay loam; common
                         medium and large subangular stone fragments
                         some small mottling (10 YR), yellowish brown,
                         and some (10 YR 6/1) grey to light grey mottles;
                         fine fibrous roots; gleying evident by bluish
                         grey tinge; clear irregular boundary.

C   45 - 60 cm   Clay texture; many stones; medium and suban-
                         gular fragments (10 YR 4/2) dark greyish brown;
                         many distinct medium grey (5 YR 5/1) mottles;
                         very few to no roots.

Profile: 2
Angle of slope   10°
Altitude: 260m
Parent material: Gley brown earth

Horizon 0 - 5 cm   Litter, mainly of pine needles; humus layer;
                      common very fine to medium pores; very fre-
                      quent, very fine to medium roots; abrupt
                      irregular boundary.

A   5 - 20 cm   Brown to dark brown (10 YR 4/3), clay loam
                      texture; very stony; small angular and sub-
                      angular fragments; medium crumb structure;
                      abundant fine fibrous roots; some larger
                      roots; abrupt smooth boundary.

B   20 - 30 cm   Yellowish brown (10 YR 5/3); some faint, fine
                      mottling (10 YR 6/8), orange in colour; very
                      stony; many roots; sandy clay loam, with a
                      firm consistency; clear wavy boundary.

C   30 - 50 cm   Dark bluish grey (5 YR 3/1), blocky structure
                      and clay texture; silty clay; very few pores;
                      very few to no roots.

D   50 - 60 cm   Dark greyish brown (10 YR 4/2); some blue-
                      grey streaks; clay texture; very frequent,
                      fine, very few pores; very few to no roots.

Profile: 3
Angle of slope: 24°
Altitude: 275m
Parent material: Brown earth

Horizon 0 - 5 cm   0-1 cm, litter layer; 1-4 cm, organic humus
                      layer, black colour (7÷5 YR 1.7/1); silt
                      loam; abrupt smooth boundary.

A   5 - 20 cm   Dark brown (10 YR 3/3); clay loam texture;
                      crumb structure and friable consistency;
                      very frequent, very fine to medium roots;
                      stony; some gravels; some mixed organic
                      matter; clear irregular boundary.

B   20 - 35 cm   Brown in colour (7-5 YR 4/3); roots abundant;
                      stony sand clay loam; structure still crumb;
                      very few roots; clear irregular boundary.

C   35 - 60 cm   Brown to yellowish brown (7-5 YR 4/4), clay
                      loam texture and medium crumb structure; some
                      grey mottling; greyish brown (10 YR 5/2) at
                      45 cm depth; very frequent fine gravel-size
                      angular; few fine to coarse pores; very few
                      fine to coarse roots; clear irregular boundary.

D   60 - 80   Yellowish brown (10 YR 5/3); sandy clay loam
                      texture; very stony; very few to no roots.

Profile: 4
Angle of slope   10°
Altitude: 280m
Parent material: Gleyed brown earth

Horizon	0 - 5 cm	Leaves and pine needles; humus layer (2 cm); abrupt smooth boundary.
A	0 - 20 cm	Greyish brown (10 YR 5/2); grey mottles evident in waterlogged conditions; clay loam texture; few stones; thin fibrous roots; some organic humus; clear smooth boundary.
B	20 - 30 cm	Reddish brown (5 YR 4/4); few fine mottles; slight grey tinge due to gleying; slightly stony; very few to no roots; abrupt wavy boundary.
C	30 - 40 cm	Reddish brown (5 YR 4/4); clay loam texture; horizon became more stony; crumb structure; few grey mottles (5 YR 6/1); very few to no roots; abrupt wavy boundary.
D	40 - 60 cm	Bright yellowish brown (10 YR 6/6); clay loam; very stony; no roots.

Profile: 5
Angle of slope: 2°
Altitude: 260m
Parent material: Gley soil

Horizon   0 - 8 cm   Dark greyish brown (10 YR 4/2);   acid and
                      very thick;   crumb to soft granular structure;
                      humus stoneless;   clear smooth boundary.

A   8 - 20 cm   Greyish brown (10 YR 5/2);   clay texture;
                      small cloddy structure;   some reddish-yellow
                      mottling (7-5 YR 6/8);   few very fine roots;
                      some rusty mottling;   reddish brown (5 YR 4/4);
                      clear smooth boundary.

B   20 - 35 cm   Grey and yellowish-red mottling (7-5 YR 6/6);
                      clay texture, very sticky in consistency;
                      stony;   many very fine to fine pores;   few to
                      frequent gravel-size angular;   clear smooth
                      boundary.

C   35 - 50 cm   Grey (10 YR 6/1) to medium grey (5 YR 5/1);
                      frequent gravel to stones;   few fine pores;
                      no roots.

Profile: 6

Angle of slope: 15°

Altitude: 270m

Parent material: Gleyed brown earth

Horizon	0 - 7 cm	Root mat; mainly mat-grass; humus layer; silt loam; abrupt smooth boundary.
A	7 - 20 cm	Dark brown (7-5 YR 3/2); very friable sandy loam; slightly stony with small angular and subangular pebbles; fine crumb structure; many very fine roots; abrupt wavy boundary.
B	20 - 30 cm	Red (2-5 YR 4/6); very friable sandy loam; stony with small angular fragments; weak fine crumb; many very fine roots; abrupt wavy boundary.
C	30 - 45 cm	Dark red (2-5 YR 3/6); sandy loam; very stony; frequent gravel-size subangular fragments; very few to no roots; abrupt wavy boundary.
D	45 - 60 cm	Dark red (2-5 YR 3/6); very stony; mainly rubble, with outer staining similar to previous horizon; slightly more clayey; few fine pores; no roots.

Profile: 7
Angle of slope: 20°
Altitude: 275m
Parent material: Brown earth

Horizon   0 - 5 cm   Dark brown (10 YR 3/3); litter layer of
                                     grass and leaves; humus horizon (2.5 cm);
                                     silt loam; abrupt smooth boundary.

A   5 - 25 cm   Brown (7-5 YR 4/3); clay loam; very stony;
                                     subangular fragments; very few, very fine
                                     roots; abrupt wavy boundary.

B   25 - 35 cm   Brown (7-5 YR 4/3) to dark brown (10 YR 3/3);
                                     clay loam; very stony; very frequent gravel-
                                     size fragments; few fine pores; very few
                                     to no roots; abrupt wavy boundary.

C   35 - 60 cm   Pale brown (10 YR 7/4); comprised mainly of
                                     partly weathered rocks - Millstone Grit;
                                     sandy clay loam; no roots.

Profile: 8
Angle of slope: 4°
Altitude: 300m
Parent material: Gleyed brown earth

Horizon 0 - 5 cm   Dark brown (7-5 YR 4/2); silt loam; abrupt
                         smooth boundary.

A   5 - 13 cm   Dark grey (5 YR 4/1); silty clay loam with
                         few rusty mottles; slightly stony; frequent
                         gravel-size subangular fragments; blocky
                         structure, breaking to a medium crumb; very
                         few very fine roots; abrupt wavy boundary.

B   13 - 30 cm   Yellowish brown (10 YR 5/6); clay loam;
                         slightly friable; some grey mottles (5 YR 6/1);
                         medium subangular blocky, breaking to a medium
                         crumb; very stony; no roots; abrupt wavy
                         boundary.

C   30 - 50 cm   Brownish yellow (10 YR 5/6); silt clay loam;
                         very stony; moderate medium angular blocky;
                         many fine pores; no roots; clear smooth
                         boundary.

D   50 - 60 cm   Bright yellowish brown (10 YR 6/6); gravelly
                         to stony silty clay; very frequent gravel-size
                         fragments; few fine pores; no roots.

1.2 Grain Size and Chemistry Analysis

Profile	Horizon	Depth cm	Organic matter %	Grain size distribution Coarse sand %	Fine sand %	Silt & clay %	pH	Moisture content %	Ca^{2+} ppm	Mg^{2+} ppm	Na^+ ppm	K+ ppm
(1)	HO	0- 5	20.0	69.0	23.3	7.6	3.2	42	10.7	2.2	2.7	4.3
	A	5-15	9.0	48.6	34.7	16.6	3.5	28	4.6	1.2	1.26	2.3
	B	15-45	8.0	50.0	31.7	18.1	3.8	21	7.4	0.93	1.32	2.9
	C	45-60	5.0	56.3	27.7	16.0	5.9	15	40.9	5.1	2.08	3.3
(2)	HO	0- 5	28.0	60.8	29.2	10.0	3.5	35	7.6	1.6	1.83	3.9
	A	5-20	13.0	59.3	29.1	11.5	3.6	33	3.5	1.1	1.6	2.1
	B	20-30	10.0	53.5	32.7	13.6	3.7	32	5.8	2.15	2.5	2.2
	C	30-50	8.0	56.2	32.0	11.8	4.4	30	30.6	3.7	1.7	2.2
	D	50-60	6.0	64.0	29.0	7.0	5.2	22	53.7	4.2	1.6	2.1
(3)	HO	0- 5	19.0	71.6	24.6	3.6	3.6	36	9.6	1.9	2.4	5.1
	A	5-20	11.0	64.2	28.6	7.1	3.4	24	3.9	1.3	2.0	3.5
	B	20-35	7.0	68.4	24.4	7.1	3.7	21	4.4	0.67	1.86	3.2
	C	35-60	5.0	77.0	12.5	10.3	3.9	20	5.5	0.63	1.4	3.3

Profile	Horizon	Depth cm	Organic matter %	Grain size distribution Coarse sand %	Fine sand %	Silt & clay %	pH	Moisture content %	Ca^{2+} ppm	Mg^{2+} ppm	Na^+ ppm	K^+ ppm
(4)	HO	0- 5	17.0	54.5	30.6	14.7	3.6	36	3.9	0.8	1.1	2.3
	A	0-20	9.0	58.2	28.8	12.9	3.6	22	4.8	0.5	1.2	2.8
	B	20-30	7.0	74.1	18.3	7.4	3.8	21	34.4	1.8	1.3	2.6
	C	30-40	6.0	52.1	30.6	17.2	4.0	19	58.0	2.4	2.7	2.4
	D	40-60	4.0	68.0	25.0	7.0	5.9	17	59.0	2.5	1.8	2.3
(5)	HO	0- 8	5.0	84.4	13.1	2.3	5.2	37	55.0	15.3	1.4	9.7
	A	8-20	5.0	68.6	25.7	5.6	5.1	41	50.2	12.9	1.5	10.4
	B	20-35	4.0	55.9	35.4	8.5	5.3	31	57.0	17.6	1.1	8.4
	C	35-50	4.0	60.0	30.0	10.0	5.3	30	63.0	25.5	1.6	6.0
(6)	HO	0- 7	20.0	62.8	27.7	9.3	4.0	53	22.4	4.9	1.5	12.3
	A	7-20	7.0	74.0	17.7	8.1	4.1	26	8.5	1.6	0.64	4.9
	B	20-30	6.0	85.1	10.5	4.2	4.2	23	6.4	1.1	0.81	3.3
	C	30-45	5.0	70.0	22.0	8.0	4.2	22	5.9	0.8	0.45	1.2
	D	45-60	7.0	78.0	12.0	10.0	4.3	21	3.6	0.5	0.46	1.7

| Profile | Horizon | Depth cm | Organic matter % | Grain size distribution | | | pH | Moisture content % | Ca^{2+} ppm | Mg^{2+} ppm | Na^+ ppm | K^+ ppm |
				Coarse sand %	Fine sand %	Silt & clay %						
(7)	HO	0- 5	31.0	53.8	31.5	14.6	3.9	55	30.1	4.9	0.75	14.0
	A	5-25	25.0	51.8	36.1	12.0	3.7	30	37.6	5.6	0.71	18.0
	B	25-35	11.0	87.7	8.6	3.6	4.0	25	12.0	2.3	1.1	8.9
	C	35-60	5.0	75.0	18.0	7.0	4.3	23	20.9	2.7	0.47	6.5
(8)	HO	0- 5	17.0	64.3	30.3	5.1	4.3	45	41.9	4.3	0.53	14.1
	A	5-13	9.0	63.3	28.4	8.1	4.4	35	23.8	2.4	0.68	9.4
	B	13-30	7.0	61.4	29.8	8.6	4.7	27	41.4	2.6	0.18	8.6
	C	30-50	5.0	76.7	17.4	5.8	4.8	24	125.0	8.4	0.47	7.9
	D	50-60	3.0	78.0	14.0	8.0	4.9	21	106.0	9.4	0.91	3.1

1.3 General Characteristics of the Bank Material Properties and Channel Form
of the Eight Measurement Sites

| Site | Horizon | Depth cm | Grain size distribution | | | Ca^{2+} ppm | Mg^{2+} ppm | Na^+ ppm | K^+ ppm | pH |
			Coarse sand %	Fine sand	Silt & clay %					
1	A	0-30	56.5	36.1	7.4	3.5	0.79	0.42	2.1	3.7
	B	30-40	61.3	27.4	11.2	5.1	0.38	0.52	1.3	4.0
	C	40-100	63.0	32.0	5.0	6.7	1.1	0.74	3.7	5.0
2	A	0-40	61.5	32.4	6.1	2.4	0.55	0.43	2.87	3.9
	B	40-100	44.6	29.3	26.1	24.1	6.3	1.11	3.74	5.0
3	A	0-80	85.8	13.7	0.38	21.3	4.7	0.62	2.8	4.7
	B	80-100	53.9	27.2	18.8	104.6	26.4	1.16	7.64	7.8
4	A	0-40	61.8	32.9	5.3	3.5	0.88	0.79	1.81	4.0
	B	40-70	41.8	34.9	23.1	77.1	9.13	1.75	2.51	4.8
	C	70-100	62.1	32.0	5.8	45.8	4.8	1.21	1.34	4.9

| Site | Horizon | Depth cm | Grain size distribution | | | Ca^{2+} ppm | Mg^{2+} ppm | Na^+ ppm | K^+ ppm | pH |
			Coarse sand %	Fine sand %	Silt & clay %					
5	A	0-40	62.0	29.2	8.7	1.81	0.29	0.38	2.6	4.3
	B	40-100	69.7	20.5	10.1	0.94	0.11	0.43	1.7	4.4
	C	100-140	74.7	21.1	4.1	8.9	0.98	0.52	2.47	4.7
6	A	0-40	50.2	38.4	11.3	2.59	0.63	0.50	1.17	3.4
	B	40-80	56.6	36.7	5.3	29.1	6.95	0.63	3.83	4.4
7	A	0-40	55.0	33.5	11.5	4.5	1.1	2.45	1.2	3.4
	B	40-80	69.3	25.3	5.4	6.8	1.5	1.3	1.2	3.8
8	A	0-40	46.2	29.3	24.5	50.8	4.3	0.76	2.9	4.0
	B	40-80	59.2	33.1	7.5	32.1	2.8	0.81	2.3	4.3
	C	80-120	52.8	27.4	19.6	24.7	3.02	0.53	4.19	4.5

APPENDIX   2

CHEMISTRY   OF   SEDIMENT

2.1   The Concentration of Leachable Elements in Sediment
(in ppm)

2.2   The Concentration of Leachable Elements in Dry Suspended
Sediment (in ppm)

2.1(a) Bed Load (sediment load from the stream bed)

Date: 24.07.1985

| | | Particle size distribution | | |
Station No.	pH	% coarse sand	% fine sand	% silt & clay
1	7.5	87.2	10.5	1.96
2	7.2	78.2	19.5	2.1
3	7.6	76.0	20.8	3.1
4	7.7	75.8	19.8	4.3
5	7.85	84.1	13.9	1.9
6	7.0	77.8	20.3	1.8
7	7.3	94.4	5.1	0.38

Chemistry analyses (ppm) (2mm sieve)

Station No.	Ca^{2+}	Mg^{2+}	Na^+	K^+	SO_4^{2-}	PO_4^{3-}	S^{2-}	Fe	Mn
1	67.1	15.1	1.77	1.91	5.51	0	1.82	0	0.01
2	55.6	12.08	1.99	1.56	7.1	0	2.33	0	0.10
3	148.16	39.19	3.09	10.59	7.93	0.064	2.62	0.02	7.90
4	109.15	23.13	2.46	4.18	6.12	0	2.02	0	0.33
5	80.7	19.0	1.93	3.34	5.12	0	1.69	0.06	0.10
6	88.86	23.3	2.24	4.96	5.66	0.059	1.87	1.73	0.07
7	48.56	13.01	2.04	1.55	4.6	0	1.34	0	0.06

2.1(b) Bed Load (sediment load from the stream bed)

Date: 04.09.1985

Particle size distribution

Station No.	pH	% coarse sand	% fine sand	% silt & clay
1	7.4	95.9	3.74	0.336
2	7.35	89.6	10.0	0.295
3	7.4	69.2	27.4	3.1
4	7.4	65.9	31.1	3.0
5	7.8	95.0	4.54	0.406
6	6.8	79.8	17.8	2.2
7	7.2	95.0	4.5	0.417

Chemistry analyses (ppm) (2mm sieve)

Station No.	Ca^{2+}	Mg^{2+}	Na^+	K^+	SO_4^{2-}	PO_4^{3-}	S^{2-}	Fe	Mn
1	36.44	7.11	1.50	1.30	2.8	0	0.93	0	0.27
2	29.31	5.93	3.07	2.03	3.0	0.049	1.0	0	0.26
3	63.5	16.09	1.12	2.85	3.2	0	1.07	0	0.97
4	60.77	12.84	1.73	2.91	3.2	0	1.07	0	0.98
5	52.41	13.29	1.09	2.24	3.0	0	0.99	0	0.31
6	55.9	14.01	1.29	2.64	3.2	0	1.07	0	0.18
7	28.5	8.05	0.70	1.02	3.1	0.019	1.02	0	0.17

2.1(c) Bed Load (sediment load from the stream bed)

Date: 12.12.1985

Particle size distribution

Station No.	pH	% coarse sand	% fine sand	% silt & clay
1	6.7	92.3	6.78	0.875
2	6.4	66.7	29.7	3.45
3	6.5	69.3	27.1	3.53
4	6.4	77.9	19.1	2.87
5	6.6	55.2	41.7	5.1
6	6.0	82.2	13.5	4.2
7	6.4	94.02	4.87	1.04

Chemistry analyses (ppm) (2mm sieve)

	Ca^{2+}	Mg^{2+}	Na^+	K^+	SO_4^{2-}	PO_4^{3-}	S^{2-}	Fe	Mn
1	44.8	9.17	0.96	1.89	0.06	-0.16	0.02	-0.10	0.44
2	87.4	15.07	1.31	2.06	3.63	-0.42	1.20	0.14	0.82
3	87.1	20.05	1.62	2.73	2.84	-0.37	0.94	0.04	0.54
4	60.09	10.28	1.14	0.97	0.57	-0.07	0.19	0.00	7.67
5	70.3	11.05	0.58	1.22	2.15	-0.07	0.71	-0.09	0.71
6	102.5	23.5	1.33	3.27	5.69	-0.10	1.88	-0.09	1.10
7	64.06	13.5	1.14	1.2	0.75	-0.18	0.25	-0.09	0.19

Chemistry analyses of clay and silt

1	156.8	29.3	3.30	4.74	9.36	229.9	3.09	-0.05	55.4
2	114.06	21.40	2.63	2.35	4.9	1.51	1.62	-0.06	2.03
3	149.5	35.2	3.22	5.05	6.5	19.21	2.15	-0.09	15.38
4	121.42	20.54	4.06	3.13	5.6	2.44	1.87	-0.09	19.49
5	142.05	22.27	4.76	3.23	7.3	3.13	2.44	-0.10	3.50
6	135.68	34.21	6.03	4.97	10.2	23.16	3.37	-0.10	18.79
7	121.6	29.94	4.39	3.99	9.18	21.35	3.03	-0.10	6.50

2.1(d)   Bed Load (sediment load from the stream bed)

Date: 10.02.1986

Station	Particle size distribution		
No.	% coarse sand	% fine sand	% silt & clay
1	95.2	4.74	0.066
2	69.7	28.2	2.01
3	85.5	13.14	1.37
4	76.1	21.5	2.33
5	87.7	12.0	0.170
6	85.9	11.5	2.4
7	82.9	14.1	2.93

Table 2.1(d) (Continued)

Chemistry analyses (ppm)

		Ca^{2+}	Mg^{2+}	Na^+	K^+	SO_4^{2-}	PO_4^{3-}	Fe	Mn	S^{2-}
Coarse	1	10.6	2.06	2.00	12.6	0.0	0.0	0.17	0.53	0.0
sand	2	10.54	1.92	2.06	12.9	0.0	0.0	0.17	0.53	0.0
	3	10.27	1.22	2.09	13.39	0.0	0.0	0.17	0.46	0.0
	4	11.70	2.0	2.19	13.57	0.0	0.0	0.18	0.58	0.0
	5	11.52	2.06	2.24	14.34	0.0	0.0	0.19	0.58	0.0
	6	10.85	2.0	2.32	14.6	0.0	0.0	0.20	0.58	0.0
	7	2.68	1.52	2.17	15.18	0.0	0.0	0.20	0.41	0.0
Fine	1	52.02	9.47	0.97	1.09	4.4	0.50	0.0	0.57	1.46
sand	2	44.83	8.24	1.74	0.32	3.69	0.18	0.0	0.62	1.22
	3	57.4	13.4	1.16	1.79	4.54	0.20	0.0	0.51	1.50
	4	45.8	8.98	0.66	0.72	3.03	0.27	0.0	0.74	1.00
	5	32.61	6.90	2.18	0.21	2.96	0.06	0.0	0.23	0.98
	6	67.2	15.8	1.25	1.65	5.3	1.02	0.0	1.88	1.76
	7	46.1	10.21	1.92	0.65	3.1	0.81	0.0	0.35	1.02
Clay	1	39.7	8.08	2.55	0.07	4.54	13.72	0.0	3.96	1.50
	2	106.7	19.8	6.96	3.08	12.18	2.01	0.0	1.44	4.02
	3	108.6	25.5	4.64	4.09	8.8	1.33	0.0	1.14	2.91
	4	99.02	19.57	2.27	3.64	7.09	17.3	0.0	8.64	2.34
	5	81.40	18.12	3.52	2.83	6.87	1.29	0.0	1.03	2.27
	6	133.4	30.3	2.64	5.30	12.06	205.4	0.0	57.2	3.98
	7	110.4	25.9	7.45	5.34	9.8	56.6	0.0	2.98	3.24

2.2 The Concentration of Leachable Elements in Dry Suspended Sediment (ppm)

Station No.	Ca^{2+}	Mg^{2+}	Na^+	K^+	SO_4^{2-}	PO_4^{3-}	Fe	Mn	S^{2-}
1	8.07	0.93	3.61	9.20	10.8	0.0	0.12	0.38	3.59
2	10.6	2.02	1.85	11.94	0.0	0.0	0.15	0.53	0.0
3	10.04	1.79	1.99	12.26	0.0	0.0	0.15	0.51	0.0
4	11.32	1.84	1.94	12.2	0.0	0.0	0.16	0.51	0.0
5	7.13	0.49	1.64	11.3	0.0	0.0	0.14	0.48	0.0
6	2.48	0.39	1.60	11.97	0.0	0.0	0.14	0.34	0.0
7	2.66	0.46	1.59	11.50	0.0	0.0	0.14	0.34	0.0