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SEDIMENT BUDGET AND SOURCE IN THE
CATCHMENT OF THE RIVER ROTHER,

WEST SUSSEX.



Peter Allan Wood

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ABSTRACT

The purpose of the study was

- a) to undertake a quantitative assessment of the proportions of river sediment derived from the various rock types within the catchment.
- b) to determine the rate of removal of sediment from the catchment.

The former purpose involved the determination of the mineralogy of source rocks, soils, alluvium and sediment by X.R.D. and heavy mineral analysis. The data indicate that each source rock has a characteristic mineralogy, but that this is not sufficiently variable for a quantitative assessment of proportions of sediment from each source rock to be determined. Certain conclusions, however, are drawn from the data, including a tentative formation, by sorting on a basis of specific gravity, of heavy mineral assemblage zones in channel sediment, that are probably indicative of areas of aggradation and degradation.

To determine the rate of sediment loss from the catchment, the dissolved load, the suspended load and the bed load were investigated. The dissolved load includes Ca^{2+} and HCO_3^- formed from the solution of Chalk, and erosion rates of CaCO_3 have been estimated at approximately $39.8 \text{ tonnes/km}^2/\text{year}$.

Suspended sediment concentrations were determined for samples collected from a variety of stations during a variety of flow conditions. An estimated 2,182 tonnes of suspended sediment was lost from the catchment in 1972, of which 1,720 tonnes was non-organic. The data indicates that the frequency and duration of storm events is a major controlling factor for suspended sediment concentration.

GENERAL DESCRIPTION OF THE STUDY CATCHMENT 8

Rates of bed load movement were determined using fluorescent sand tracers for two stretches of the Rother and a relationship between grain size, river discharge and sediment loss is presented for each. Modifications of techniques and methodology for use of fluorescent tracers are suggested and the data indicates the probability of aggradation of sizes of medium sand and larger between the two experimental stretches.

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Map of study catchment to
show geology, topography
and sampling locations.

Enclosure

INTRODUCTION

The subject of this study is the effect of the discharge of sewage on the water quality of the River ...

The purpose of this study is to determine the effect of the discharge of sewage on the water quality of the River ...

The results of the study show that the discharge of sewage has a significant effect on the water quality of the River ...

The following table shows the results of the study:

Parameter	Before Discharge	After Discharge
Dissolved Oxygen	8.5 mg/l	6.5 mg/l
Biochemical Oxygen Demand (BOD)	1.5 mg/l	4.5 mg/l
Chemical Oxygen Demand (COD)	2.0 mg/l	5.0 mg/l
Total Suspended Solids (TSS)	10 mg/l	25 mg/l

It is increasingly necessary to control the discharge of sewage into the River ...

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INTRODUCTION

individual scheme is clearly not always practical,

and the prediction approach using information obtained

"Two practical objectives of sedimentation

research are to understand the effects of major

factors on sediment discharge in streams and to

develop methods for computing the sediment discharge.

An understanding of the effects of the major factors

is essential to evaluate correctly the somewhat

incomplete and inexact information available on sediment

discharge and on the behaviour of sediment-laden

streams. Methods for computing sediment discharge are

needed in studies and computations relating to channel

design and maintenance, sediment yields from drainage

basins, rates of scour or fill in natural or artificial

channels, and depletion of reservoir storage by sediment

accretion," (Colby, 1964).

2. To determine the rate of removal of material by

"Problems associated with rates of transport

of sediment by natural and artificial waterways are

many, both in number and in type. Among the problems

are those involving river management, design and

operation of canals and reservoirs, and degradation

around bridge piers and below dams," (Rathbun, Kennedy

and Culbertson, 1971).

The area of study is the catchment of the River

"It is increasingly necessary therefore to

measure or predict the sediment transport characteristics

of a river whose regulation is proposed. The field

measurement of the bed load characteristics for an individual scheme is clearly not always practical, and the prediction approach using information obtained from other rivers becomes necessary," (Painter, 1972).

"Individual studies, while limited in scope, should be considered as building blocks toward complete understanding of the ways and means of sediment transport,"

(Teleki, 1966). The present study is of a rural catchment of poorly consolidated sands and clays. The objectives of this study are twofold:

1. To determine the relative proportions of the total load derived from each of the parent rock types within the catchment.

2. To determine the rate of removal of material by the stream, from the catchment, with special reference to bed load.

It is hoped that the study will supplement and increase the knowledge of fluvial transport and sedimentation.

GENERAL DESCRIPTION OF THE STUDY CATCHMENT

The area of study is the catchment of the River Rother above Midhurst, West Sussex, which is the major tributary of the River Arun. The Rother rises near Petersfield Anticline. The effects of these anticlines Selborne; flows southwards to Peterfield and then turns

through ninety degrees and flows east to join the Arun. Although the strata in the region are thrown into numerous folds, the river seems only in places to coincide with the latter, and appears to be a true subsequent river of the consequent Arun (Bury, 1910), during the formation of which numerous consequent streams must have been captured.

Division	Area	Length of channel km
Upper Chalk	5.14	3.34
Middle Chalk	16.82	8.89
Lower Chalk	35.07	15.77
Upper Greensand	24.84	13.58
Folkestone Beds	19.19	10.45
Sandgate/Bargate Beds	36.66	19.66
Hythe Beds	3.40	1.88
Weald Clay	12.77	6.95
Total	183.66	100.0

GEOLOGICAL STRUCTURE OF THE STUDY CATCHMENT

The area is situated at the western end of the Wealden anticlinorium which dominates the overall geological structure. Within this major anticlinorium three minor anticlines affect the structure in the study catchment (Geological Survey Memoir 301 and Geological Survey Regional Guide). The asymmetrical Fernhurst Anticline is replaced en echelon, 4 km. (2½ miles) to the south-west by the Harting Combe Anticline, and this is replaced en echelon to the south-west by the Petersfield Anticline. The effects of these anticlines

on the overall Wealden structure is to produce a
 extension of the Weald Clay outcrop, and to
 slight south westerly bulge of the outcrops of the
 Table 1. Area of outcrop of the various formations of
 the Cretaceous occurring within the catchment, and the
 length of channel developed on them.

Division	Area		Length of channel km
	km ²	%	
Upper Chalk	2.62	1.42	0.0
Middle Chalk	6.14	3.34	0.0
Lower Chalk	16.32	8.89	0.8
Upper Greensand	30.07	16.37	20.9
Gault	32.27	17.57	66.5
Folkestone Beds	24.84	13.53	35.5
Sandgate/Bargate Beds	19.19	10.45	30.4
Hythe Beds	36.00	19.60	15.7
Atherfield Clay	3.44	1.88	7.7
Weald Clay	12.77	6.95	20.9

Total 183.66 100.0 198.4

represented by part of the Wealden Series and by the
 Lower Greensand.

Wealden Series

The Wealden Series forms the oldest rocks in the
 area and in the study catchment this Series is represented
 only by the Weald Clay.

Weald Clay. The Weald Clay consists of shales and
 mudstones with subordinate siltstones, sandstones,
 and occasional shelly limestones and clay ironstones.

on the overall Wealden structure is to produce a westerly extension of the Weald Clay outcrop, and to form a slight south-westerly bulge of the outcrops of the Upper and Lower Greensands and Gault Clay (Fig. 1).

There are no significant faults in the area.

THE ROCKS WITHIN THE STUDY CATCHMENT

The Cretaceous rocks underlying the catchment consist principally of clays, sandstones and chalk. The following description is taken predominantly from the Geological Survey Regional Guide, the Geological Survey Memoir for Sheet 301, Kirkaldy (1933), Humphries (1964) and Fowler (1895).

Lower Cretaceous

In the study catchment the rocks of this age are represented by part of the Wealden Series and by the Lower Greensand.

Wealden Series

The Wealden Series forms the oldest rocks in the area and in the study catchment this Series is represented only by the Weald Clay.

Weald Clay. The Weald Clay consists of shales and mudstones with subordinate siltstones, sandstones, and occasional shelly limestones and clay ironstones.

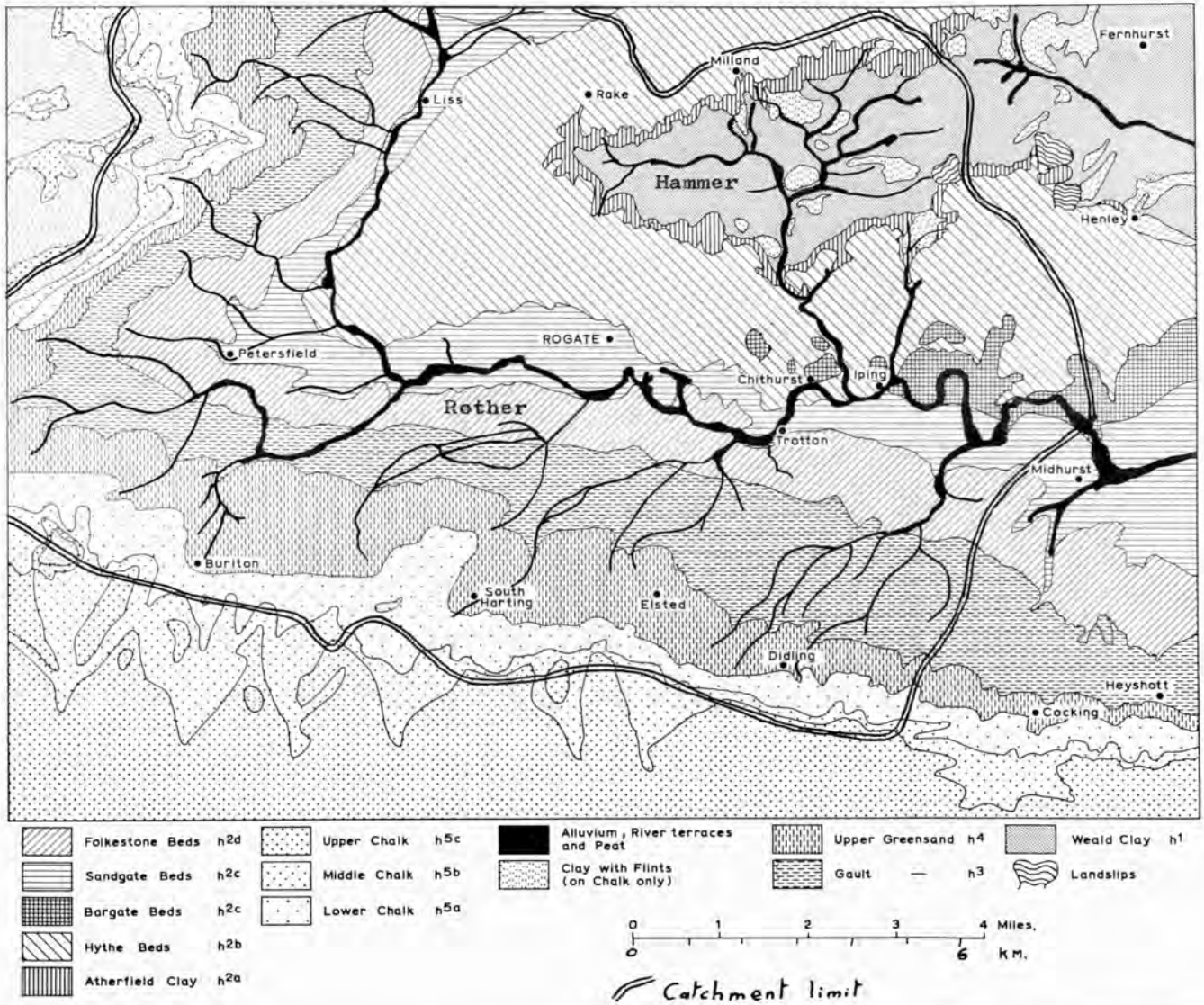


Fig. 1. Geology of the Rother catchment.

When fresh the beds are normally dark grey but weather to mottled yellow and brown.

Fig. 1 shows the distribution of the Weald Clay outcrop. A sandstone bed (7 ef of Topley, 1875) is the major sandy horizon within the Weald Clay of the catchment. Weathering of this sandstone may produce a superficial deposit which may be regarded as a type of Head (Geological Survey Memoir 301).

Lower Greensand

This formation is predominantly arenaceous, but important subsidiary amounts of silty and argillaceous material are present. Chert, ironstone and calcareous material also occur in small amounts. When fresh the rocks commonly have a greenish colouration due to the presence of glauconite, but on exposure to the atmosphere this is rapidly oxidised to limonite which may give rise to a yellow or reddish brown staining.

The Lower Greensand is divided into four major lithological divisions: the Atherfield Clay, the Hythe Beds, the Sandgate Beds, and the Folkestone Beds. Within each of these divisions however, there is considerable lateral and vertical variation as shown by Humphries (1964, Fig. 2, page 45).

The Hythe Beds in the vicinity of Maidhurst are Atherfield Clay. The Atherfield Clay consists of

shales and mudstones which weather to grey, blue, green and brown mottled clays and silty clays and in the study catchment it is probably no more than 12.2 m. (40 ft.) thick. The junction with the underlying Weald Clay is usually sharply defined (where visible), but that with the overlying Hythe Beds is less distinct, the topmost part of the Atherfield Clay commonly being sandy and glauconitic.

Hythe Beds. The Hythe Beds within the study catchment are more arenaceous than in the rest of the Weald and consist of fine-grained glauconitic sand and sandstone (the "hassock" of Kent and East Sussex). This material is greenish grey when fresh but becomes a greenish buff to pale yellowish brown when weathered. A scattering of glauconite grains gives the distinctive "pepper and salt" texture of hard specimens.

In the lower part of the Hythe Beds there is a considerable admixture of clay and silt suggesting a transition with the Atherfield Clay (Humphries, 1964) and this sized material occasionally forms clay and silty horizons throughout the Hythe Beds. In the upper part of the formation especially, the sands are hardened to beds of compact non-calcareous sandstones with subordinate lenticular beds of chert.

The Hythe Beds in the vicinity of Midhurst are approximately 76 m. (250 ft.) thick, and west of

Midhurst loams become important in the lower beds which thicken towards Petersfield where they are 79 m. (260 ft.) thick. North of Petersfield the loams of the lower part of the formation thin out and become replaced by the more typical sands and sandstones.

Sandgate Beds. In the Wealden District the Sandgate Beds are more variable, both lithologically and in thickness, than any of the other Lower Greensand formations. In the study catchment the lower beds, called the Bargate Beds, are quite well developed and are characterised by layers and lenses of pebbly calcareous sandstone. The upper part of the Sandgate Beds in the catchment are ferruginous clayey sands and silts that are up to 46 m. (150 ft.) thick and include in their upper part a soft, micaceous yellow sandstone, the Pulborough Sand Rock, overlain by dark grey shales known as the Marehill Clay. Approximately 15 m. (50 ft.)

Bargate Beds. On the south side of the Vale of Fernhurst the Bargate Beds consist of up to 15 m. (50 ft.) of fairly uniform fine-grained hard calcareous sandstone bands and doggers interbedded with glauconitic loamy sand and beds of cherty sandstone. Whereas near Midhurst this horizon is not traceable to the south of Petersfield, and for 4.8 km. (3 miles) west the Bargate Beds can be traced continuously, at Iping and Chithurst the formation becomes less persistent and occurs as localised lenticles below the boundary between the Sandgate Beds

In marked contrast to the transitional junction below

and Hythe Beds, with which division they appear to be interbedded. The maximum development of Bargate Beds in the area is about 11 m. (35 ft.).

The Folkstone Beds consist predominantly Sandgate Beds. The Sandgate Beds comprise both fine and poorly graded poorly consolidated quartzose sands and locally with glauconite, limonite, sandy ironstone and clay. South of the Vale of Fernhurst these beds overlie the Bargate or Hythe Beds with a persistent sharply defined base (Holmes, 1963), and they extend west to Petersfield and north from there. They consist mainly of soft glauconitic and irregularly iron-stained, medium grained, loamy sand with scattered quartz pebbles. These beds are approximately 21 m.

(70 ft.) thick at Trotton.

Sandy ironstones (the Selham Ironshot Sands) are taken locally as the base of the formation eg. around Petersfield there is approximately 15 m. (50 ft.) of ironshot sands overlain by 8 m. (25 ft.) of loams. Locally however, above the current bedded horizon,

The top of the Sandgate Beds between Midhurst and Petersfield becomes more silty and forms the soft yellow micaceous sandstone of the Pulborough Sand Rock. This horizon is not traceable to the north of Petersfield.

The highest member of the Sandgate Beds, the Marehill Clay, can be traced throughout the area, maintaining a constant thickness of about 11 m. (35 ft.).

In marked contrast to the transitional junction below

the Marehill Clay, that between it and the overlying Folkestone Sands is extremely sharp.

Folkestone Beds. The Folkestone Beds consist predominantly of coarser grained poorly consolidated quartzose sands with seams of pebbles and clay, and veins and doggers of hard ferruginous sandstone ("carstone"). The sands are generally stained yellow to reddish brown by limonite but clean, white sands ("silver sands") occur. The base of the formation is locally represented by an ironstone.

The Folkestone Beds contain the most persistent intraformational boundary within the Lower Greensand of the area; between a lower group of fine quartz sand with local ill-graded facies and an upper group of coarse sand showing well developed current bedding with pebbles of quartz and lydite and some ironstone. Locally however, above the current bedded horizon, especially between Midhurst and Petersfield, the sands become fine grained, without current bedding and occasionally show a strong development of seams and wisps of pipe clay.

The total thickness of the Folkestone Beds is 40 m. (130 ft.) at Rogate becoming 43 m. (140 ft.) at Petersfield and thickening northwards to 61 m. (200 ft.)

at Woolmar Forest, the Lower Greensand. This is
 replaced laterally in the vicinity of Withersat by an
 Upper Cretaceous

The Upper Cretaceous is represented in the study
 catchment by the Gault and Upper Greensand, and by
 the Chalk. (200 ft.).

Gault and Upper Greensand

The Gault and Upper Greensand are lithological
 variants of a single sequence which spans the Middle
 and Upper Albian, the term Gault being applied to
 the more argillaceous material. Consequently, in some
 parts of the Weald the Upper Greensand is the lateral
 equivalent of part of the Gault.

The Gault. The Gault consists of dark bluish grey
 to pale grey soft mudstones and silty mudstones
 which weather to yellow and brown clays. The basal
 part of the formation is commonly silty or sandy,
 and at other levels the clays may be either glauconitic,
 calcareous or have some development of gypsum (D. Cowen,
 personal communication). Phosphatic nodules occur at
 several horizons within the Gault of the catchment,
 notably towards the top of the division, where a
 persistent band of nodules marks the junction of the
 Lower Gault and the Upper Gault. There is also a
 well developed phosphatic nodule bed at the junction

of the Gault with the Lower Greensand. This is replaced laterally in the vicinity of Midhurst by an iron grit. The top of the Upper Greensand just north of Selborne.

Locally the thickness of the formation varies considerably but over much of the study catchment it is in the region of 61 m. (200 ft.). of nearly 100 ft. at Selborne, and thinning northwards to the Upper Greensand. The Upper Greensand of the Weald shows great lithological variety, in which three broad rock-types can be recognised; all of which occur within the study catchment, particularly near Selborne.

Poorly consolidated siltstones occupy the lower part of the formation and these form a transitional junction with the Gault. These siltstones thin east and appear to be absent in the vicinity of Midhurst. In the lower parts of the Chalk there is very little detrital matter, and generally the Chalk can be described as a fine-grained, homogeneous rock. The second rock type is a predominantly sandy series of beds, that overlie the siltstones, and contain small amounts of clay and silt. Much of this sandstone is referred to as "Malmstone", a pale matrix coloured rock containing abundant sponge spicules and by a high proportion of colloidal (soluble) silica with some clay, calcareous matter and mica.

considerably within certain limits, giving rise to The top of the Upper Greensand in the Midhurst area is marked by clayey sandstones speckled with Chalk of different lithological character. The presence of a high proportion of *Inoceramus* shells or other shell fragments is characteristic of this horizon.

glauconite grains which are dark olive green when fresh but weather to grey and brown. Similar beds occur towards the top of the Upper Greensand just north of Selborne. coccolith fraction predominates in the

The Upper Greensand is thickest in the western part of the Weald reaching a maximum of nearly 61 m. (200 ft.) at Selborne, and thinning northwards and southwards. At Midhurst it is approximately 30.5 m. (100 ft.) thick. Natural exposures of the Upper Greensand are rare but small outcrops are seen in the sunken roadways of the catchment, particularly near Selborne.

The Chalk

Except in the lower parts of the Chalk there is very little detrital matter, and generally the Chalk can be considered as a soft, white, friable limestone, consisting of over 95% of calcium carbonate. Ordinary white Chalk consists of a coarse fraction composed of shell debris and foraminifera embedded in a fine matrix of coccoliths (microscopic calcareous bodies produced by planktonic algae) and their disintegration products. The proportion of coarse to fine material varies considerably within certain limits, giving rise to Chalk of different lithological character. The presence of a high proportion of Inoceramus prisms or other shell is thickness. It is a sandy, glassy, soft, sometimes

debris produces a friable Chalk with a rather gritty texture. A nodular Chalk contains either abundant foraminifera, problematical bodies termed "spheres", or both, while the coccolith fraction predominates in the soft white Chalks of the Micraster zones.

Though at first sight the Chalk has a uniform appearance, these distinct lithologies do occur. However, there is little lateral variation because at any given time during deposition conditions were similar over the area.

Heavy rusty brown nodules occur particularly in the Lower Chalk, and these reveal upon fracture, a mass of radiating brassy crystals of an iron sulphide mineral, either pyrite or marcasite.

The Chalk is about 366 m. (1200 ft.) thick near Chichester, and good exposures are available in the area.

The Chalk can be sub-divided into the Lower, Middle and Upper Chalk. (30 ft.) flints and beds of nodular

Chalk also occur.

Lower Chalk. A considerable amount of argillaceous and arenaceous matter is present in the Lower Chalk; the proportion of non-calcareous substances varying from about 50% of the total in the lower beds to about 10% in the upper beds. The lowest beds, named the Chloritic Marl, varies from a few centimetres up to 3.0 m. (10 ft.) in thickness. It is a sandy glauconitic marl, sometimes

with phosphatic nodules and derived fossils at the base.

Upper Chalk is more regular in the middle of the

There is a gradual passage upwards into thickly bedded Chalk, alternating with harder bands, which in turn pass up into grey Chalk with marly partings. These beds are grouped together as the Chalk Marl, and these are succeeded by massively bedded Chalk which is predominantly grey in the lower part (Grey Chalk).

Above this comes the Plenus Marls, a few metres of alternating beds of yellowish or dark greenish grey marls, and lighter coloured marly Chalk.

Middle Chalk. At the base of the Middle Chalk is a lithological break marked by approximately 3 m. (10 ft.) of hard, marl streaked, greyish yellow Chalk enclosing very hard kernel-like nodules called the Melbourn Rock. The Melbourn Rock and the Chalk overlying it has a gritty texture due to the presence of Inoceramus prisms.

This passes gradually upwards into massively bedded, white Chalk with thin grey marly seams in the upper part. In the top 9 m. (30 ft.) flints and beds of nodular Chalk also occur.

Upper Chalk. The bulk of the Upper Chalk is composed of the familiar soft white Chalk with flints, but in the lower part are many beds of hard, rough, nodular Chalk. At the base there is a sequence of nodular beds, flint

bands and a marl seam. The flint distribution within the
 the area of Chalk, and has a very limited extent. The
 Upper Chalk is more regular in the middle of the
 thickness of the deposit varies greatly, and it
 formation, with regularly spaced horizons of nodular
 fragments fill up basin-like hollows and "pockets".
 or tabular flint, than it is in the upper part of the
 formation.

SUPERFICIAL DEPOSITS

Superficial deposits are of very limited extent
 within the study catchment and consist of Head, Clay-
 with-flints, River Terrace Gravels, and River Alluvium.

Head

The term Head is used here as a lithological term
 for superficial deposits of a structureless and/or
 rubbly character. The actual method of formation of the
 deposit does not concern this thesis but is well
 explained by Dines and others (1940).

In the study area, the distribution of Head is
 confined to the Hammer sub-catchment. Here are found
 areas of a deposit which is principally a mixture of
 debris from the Hythe Beds, and the Weald Clay 7 of
 Sandstone, and even some clay debris.

Clay-with-Flints

Clay-with-flints in the study area is confined to
 course of the main stream of the Rother, and along some

of the length of some of the tributaries. However, the areas of Chalk, and has a very limited extent. The thickness of the deposit varies greatly, and it frequently fills up basin-like hollows and "pipes".

Clay-with-flints sensu stricto as defined by Loveday (1962) can be applied to material that is unmottled, yellowish-red very firm clay, with a varying amount of flints of varying sizes. However, in practice a great variation occurs in the appearance of material that has been classified as Clay-with-flints.

Hodgson and others (1967) give an account of the origin and development of this material on the South Downs, and conclude that the deposits result from the action of cryoturbation and soil forming processes on a thin cover of Reading Beds clay.

River Terrace Gravels

Four terraces of river gravel have been attributed to the River Rother (Geological Survey Memoir 301). These are very restricted, and consist of mainly sub-angular flints with some fragments of chert and ironstone in a sandy gravel or sandy matrix.

River Alluvium

An alluvial plain is present along much of the course of the main stream of the Rother, and along some

of the length of some of the tributaries. However, nowhere in the study catchment does the alluvial plain become very well developed.

The alluvium is of a variable character but is generally a mixture of different grades of sand, with a variable quantity of clay and silt. In an excavation in the alluvium made during the construction of a weir near Liss, the author noticed coarse sand horizons with alternating clay partings and occasional gravel horizons. Elsewhere, alternating sandy horizons and clays were recorded.

GEOMORPHOLOGY

The geomorphological features associated with the various rock types within the study catchment are similar to those associated with the Wealden area in general.

A very brief description follows to indicate the main features of the geomorphology within the study area. A description of soils and landuse developed on each rock type is given by Yates (1960 and 1972).

Weald Clay

In the study catchment the Weald Clay forms a low lying, undulating area drained by the Hammer sub-catchment and being enclosed to the north, west and south by the

Atherfield Clay.

escarpment of the Hythe Beds. In this escarpment, one through which the Hammer Stream drains, and another Atherfield Clay 2.5 km. (1.5 miles) east which is a wind-gap occupied by a slight stream.

The Atherfield Clay crops out along the base of the Hythe Beds escarpment and exposures of this Clay are scarce, the outcrop being much obscured by landslip, talus and downwash from above. However, a spring line marks the top of the Atherfield Clay, and occasionally a slight feature marks its base. The Hythe dip slope.

Hythe Beds

The Hythe Beds form an almost continuous scarp and dip feature in the study area, reaching a height of 206 m. (676 ft.) at Telegraph Hill (SU 8726) and 162 m. (531 ft.) at Combe Hill (SU 7926). The changes in general height of the escarpment may reflect variation in thickness and lithology of the beds (Fowler 1895, and Humphries 1964).

However, Chorley (1969a) working on the Lower Greensand ridge of Cambridgeshire and Bedfordshire concluded that structural controls are dominant in explaining the prominent feature (Humphries, 1964). Occasionally changes in height and that lithological controls are subordinate. The Hythe escarpment in the study area has very little surface expression as only a slight feature occurs, and these beds form a lateral extension of the vale developed on the Sandgate Beds. Occasional landslips have occurred on the scarp slope where the Hythe Beds overlie the Atherfield Clay.

There are two main breaks in this escarpment, one through which the Hammer Stream drains, and another about 2.4 km. (1½ miles) east which is a wind-gap occupied by a misfit stream.

Bargate Beds

The base of the Bargate Beds is marked by a very weak surface feature that is occasionally detectable on or towards the bottom of the Hythe dip slope. This feature is occasionally dissected by steep sided streams that are Sandgate Beds summer.

The Sandgate Beds form a vale at the foot of the dip slope of the Hythe Beds but where the Selham Ironshot Sands and the Pulborough Sandrock occur a prominent feature may be developed (Humphries, 1964). This feature is occasionally dissected by gullies and steep sided dry valleys.

Folkestone Beds Lower and Middle Chalk are mainly confined to limited areas on the scarp slope.

In the study area the Folkestone Beds usually produce a good feature at their base and form a prominent feature (Humphries, 1964). Occasionally however, the transition from Sandgate Beds to Folkestone Beds has very little surface expression as only a slight feature occurs, and these beds form a lateral extension of the vale developed on the Sandgate Beds.

Gault ON AND RIVER DEVELOPMENT

The Gault forms a fairly flat but somewhat undulating area between the area of Folkestone Beds and the Upper Greensand bench.

The study area cannot be isolated from Upper Greensand development of the Wealden Area in general.

This formation forms a bench at approximately 76 m. (250 ft.) in front of the Chalk scarp slope, which is occasionally dissected by steep sided streams that are often dry in summer.

(Bury, 1908, 1910, 1921; Davies, 1885; Wooldridge, Chalk 1927, 1928, 1930, 1960; Wooldridge and Kirkaldy, 1937; Wooldridge and Linton, 1933; and Sparks, 1943).

The Chalk gives rise to extensive areas of undulating downland scenery forming a scarp and dip feature dissected by combs and steep sided dry valleys. The outcrops of Lower and Middle Chalk are mainly confined to limited areas on the scarp slope.

As the sea retreated the drainage on the freshly uncovered land ran straight downslope to the sea, cutting across geological structures in its path (consequent drainage). The early drainage has subsequently been greatly modified and at present only the gaps in the Chalk escarpments of the North and South Downs bear any direct relation to it. Much of the modification is due to the Pleistocene glaciation, the breaching of the various geological

DENUDATION AND RIVER DEVELOPMENT

Denudation and river development as a historical record of the study catchment must not be overlooked as it provides an understanding of the catchment. However, this aspect of the study area cannot be isolated from the overall development of the Wealden Area in general. A suitable summary of the Wealden Area is available in the Geological Survey Regional Guide, and a more detailed study is that of Wooldridge and Linton (1955) which reviews much of the former literature on the subject (Bury, 1908, 1910, 1922; Davies, 1895; Wooldridge, 1926, 1927, 1928, 1938, 1950; Wooldridge and Kirkaldy, 1933, 1937; Wooldridge and Linton, 1938; and Sparks, 1949).

During the Pliocene and early Pleistocene the Weald was an island undergoing subaerial denudation, upon which a drainage pattern largely concordant with the geological structures of the area probably developed. As the sea retreated the drainage on the freshly uncovered land ran straight downslope to the sea, cutting across geological structures in its path (consequent streams). The early drainage has subsequently been greatly modified and at present only the gaps in the Chalk escarpments of the North and South Downs bear any direct relation to it. Much of the modification is due to the Pleistocene glaciation, the breaching of the various geological

strata, and the effects of river capture.

Within the study catchment some of this development can be seen. The Rother is a major tributary of the consequent Arun which is presumed to have originated on the newly emerged surface of the Wealden Anticline. Another consequent stream is represented by a gap in the Chalk escarpment called the Cocking Gap, south of which is the mis-fit Lavant Stream. Other dry valleys head south from Compton and Buriton.

The main stream of the Rother is a subsequent stream of the Arun that is adjusted to structure. For all of its length the main stream follows the outcrop of the Lower Greensand, mainly flowing over the Sandgate Beds. The Rother however, during its development as a subsequent stream must have captured numerous consequent streams; those which are now marked by dry-courses and mis-fit streams.

The Hammer Stream, a major tributary of the Rother may be considered as a secondary consequent stream, that issues southwards via a water gap through the Hythe escarpment. Wooldridge (1950) has also described the Hammer Stream as having captured the head of a smaller stream to the east, which now rises on the floor of a wind-gap and flows south.

GENERAL EFFECTS OF LITHOLOGY ON EROSION

The Gault and Folkestone Beds during periods of prolonged

After the Tertiary folding and formation of the Wealden Anticline subsequent subaerial erosion has produced the present day topography. The effects of lithology on topography has been described but there must be a related effect on the rate and nature of present day erosion.

The Gault and Weald Clay areas generally form flat lowland areas where drainage is more intensive and rates of erosion probably high due to the soft nature of the rock. Also, the impermeable nature of these rocks encourages surface drainage, and such areas respond quickly to rainfall giving increased discharge in the streams.

The Lower Greensand, especially the Hythe and Folkestone Beds, form upstanding features in the landscape. This is partly due to their permeable nature which reduces erosion by reducing surface wash and overland drainage, and encourages groundwater movement. The Folkestone Beds are less well consolidated than the Hythe Beds in the catchment which may explain their lack of height as an escarpment feature when compared with the Hythe escarpment. Observations by the author however, indicate that large quantities of material are moved by

rainwash from sparsely vegetated and ploughed areas on the Hythe and Folkestone Beds during periods of prolonged rainfall. The occurrence of wind erosion in such areas has been observed by the author. The Lower Greensand areas respond slowly to rainfall and increased river discharges are only obtained after prolonged rainfall.

The relatively well cemented Malmstone of the Upper Greensand forms a bench at the base of the Chalk River escarpment, that is dissected by quite steep sided valleys. It is these streams that have the most youthful appearance of all the streams in the catchment. This could mean that they are sites of active river erosion at the present time.

On the Chalk surface drainage is again lacking because of the high permeability of the Chalk. Consequently there is little surface wash, except during periods of heavy rainfall. However, solution of the Chalk by groundwater is very important, and water issuing from springs at the base of the escarpment into the study catchment are often if not always saturated with calcium carbonate. So present day erosion of the Chalk, unlike the other rocks of the catchment, is mainly occurring below the surface.

Rather therefore, than a substantial groundwater component. The role of man as an agent of erosion in the study typical hydrograph, while the Area can be subjected to

catchment is evident in the widespread occurrence of ploughing, the presence of sunken roads and lanes, and the construction of roads and of houses. Man's ability to increase the sediment load of streams has been previously documented (e.g. Douglas 1967). All spring-fed streams draining from the Chalk escarpment. In contrast, HYDROLOGY AND THE HYDROMETRIC NETWORK is, due mainly to the presence of the Lower Greensand outcrop, particularly

The study catchment is managed by the Sussex River Authority and within their area the combined effects of geology and topography enable certain areas to be classified as primarily groundwater or surface-water orientated, (Sussex River Authority, First Periodic Survey). The study catchment is an area with a combined surface and groundwater orientation. This emphasizes the permeability of the Lower Greensand and of the Chalk which may be considered as two large aquifers, from which spring lines issue at their junctions with the Weald Clay and the Upper Greensand respectively. Total rainfall amounts were much lower, with consequent reduction. The Rother, although being a tributary of the Arun, contrasts with it sharply, for while the Arun drains a catchment consisting almost entirely of Weald Clay, the Rother drains large areas of Lower Greensand together with the scarp-face of the Chalk Downs. Flow in the Rother therefore, has a substantial groundwater component with a consequent smoothing effect upon the typical hydrograph, while the Arun can be subjected to

more extreme conditions of drought and flood. (Sussex River Authority, First Periodic Survey). This is due to the

There is also a contrast between the left and right bank drainage within the study catchment, with the right bank of the Rother picking up numerous small spring-fed tributaries draining from the Chalk escarpment. In contrast, there are very few left bank tributaries, due mainly to the extent of the Lower Greensand outcrop, particularly the Hythe Beds, which is almost devoid of surface drainage. Virtually all the left bank contribution to the flow is provided by the Hammer Stream. This stream drains the Weald Clay areas of the study catchment and so, like the Arun, it contrasts with the Rother by having greater extremes of discharge and by having a more 'flashy' character.

THE LIMITS OF THE CATCHMENT

This present study of the catchment has been hindered by the fact that during the study period the hydrological regime was a little different than for the 'average' year. Total rainfall amounts were much lower, with consequent reduction in the discharge levels, and prolonged periods when ground water seepage provided most of the flow. The gauging station (117.5 sq. km.) is smaller than the study catchment. However, the area in general has a water balance that illustrates well the main feature of the hydrological regime. That is the remarkable degree to which observed summer run-off values exceed those predicted by the peak flow during a storm hydrograph. The peak flow occurs

rainfall/evaporation/soil-moisture balance (Sussex River Authority, First Periodic Survey). This is due to the effects of the Chalk and Lower Greensand aquifers in maintaining quite high summer flows. The catchment is the approximate delineation of the area drained by it. With

The Sussex River Authority have developed a hydrometric network in the area. Rainfall data are available from various stations over the area, while the climatological station at nearby Fernhurst provides evaporation data. River flow is gauged continuously by an all-stage gauging station at Iping Mill. Another continuously recorded gauging station was completed near Liss in the summer of 1972. Stage posts have been introduced at significant points of the river system. The true drainage area is greater in extent than the topographic basin.

THE LIMITS OF THE CATCHMENT

The catchment area as indicated in Fig. 1 is the basin. The downstream limit of the study catchment is North Mill, Easebourne near Midhurst. This limit is fixed downstream of Iping Mill gauging station so that a suitable section would be included for some of the experimentation. The catchment upstream of the Iping Mill gauging station (153.9 sq. km.) is smaller than the study catchment (183.7 sq. km.) but it does however, approximate closely to a model of the latter, both in terms of drainage pattern and geological cover, and in discharge. There is however, a delay in time for the passing of the peak flow during a storm hydrograph. The peak flow occurs

at the Iping Mill two hours before it reaches the farther downstream North Mill.

The average annual total of rainfall varies from 1,000 mm. to 1,500 mm. A problem arising with the study catchment is the accurate determination of the area drained by it. With many catchments the watershed can be regarded as the limit of drainage, as the groundwater divides are coincident with the topographic divide. With the present study however, the topographic divide between the study catchment and adjacent catchments are almost everywhere on the Chalk or Lower Greensand which are zones of high rates of groundwater movement. It is possible therefore, that the groundwater divide is not coincident with the topographic divide and that the true drainage area is greater or lesser than the topographic basin.

The catchment area as indicated in Fig. 1 is the basin as determined by the topographic divide.

CLIMATE AND METEOROLOGY

The study area receives a temperate climate, with winters that are only rarely severe and summers well provided with both rain and sunshine. No part of the area is more than 45 km. from the coast, so extremes of temperature are rare, although exposure to wind varies greatly from place to place according to the nature of

the topography. sub-divisions include: bed load and

bed load (Laursen, 1958; Painter, 1972 and many

The average annual total of rainfall varies from 940-960 mm.. A map of the distribution of annual rainfall (Sussex River Authority, First Periodic Review, page 22) shows a general decrease in rainfall totals from 1,000 mm. on the Chalk areas to 850 mm. towards the north-east of the study area. Consequently, the Chalk aquifer receives a higher rainfall total than the Lower Greensand aquifer.

loads on siltate on the river bed (saltation load).

The mean annual temperature varies little within the study area, and its effects on the hydrological regime are limited.

for an: down particle on the river bed to be set

THE TOTAL LOAD OF STREAMS are to exert upon that particle

A finite force of a magnitude that depends on the shape,

size It is perhaps advisable for a brief review of the

terms that have been used in connection with stream transport.

The total load of a stream is the total material that is moved by a stream. It is mainly derived from the solid rocks and drift deposits of the catchment; however, some organic material may be removed by the stream and is therefore a part of the total load.

in comparison to the total depth of flow.

The total sediment load of a stream includes all of the total load except that part removed in solution. Attempts have been made to divide the total load, and each sub-division can include an organic fraction.

The most common sub-divisions include: bed load and suspended load (Laursen, 1958; Painter, 1972 and many others), colloidal load and dissolved load.

BED LOAD

The bed load is that part of the total sediment load that moves essentially in contact with the river bed. Particles of the bed load may roll or slide along (contact load), or saltate on the river bed (saltation load), and their downstream velocity is essentially slower than the velocity of the river water.

For any given particle on the river bed to be set in motion the flow will have to exert upon that particle a finite force of a magnitude that depends on the shape, size and density of the particle, and its relationship to the surrounding particles. Once particles are in motion on the river bed, then the number, the size, and the velocity of the particles will determine the rate of bed load transportation. For a particle to saltate along the river bed it must momentarily leave the river bed. However the vertical component of a saltating particle is small in comparison to the total depth of flow.

The rate of bed load movement usually increases with increased discharge. Bed load may also be called traction load and it often forms only a small part of the total

sediment load. Gradients have been observed.

SUSPENDED LOAD

The suspended load is that part of the total sediment load in which the particles move entirely surrounded by, and at essentially the same velocity as the river water. The various particles moving in suspension are large enough to be affected by gravity and may come into contact with the river bed with a frequency depending upon their size.

A suspension of particles heavier than the fluid (and too large for Brownian Movement) is possible because of the mixing action of turbulent flow. In turbulent flow vertical mixing of fluid occurs and for reasons of continuity (Laursen 1958) equal volumes of fluid must move up and down past any plane parallel to the water surface. Laursen explains that as suspended particles are influenced by gravity, then the mixing action of turbulent flow can only offset the action of gravity if there are more particles in the fluid moving up than there are in the fluid moving down, i.e. there must be a vertical concentration gradient of suspended sediment in the flow, such that the concentration is greater at the lower levels, if the mixing action is to maintain a statistically steady state of suspended sediment concentration. Such

concentration gradients have been observed, caused by a
 particles entering the flow, generally from the river bed.

The suspended sediment concentration usually increases with increased river discharge, and the load is generally estimated as being the product of suspended sediment concentration and fluid discharge. A lift force greater than the weight of the particle and that the interchange of particles between the bed and flow the
 (Duffly, 1948; Rouse, 1937).

The above definition of bed load states that saltation may occur where the particles momentarily leave the river bed; while the definition for suspended load indicates that particles may occasionally come into contact with the river bed. Clearly there is some difficulty in distinguishing between these two types of sediment load as in any given channel, with turbulent flow, it is probable that all the grains of a particular grain size (albeit a very limited size range) are just as likely to be moved as bed load or suspended load.

J. Lawson (1958) rejects both of these theories and says that A sediment particle which is suspended in turbulent flow will follow an erratic path which depends on the speed and direction of the fluid motion about it. Even if the particle were the same density as the fluid and therefore not subject to the forces of gravity, some of them would reach the stream bed because of the turbulent mixing action. For a steady state of suspended concentration to be maintained within the field of flow, each particle

that returns to the channel bed must be replaced by a particle entering the flow, generally from the river bed. Speculation as to the mechanism whereby sediment particles may be removed from the river bed are confined to three theories:-

1. The flow around the particle results in a lift force greater than the weight of the particle and that the particle consequently moves up from the bed into the flow (Jeffrys, 1929; Rubey, 1938).

Bagnold (1956) indicates that whatever the precise cause of a grain leaving the bed, it is unlikely that any upward force continues to act on the grain after its distance from the bed has exceeded half a diameter or less.

2. The mixing action of turbulent flow is sufficiently strong at the bed to remove the particle from the bed (Rubey, 1938; Rouse, 1939). If this mechanism were the cause it can account for the occurrence of particles throughout the depth of flow, and is not confined to a limited area near the bed.

3. Laursen (1958) rejects both of these theories and says that a more plausible explanation of how a sediment particle can leave the bed can be based on Newton's First Law of Motion; that a body in motion will move uniformly in a straight line until acted upon by some force. He considers a particle moving up the upstream slope of a dune, and the forces on this particle are:-

- a) the propelling forces of pressure and shear due to the flow around the particle.

b) the force of gravity.

c) the reaction force of the bed that can be resolved into:-

(i) the support force acting normally

(ii) the resistance force acting tangentially

As the particle approaches the crest of the dune all these forces will be acting on the particle, but just after the crest the bed force supporting the particle and the bed force resisting motion will be lost, whereas the fluid forces and gravity will continue to act. The particles' movement will depend on the velocity (both direction and magnitude) of the particle as it leaves the crest of the dune and the forces thereafter acting upon it. If the velocity and propelling forces are small and the particle is large, it will merely roll over the crest and down the lee slope of the dune. However, if the gravitational force is small in comparison to the momentum of the particle, it will only gradually deviate from its initial direction of motion and will tend to move in the parabolic path of a projectile. It is while on this parabolic path that the particle is subject to the mixing action of turbulent flow. Laursen states that in a bed covered with dunes this tendency for particles to leave the bed at the crests can be seen. However, Bagnold (1956), states that grains can be seen to enter upwards into the flow from seemingly random rest positions. It is possible that other bed roughness elements such as ripples or even individual

Certain elements and compounds may be removed by

grains are sufficient to remove the reaction forces of the bed.

Kalinske (1947) also gives an analysis of bed load sediment movement.

COLLOIDAL LOAD

The colloidal load is similar to the suspended load in that it is distributed throughout the flow and has essentially the same velocity as the fluid, but it differs from it as colloidal load consists of small particles that will not settle out in a still pool under the influence of gravity. The particles are small enough to be maintained in suspension by Brownian Movement and so form a colloidal suspension. The colloidal load also differs from the suspended load as it does not have a vertical concentration gradient but is equally distributed in the field of flow.

There is no definite relationship between colloidal load and discharge. The colloidal load can be estimated as being the product of colloidal sediment concentration and fluid discharge.

DISSOLVED LOAD

Certain elements and compounds may be removed by

the river in solution, and it is this material in solution that forms the dissolved load. Sources of supply of dissolved material include rock weathering, wash-out from the atmosphere, biological activity, agriculture and effluents (Edwards, 1973a). From a geological view point, the solution of rocks, rock minerals and cements is of major interest. This process probably reaches its greatest importance in the solution of carbonate rocks.

There is no vertical concentration gradient of dissolved material within the flow field and the relationship between dissolved load and discharge is variable (Durum, 1953 and Edwards, 1973a).

The dissolved load may also be called the solution load and is generally estimated as being the product of concentration and fluid discharge.

USE OF THE TERM WASH LOAD

During a study of sediment movement on the Enoree River, Einstein and others (1940) found that material both on the river bed and in suspension that was larger than 42 mesh (0.351 mm., +1.51 ϕ) moved at a rate that seemed to be a function of discharge. This is in agreement for the definitions of bed load and suspended load as set out above. Contrasting to this, the material finer

than +1.51 ϕ was merely 'washed through' the control stretch without deposition, and no definite relation existed between this load of fine material, and the stream discharge. The quantity of this sized material in the stream depended on other drainage basin factors such as rainfall, runoff, vegetation cover etc..

Einstein and others suggested that while the terms bed load and suspended load classify the total sediment in a convenient manner for qualitative analysis, they are of little use for a quantitative study. Consequently they adapted the following terms and definitions :-

Bed load: "is that part of the total sediment load composed of all particles greater than a limiting size (+1.51 ϕ for the Enoree River) whether moving on the bed or in suspension, and includes all bed material in motion".

Wash load: "is that part of the total sediment load composed of all particles finer than the limiting size (+1.51 ϕ for the Enoree River) which usually is washed into and through the reach under consideration". Consequently material smaller than the limiting size forms only a very small part of the river bed sediment. The wash load may enter a river by sheet wash, bank-caving etc. and does not necessarily bear a relationship to discharge.

The illustration of distinction between the different parts of the solids load of a stream (1940, page 632) indicates the various grain sizes involved in the wash load as occurring throughout the depth of flow and as not having any vertical concentration gradient. However, material involved in the bed load is indicated as having a concentration gradient and as being moved both in suspension (throughout the depth of flow), and by creep (near the stream bed).

Consequently, it appears that Einstein's term wash load is equivalent to the term colloidal load as set out above i.e. fine particulate matter occurring throughout the depth of flow without any vertical concentration ^{gradient and} /not having any definite relationship with discharge. Similarly, their term bed load can be considered to be a combination of bed load and suspended load as defined above.

Dury (in Chorley, 1969) says that wash load is that part of the suspended load which, although consisting of solid particles, is so fine grained that its settling velocity is very small or nil. He also maintains that it is carried in colloidal suspension.

Bagnold (1966) suggests that wash load is that part of the suspended load whose contribution to the total suspension work rate is relatively negligible. It is material of a fine nature that is readily maintained in

suspension due to its having so small a fall velocity. So again Bagnold is supporting the tendency of a colloidal mechanism.

Wash load then, is that part of the sediment load that consists of fine grained particulate matter, and occurs throughout the depth of flow without any vertical concentration gradient. The particles form a colloid and are maintained in suspension by Brownian Movement, and the concentration has no definite relationship with discharge.

Wash load is equivalent to the term colloidal load as defined above. Sediment is considered to have been placed on the river bed within the stretch concerned.

TERMS USED IN THIS THESIS

suspended sediment size is lacking in river bed sediments of the stretch concerned.

It is evident that there is a similarity in the definitions of some of the above terms. Also, it is often difficult to determine the exact quantity of each of the components of the total load.

The following terms and definitions are applied to the present study and some are in agreement with the definitions of Brown and Ritter (1971).

river water.

Dissolved Load

The majority of the material of the bed load is derived from the river bed.

The dissolved load is the amount of material removed

in solution. Calcium is the only element of the dissolved load considered in the present study.

Suspended Load

The suspended load is that part of the total clastic sediment load whose particles move entirely surrounded by, and at essentially the same velocity as, the river water. For simplicity in determining concentrations of suspended load it here includes colloidal load.

Very little of the material of a size suitable to be carried as suspended sediment is considered to have been picked up from the river bed within the stretch concerned. Similarly, material of the suspended sediment size is lacking in river bed sediments of the stretch concerned.

Bed Load

The bed load is that part of the total clastic sediment load that moves essentially in contact with or immediately above the river bed. Particles of the bed load may roll, slide or saltate on the river bed, and their downstream velocity is essentially slower than the velocity of the river water.

The majority of the material of the bed load is derived from the river bed sediment.

SECTION I

INTRODUCTION

The first part of this report is devoted to a general survey of the rock types and their distribution in the study area. In order to determine the extent of the various rock types, a series of field investigations were carried out. The results of these investigations are given in the following sections.

SECTION I

THE YIELD OF SEDIMENT FROM EACH

ROCK TYPE

INTRODUCTION

The yield of sediment from each rock type is a function of many factors, including the type of rock, the degree of weathering, and the amount of water available. The following table gives a summary of the results of the investigations.

It is evident from the above that the yield of sediment from each rock type is a function of many factors, including the type of rock, the degree of weathering, and the amount of water available.

SECTION I

and so before any diagnostic **INTRODUCTION** determined several samples

of river bed sediment and of suspended sediment were studied to see if

Within the study area the rock types are varied both in lithology and degree of cementation and compaction. In order to determine that microfossils were lacking in the river sediment,

the relative proportions of sediment derived from each of these

parent rock types several preliminary investigations of the parent

rocks were undertaken. The purpose of these investigations was to

The presence of naturally fluorescent grains within the rocks of the catchment was considered unlikely. However the possibility was investigated as fluorescent material was to be used in later

then be used as an indicator for the presence of material derived from experiments to study bed movement. Samples of both river sediment

the rock if it occurred in the river sediment. A quantitative and of rock types looked at under an ultra-violet light source indicated approach should determine the proportion derived from each parent rock. an absence of naturally fluorescent grains.

Preliminary investigations were within the fields of micropalaeontology, naturally occurring fluorescent grains, mineralogy, and the direct identification of the pebble fraction. The possibility of diagnostic minerals within the various rock types of the catchment was investigated.

PRELIMINARY INVESTIGATIONS

Micropalaeontology

Microfossils are present in the Cretaceous Rocks within the catchment (Anderson, 1967, Chapman, 1894, etc.) and it was hoped that particular species would have a sufficiently limited vertical distribution to be diagnostic of the rock within which it occurs (e.g. the ostracod zone species Cypridea valdensis [Anderson, 1967] would be diagnostic for the Weald Clay within the catchment).

However, the possibility that microfossils would not survive the processes of weathering, erosion and fluvial transport was present, a high proportion of quartz with an admixture of glauconite and some muscovite.

and so before any diagnostic species were determined several samples of river bed sediment and of suspended sediment were studied to see if any microfossils were present. The results of these studies indicate that microfossils were lacking in the river sediment.

The possibility of a variation in the state of weathering

Naturally Occurring Fluorescent Grains

However there was no readily visible difference in the weathering of clauonite between the sandstones. The greatest variation appeared to be due to the variation in freshness of samples collected. The presence of naturally fluorescent grains within the rocks of the catchment was considered unlikely. However the possibility was investigated as fluorescent material was to be used in tracer experiments to study bed movement. Samples of both river sediment and of rock types looked at under an ultra-violet light source indicated an absence of naturally fluorescent grains.

Mineralogy

A provisional survey of the transparent minerals of the various rocks, thus appeared to be a preliminary study (Section 1, Chapter 1). The possibility of diagnostic minerals within the various rock types of the catchment was investigated.

Mineral Analysis of Sand Sized Fraction

Details of previous work in this field are given later (in this introduction). The main sources of sand sized sediment within this catchment would be the Upper and Lower Greensands and the sandstones within the Weald Clay. Rock samples of these (the Upper Greensand, the Folkestone Beds, the Sandgate Beds, the Bargate Beds, the Hythe Beds and the sandstone [7 ef] of the Weald Clay) were subjected to preliminary investigation by studying the light mineral and heavy mineral fractions. Analysis of the light fraction of all the samples gave a high proportion of quartz with an admixture of glauconite and some muscovite.

Quartz: Results of the various preliminary investigations indicate

Sphericity and roundness analysis of the quartz grains did not provide any diagnostic features for the various rock types.

Glauconite:

The possibility of a variation in the state of weathering of glauconite grains between the different sandstones was investigated. However there was no readily visible difference in the weathered state of glauconite between the sandstones. The greatest variation appeared to be due to the variation in freshness of samples collected.

Heavy Fraction. The opaque heavy minerals include limonite and ilmenite, but a detailed analysis of these was not undertaken as it was considered unlikely to provide diagnostic minerals.

On a provisional survey of the transparent minerals of the various rocks there appeared to be sufficient variation in the mineral assemblages to require a more detailed study (Section 1, Chapter 1).

Mineral Analysis of Clay and Silt Sized Fraction

Samples of rock that would yield sediment of clay and silt size were analysed for their mineralogy by X-ray diffraction techniques.

The results of this mineral analysis indicated the possibility of diagnostic minerals within some rock types. A more detailed study would illuminate upon this (Section 1, Chapter 2).

Direct Identification of Pebble Sized Fraction

Material of fine and very fine pebble size on the river bed could be identified by the unaided eye and related directly to the source rock (Section 1, Chapter 3).

The results of the various preliminary investigation indicate that for the material of: (Whetten, KeUay, and Hanson, 1969):

d) Pebble size - direct identification could be used to determine the source rock type. Rittenhouse (1943) states that heavy mineral variation may provide diagnostic minerals for each rock type.

Sand size - heavy mineral variation may provide diagnostic minerals for each rock type.

Clay and Silt size - the mineralogy, as determined by X-ray diffraction, may be sufficiently variable to distinguish between different rock types.

PREVIOUS WORK

The results of provisional studies show that variation in mineralogy between the rocks within the study catchment may provide diagnostic minerals or mineral assemblages that could be used as indicators for the presence of material derived from these rocks occurring in the river sediment. The main approaches to be used are heavy-mineral analysis, X-ray diffraction and direct identification of pebble sized material.

Heavy Mineral Analysis

Heavy mineral investigations occur widely in the literature.

They include:

- a) studies of geological formations (Groves, 1931; Allen, 1948; two papers; Wood, 1956; Smith, 1961; and Hancock, 1969);
- b) studies of offshore and coastal areas (Krumbein and Rasmussen, 1941; Swift and others, 1971; and Siddiquie and Mallik, 1972);
- c) studies of fluvial environments (Russel, 1937; Rittenhouse, 1943

and 1945; Van Andel, 1950; Kruit and Van Andel, 1955; Carroll, 1957; Kelly and Whetten, 1969; and Whetten, Kelley and Hanson, 1969);

d) some discussion on analysis, comparison and representation of heavy mineral assemblages (Dryden, 1931 and 1935; Carroll, 1938; Rittenhouse, 1943; and Imbrie and Van Andel, 1964).

Rittenhouse (1943) states that most heavy mineral studies are concerned with one or more of six objectives, one of which is "to locate the sources or to evaluate the relative importance of various sources of a deposit". This indicates the possibility of this technique to overcome the present problem.

Russell (1937) studied the mineral composition of the Mississippi River sands and concluded that heavy minerals such as zircon, rutile and garnet show no indication of becoming eliminated by the processes of river transportation. This fact has a bearing on the present problem.

Rittenhouse (1943 and 1944) attempted to evaluate the sediment sources in the Middle Rio Grande Valley by using heavy minerals. The 1943 paper is principally concerned with transport and deposition of heavy minerals including a discussion of methodology and presentation of data. He draws attention to Rubey (1933) who in contrast to other workers of the time used weight, rather than numbers of minerals, as a basis for his reasoning. Rittenhouse explains the influences of granular variation on heavy mineral occurrence and then explains the principles of hydraulic equivalent sizes and hydraulic ratios to overcome this variation in a study of heavy minerals of river sediments. His 1944 paper is an evaluation of the various sources of sediment to

the Middle Rio Grande Valley. He determined the relative importance as sediment sources of various parts of the drainage basin. These source evaluations are based on the hydraulic ratios of the heavy minerals, and on the principle of contamination, i.e. mixing of sand brought by a tributary with the sand of the main stream. He outlines the reasons why other methods of representing heavy mineral compositions are not suitable for source evaluations.

Van Andel (1950) underwent an extensive study of the mineralogy of the sediment of the River Rhine and its tributaries. Very little mineralogy of the rocks within the catchment is given, but mineral associations from the various supply provinces were determined by a study of the mineralogy of the river bed sediments of streams draining the areas. Van Andel then gives an account of the downstream variation in mineral associations of the Rhine. However, unlike Rittenhouse (1944) he does not give a quantitative evaluation of the relative proportions of sediment supplied to the Rhine by the supply provinces. He discusses reasons why he is unable to apply the principle of hydraulic ratios on the Rhine sands and so represents his data as percentages. Van Andel also investigates the fraction analysis method (Zonneveld, 1946) of eliminating the granular influence. He concludes that in the case of the Rhine the normal mineral analysis is sufficient for a petrological study of the sediments, but accepts that special problems may occasionally be solved by means of fraction analysis.

Van Andel (in Kruit and Van Andel, 1955) also made an extensive study of the sources and deposition of heavy minerals of the Rhine

Delta. He successfully showed that at least 80% of the Rhone Delta sediments have been derived from the Alps and that a comparatively small contribution has been derived from the Massif Central.

Dorothy Carroll (1957) undertook a statistical study of the heavy minerals of the South River, Virginia. She explains that despite the restricted number of heavy mineral species from the sedimentary rocks within the catchment, it was possible to determine statistically significant differences in the mineral assemblages of the tributaries. This was done by including the weight in grams of the opaque grains and zircon, and also the varieties of zircon grains present.

Thus the estimation of sediment source using heavy minerals has been successfully done on occasions. It may be possible, then, despite the restricted mineral assemblages within the rocks of the catchment, to determine diagnostic minerals or mineral assemblages. The present study differs from that of Carroll (1957), Van Andel (1950 and 1955) and Rittenhouse (1944) in that diagnostic minerals are sought for that refer to rock formations and not to tributaries.

Heavy mineral studies of the Cretaceous rocks of the Weald have been many (Davies, 1915-1916; Boswell, 1923; Groves, 1931; Hayward, 1932; Allen, 1948, two papers; Worrall, 1954; Wood, 1956, and several others).

Davies (1915-1916) describes the mineralogy of the rocks of the Croydon area and gives the assemblages for members of the Cretaceous from the Weald Clay to the Chalk.

Groves (1931) studied the distribution of Dartmoor granite detritus in the sediments of southern England including a study of the Cretaceous rocks of the Weald. He states that samples from the Aptian of the Weald (Lower Greensand) yield mineral assemblages quite different from those of isolated sandy horizons within the Weald Clay. Also, the sediments of the Upper Cretaceous are characterized by large quantities of detritus from the Dartmoor granite which are lacking in the Lower Greensand.

Allen (1948, two papers) gives an account of the petrology of two sandstones within the Weald Clay.

The heavy minerals of the various Lower Greensand members in the Dorking-Leith Hill District are given by Hayward (1932). Similar work has been done in East Kent (Worrall, 1954) and in the Western Weald (Wood, 1956). The results of these works indicate a greater abundance of tourmaline in the Hythe Beds than in the Sandgate Beds (due mainly to the coarser nature of the Hythe Beds) and a greater abundance of kyanite in the Folkestone Beds. Wood (1956) states that not only is kyanite more abundant in the Folkestone Sands but it differs from the pale yellowish kyanites of the Hythe Beds and Sandgate Beds by being larger, more angular, and reddish-brown in colour.

The results of heavy mineral analysis of some Upper Greensand deposits outside the Wealden District are given by Boswell (1923) and detrital mineral analysis of the Chalk are given by Smith (1961), Weir and Catt (1965) and Hancock (1969).

The clay mineralogy of river sediments on the island of Puerto Rico

From a survey of the literature, then, there is an indication that the heavy mineral assemblages of the sand sized fraction of the rocks within the study catchment are sufficiently variable for diagnostic minerals to be determined.

X-Ray Diffraction

There has been much discussion on the techniques of X-ray diffraction (Buerger, 1942; Brunton, 1955; Arzoooff and Buerger, 1958; Gibbs, 1965; and many others) and on the problem of quantitative estimations (Johns, Grim and Bradley, 1954; Bertrand and Laisel, 1961; Norrish and Taylor, 1962; Gibbs, 1965, and others).

X-ray diffraction methods of determining the mineralogy of fine grained sediments and materials can be used in many fields including research into geological formations, soils and deep-sea sediments (Biscaye, 1965). X-ray diffraction studies of river sediments, however, are mainly from the Americas.

Knebel and others (1963) undertook a qualitative and quantitative evaluation of the clay minerals of the Columbia River. They conclude that there is a variation in the relative amounts of clay minerals in the bottom sediments between the reservoirs of the Columbia River. Analysis of some samples indicate significant differences in three areas of the Columbia River basin based on this variability in clay mineralogy. They suggest that part of these differences may be attributed to the presence and distribution of two distinct types of weathering environment over the catchment.

The clay mineralogy of river sediments on the island of Puerto Rico and others (1972).

was determined by Ehlmann (1968) and he included a brief statement on the petrology of the source rocks and of the mineralogy of the soils developed on the island. Like Knebel and others (1968) he concludes that the clay mineralogy of the stream sediment reflects the variation in climatic conditions and its effects on the weathering of source rocks.

Rodolfo (1970) gives an account of the suspended sediment of the Southern California Watershed. X-ray diffraction analysis of the silt and clay fraction was undertaken to determine the mineralogy. Of the three rivers studied, the San Gabriel suspension differed from the Santa Ana and Los Angeles by having abundant quantities of illite.

Thus some X-ray diffraction analysis of river sediments has been done, and some variations between rivers, and tributaries of rivers have been determined. It appears that a similar study of the present study catchment must be accompanied by a study of the mineralogy of soils as well as the rock types that provide sediment of clay and silt size.

The clay mineralogy of the Cretaceous rocks have been summarised by Ferrin (1971) and Weir and Catt (1965).

Direct Identification

The concept of the direct identification and correlation of sediment material of pebble size with source rocks is an obvious and simple principle. Wolman (1954) introduced a method of sampling coarse river bed material and recent work on coarse sediment and coarse sediment transport includes the study on Knik River in Alaska by Bradley and others (1972).

CHAPTER I

So some studies have been done in fields relating to the present problem of sediment source. The present study, however, differs from others in that the source will be described geologically (i.e. to the source rocks of the catchment) and not geographically (i.e. to source areas of the catchment). Rocks occurring within the study catchment that are a potential source of river sediment of sand size (between -1ϕ and $+4 \phi$) were subjected to heavy mineral analysis with a view to determining diagnostic minerals or mineral assemblages. This possibility was suggested by a preliminary study, and a survey of the literature. The results of mechanical analyses (Appendix I) of the source rocks indicated that the principle sources of this sized material are likely to be the sandstone (7af) within the Weald Clay, the Hythe Beds, Bargate Beds, Sandgate Beds, Folkestone Beds and the Upper Greensand. However, some heavy mineral analysis was also done on samples of the Weald Clay, Atherfield Clay, and the Gault.

As the heavy mineral work of previous workers (Wood, 1956, etc.) included the study catchment, and as the horizontal variation within the sandstones is very restricted, the first phase of the study of source rocks was intentionally restricted.

COLLECTION OF SAMPLES OF SOURCE ROCKS, AND LABORATORY PROCEDURES

Where possible most exposures of source rocks were sampled by a method of channel sampling similar to that described by Krumbain and Pettijohn (1938, p.17). It was considered that this method would give a sample that would have the average characteristics of the formation sampled. As the objectives of ^{the study was} a correlation with river sediments, the masking of the details within the exposure by this method of

CHAPTER I

MINERALOGY OF THE SAND SIZED FRACTION

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INTRODUCTION

separated in bromoform (specific gravity 2.88-2.91) using apparatus

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Some heavy mineral separations included the complete size range

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COLLECTION OF SAMPLES OF SOURCE ROCKS, AND LABORATORY PROCEDURES

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give a sample that would have the average characteristics of the formation

sampled. As the objectives of ^{the study was} a correlation with river sediments,

the masking of the details within the exposure by this method of

sampling is of no concern.

The samples were boiled in hydrochloric acid to remove any iron staining from the grains, and the heavy mineral residues were separated in bromoform (specific gravity 2.88-2.91) using apparatus similar to that described by Krumbein and Pettijohn (1938, Fig.153, p.335), and mounted in Canada balsam on 2mm. graticule slides.

Boiling in hydrochloric acid destroys some minerals, e.g. apatite and olivine, but the advantages of the removal of carbonates and iron compounds, and so giving a good heavy mineral separation, and easier identification of minerals, was considered to be greater than the disadvantages of losing some mineral species. Also, biotite is dissolved, and this has an advantage as its density, like that of muscovite, fluctuates about 2.9 and so it only partly settles in bromoform.

Some heavy mineral separations included the complete size range of the sample, while many were fraction analyses with size ranges restricted to the very fine sand size range (+3 ϕ to +4 ϕ) and to the fine sand size range (+2 ϕ to +3 ϕ).

Identification and counting was carried out using the petrological microscope. Each slide was subjected to successive diagonal traverses, counting all the grains in the 2mm. square, until if possible at least five hundred transparent grains had been identified. For some samples up to 1,000 grains were identified. The number of opaque grains was also determined and the percentage of transparent grains to total calculated. The zircon size index (Allen, 1949) was not determined, and consideration of an authigenic or detrital origin

of grains is not relevant to this study.

Ilmenite. This mineral was very common in the source rocks, and

RESULTS OF THE HEAVY MINERAL ANALYSIS OF SOURCE ROCKS

The transparent grains of the heavy mineral assemblages of the rocks studied were restricted to twelve mineral species.

Zircon. Zircon is the most abundant heavy mineral species in the source rocks of the study catchment. The grains were extremely varied and ranged from rolled grains (well rounded to sub-angular) to prismatic grains with pyramidal terminations. Some fractured grains occurred displaying conchoidal fractures. Zoning was observed only in a very few grains, while inclusions were common. The zircons were generally colourless or dusky. No purple or pink zircons were present.

A feature observed on a very few grains is the occurrence of an overgrowth. This overgrowth was determined by exhibiting bow-tie extinction under cross-polarised light, but its mineralogy was not determined.

Kyanite. All of the kyanite grains were colourless and commonly sub-angular prismatic grains to sub-rounded grains. Other shapes did occur however, including infrequent well developed prismatic grains, and the more common rounded grains. Some grains exhibited a ragged appearance (e.g. "frayed" ends and re-entrants) which possibly resulted from corrosion or solution. Inclusions were common.

Spinel. Spinel is not a very common mineral in the source rocks of the catchment and only a few grains were observed. The grains were various shades of green, often with small conchoidal fractures.

Shapes varied from sub-rounded to well-rounded.

Sillimanite. This mineral was very uncommon in the source rocks, and occurred as yellow or sometimes colourless grains.

Rutile. Rutile is an uncommon mineral and the colour of the grains was commonly "foxy red" or reddish-brown but occasional yellow grains were present. The grains were usually the rounded prismatic type although shorter more rounded grains did occur. Inclusions were lacking.

Amphibole. Amphibole was uncommon within the source rocks, and colour varied according to the type of amphibole, from colourless and very pale green (tremolite), through bright green (actinolite) to dark green (hornblende). The central areas of the grains was usually darker in colour than the periphery. It was in these pale peripheries that the pleochroism was best observed. The grains varied in shape and size, but often showed a well developed cleavage, often associated with the development of fragile frayed ends.

Anatase. The colour of the anatase grains varied but were commonly yellow and brown with occasional blue grains.

Tourmaline. The colour of tourmaline varied: the common colours being yellow, browns and blues, but occasional blackish-brown grains were observed. The shape was variable, but commonly prismatic grains were observed with a varying degree of rounding from sub-angular to well rounded. Some inclusions and fractured grains were observed.

Staurolite. The grains were generally irregular in shape, ranging from sub-rounded to sub-angular. The colour varied but yellow, yellow-brown,

and brown grains were commonest and the pleochroism varied greatly.

Inclusions were present in some grains.

The results of heavy mineral

Muscovite. The grains were generally colourless and tabular, and

analysis of both samples are set out in the tables. Comparison of

they were often larger than the grade-size of associated minerals.

These suggests that heavy mineral abundance is somewhat variable from

A few grains tended to be yellow-brown in colour, while others had a

place to place in a single exposure. However, it is unlikely that

cloudy appearance, and still others had occasional small inclusions.

Garnet. The garnets in the source rocks were always colourless and

Brookite and Monzonite. These minerals have been reported from the

Lower Greensand (Wood, 1956) but no grains were observed.

Opaque Minerals. The opaque minerals were not identified to mineral

species and only their proportion was determined. However, the

presence of some opaque grains with overgrowths were noted. These

overgrowths were identified as such as they exhibited bow-tie extinction.

The overgrowths were divisible into two types:

1. Opaques with a red/brown overgrowth.

2. Opaques with a colourless overgrowth.

The overgrowths formed a well rounded periphery to the nucleus grains.

The mineralogy of the overgrowth was not determined.

Several features are shown by this fraction analysis.

ACCURACY OF DATA

The accuracy obtained in the determination of the percentage

proportions by counting a certain number of grains can be deduced

from Brydens curve for the estimation of probable error (1931; also

in Krumbein and Pettijohn, 1938).

How representative the data are for the particular formation is not certain. From some exposures two samples were collected in different places but by the same method. The results of heavy mineral analyses of both samples are set out in the tables. Comparison of these suggests that heavy mineral abundance is somewhat variable from place to place in a single exposure. However, it is unlikely that any horizontal variation is greater in a distance of over 100 m. than it is over a distance of 1 m. (Allen via Hancock, personal communication).

Mesh

Percentage

VARIATION IN MINERALOGY DUE TO GRAIN SIZE

The variation in heavy mineral occurrence and assemblages with grain size is well established. Heavy minerals are generally concentrated in the finer fractions of the sand sized material and the proportions of one heavy mineral species to another varies with grain size. For example, zircon often forms a higher proportion of the total heavy minerals in the finer grain sizes than in the coarser grain size. In order to familiarise himself with this variation, and to ascertain its bearing on the present problem the author undertook a provisional study of this variation within a single sample from the Nythe Beds. The results of this analysis are presented in Table 2.

Several features are shown by this fraction analysis. Zircon forms an increasingly higher proportion with decreasing grain size. Tourmaline and staurolite form the highest proportion within 72-100 mesh range. Muscovite forms an increasingly higher proportion with an increase in grain size until within the 52-60 mesh range and the 44-52 mesh range it is the only transparent mineral present.

From these results it was considered that fraction analysis of the source rocks may be advantageous for the present problem and it

Table 2. Heavy mineral variation with grain size, Hythe Beds. Minerals would be determined by this method. For example, mineral A may occur in the grain sizes K and N of source rock X. However, in all other source rocks, mineral A may occur only in grain size M. Consequently, mineral A would be diagnostic for grain size M of source rock X. This would not be determined in a non-fraction

Mesh	Percentage									
	Zircon	Kyanite	Rutile	Amphibole	Anatase	Tourmaline	Staurolite	Muscovite	Garnet	Unidentified
25-30										
30-44										
44-52								100		
52-60								100		
60-72						9	4	87		
72-100	4	7	2	5	26	15	37		4	
100-150	24	8	6	3	8	16	8	17		10
150-200	50	8	9	1	11	9	2	3	1	6
200-300	64	13	4		4	3	3	6		3
25-300	42	11	5	2	3	8	7	19		3

The results of the heavy mineral analysis of the source rocks of the catchment are summarized in table four (Tables 3-12) and other published data (mainly from the Healds District) are included for comparison. Location of samples from within the catchment are given either by the grid reference, or in the case of river bank exposures, grid reference.

From these results it was considered that fraction analysis of the source rocks may be advantageous for the present problem as: 1) it will overcome the effect of granular variation; 2) it is more likely that diagnostic minerals would be determined by this method. For example, mineral A may occur in the grain sizes M and N of source rock X. However, in all other source rocks, mineral A may occur only in grain size M. Consequently, mineral A would be diagnostic for grain size N of source rock X. This would not be determined in a non-fraction analysis.

It was decided to confine the fraction analysis to two fractions:

Fine Sand - 60-120 mesh (+2 to +3 ϕ)

Very Fine Sand - 120-300 mesh (+3 to +4 ϕ)

These divisions were hoped to be the most useful and also would not require as many laboratory hours as would a more complete fraction analysis.

Similarly, the analysis compares with that of Allen (1948) and SAND SIZED MINERALOGY OF THE SOURCE ROCKS (1951) as a greater proportion of zircons than of tourmaline was

All of the source rocks within the catchment are potential suppliers of sand sized sediment, but obviously the amount capable of being supplied by the clays and the Chalk is significantly smaller than that of the sandstones.

The results of the heavy mineral analysis of the source rocks of the catchment are summarised in table form (Tables 3-12) and other published data (mainly from the Wealden District) are included for comparison. Location of samples from within the catchment are given either by the grid reference, or in the case of river bank exposures,

sized sediment.

the location of the sample is indicated on Fig.2. Some of these samples were compound samples of two or more adjacent river bank exposures.

The Weald Clay (Table 3)

The size range for this analysis was restricted to material larger than 300 mesh. Muscovite predominates in the preparation from the Weald Clay sample of the study catchment, but some zircon, and kyanite was observed. Davies (1915-1916) also observed rutile, tourmaline, staurolite, garnet and hornblende in preparations of the Weald Clay.

Sandstones within the Weald Clay (Table 4)

An analysis of a sample of the 7ef sandstone collected from within the study catchment differs from that of a similar sandstone by Allen (1948) by having a greater proportion of muscovite and a smaller proportion of tourmaline.

Similarly, the analysis contrasts with that of Allen (1948) and Groves (1931) as a greater proportion of zircons than of tourmaline was observed, whereas the converse was reported by these two authors. These differences are of no consequence to the present study and can be explained easily by possible horizontal variation in mineralogy and by each author working on a different sandstones.

The heaviest of very fine sand fraction consist almost entirely of zircon grains. Analysis of the fine sand fraction was not undertaken as this forms only a small fraction of the total size range (Appendix 1), and there was the practical difficulty of collecting sufficient material. Also, the sandstone is likely to be insignificant as a source of this sized sediment.

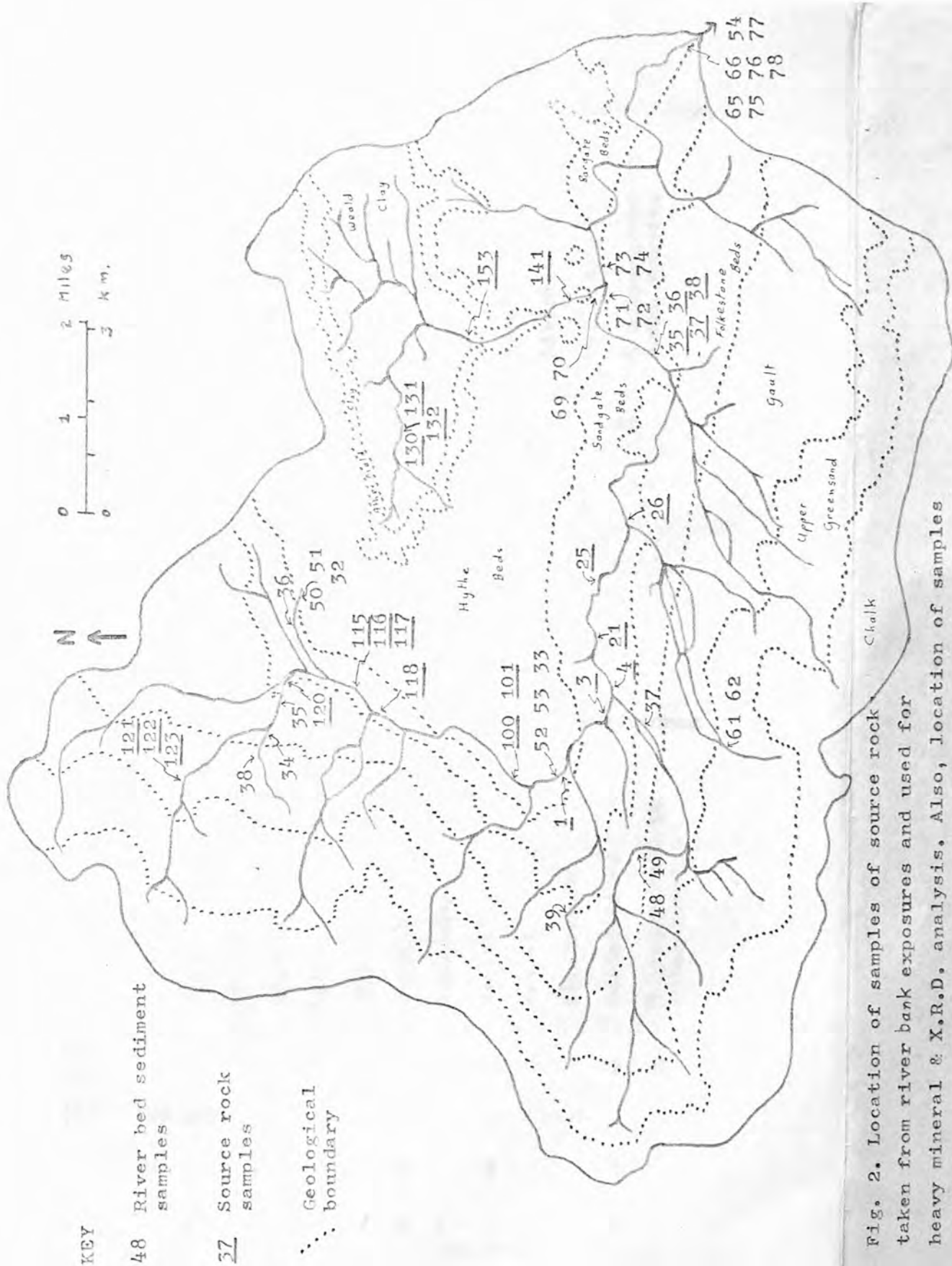


Fig. 2. Location of samples of source rock taken from river bank exposures and used for heavy mineral & X.R.D. analysis. Also, location of samples used for heavy mineral analysis collected from river bed.

Table 3. Heavy mineral assemblage by percent, Weald Clay.

Weald Clay (Table 5)

The results of the analysis of an Altonfield Clay sample collected from within the Weald Clay (Table 5) are given in Table 3. The sample was of the fine sand fraction (larger than 300 mesh only) and was analysed by the method of Davison (1965) and Davison (1975). The results are given in Table 3. The assemblage is similar to that of Wood (1952) and Wood (1954) but with a slightly higher proportion of amphibole, kyanite and muscovite. Mineral species identified and their relative percentages are given in Table 3. The results are in general agreement with Davison, Reynolds (1972) and Wood (1954). The analysis indicates that zircon is more abundant in the fine sand than in the fine sand, whereas tourmaline and staurolite are less abundant. Amphibole occurred in both size ranges.

Location	Mesh	Zircon	Kyanite	Rutile	Amphibole	Anatase	Tourmaline	Staurolite	Muscovite	Garnet	Spinel	Sillimanite	Unidentified	% transparent to total heavies
SU973	25-300	1	1		1				97					86
Davies 1915-16		✓	✓	✓	✓		✓	✓		✓			✓	

Table 4. Heavy mineral assemblage by percent, sandstones within the Weald Clay.

The results of the analysis of the total size range of the Weald Clay sandstones are given in Table 4. The results are in general agreement with Davison (1965) and Davison (1975). The assemblage is similar to that of Wood (1952) and Wood (1954) but with a higher proportion of amphibole, kyanite and muscovite. Mineral species identified and their relative percentages are given in Table 4. The results are in general agreement with Davison, Reynolds (1972) and Wood (1954). The analysis indicates that zircon is more abundant in the fine sand than in the fine sand, whereas tourmaline and staurolite are less abundant. Amphibole occurred in both size ranges.

Location	Mesh	Zircon	Kyanite	Rutile	Amphibole	Anatase	Tourmaline	Staurolite	Muscovite	Garnet	Spinel	Sillimanite	Unidentified	% transparent to total heavies
SU815 267	25-300	21	1	✓		✓	4	4	68				2	51
SU 815 267	120-300	100	✓											
Allen 1948		22		4		9	57	✓		1			7	
Groves 1931		✓	✓	✓		✓	✓	✓	✓				✓	

Atherfield Clay (Table 5)

An analysis of an Atherfield Clay sample collected from within the study catchment (larger than 300 mesh only) agrees well with the results of Wood (1965) and Davies (1915-1916). However, a high proportion of muscovite at the expense of zircon was observed.

Hythe Beds (Table 6)

The analysis of heavy minerals of the total size range of the Table 5. Heavy mineral assemblage by percent, Atherfield Clay. Hythe Beds was comparable to that of Wood except that the study catchment sample has a slightly higher proportion of amphiboles, anatase and muscovite. Mineral species identified and their relative abundance agreed with Davies, Hayward (1932) and Worrall (1954).

The fraction analysis indicates that zircon was more abundant in the very fine sand than in the fine sand, whereas tourmaline and staurolite were less abundant. Amphiboles occurred in both size ranges.

Bargate Beds (Table 7) / / 3 9 5 14 1 6 45

Wood The results of the analysis of the total size range of the 1956 85 2 1 8 6 Bargate Beds agree with that of Wood except that a higher proportion of Wood anatase and muscovite was observed. 5

Davies Fraction analysis again showed a higher proportion of tourmaline 1915-16 in the fine sand size. Indeed, the fine sand size of the sample from SU844234 had 34% tourmaline, 15% anatase and only 6% zircon. The author considers that these data are somewhat anomalous.

Amphibole and spinel are present in both the fine sand, and very fine sand size ranges.

Sandgate Beds (Table 8)

The results of the heavy mineral determination of the total size

Table 6. Heavy mineral assemblage by percent, Hythe beds.

Location	Mesh	Zircon	Kyanite	Rutile	Amphibole	Anatase	Tourmaline	Staurolite	Muscovite	Garnet	Spinel	Sillimanite	Unidentified	% transparent to total heavies
SU801	25-													

Table 5. Heavy mineral assemblage by percent, Atherfield Clay.

Location	Mesh	Zircon	Kyanite	Rutile	Amphibole	Anatase	Tourmaline	Staurolite	Muscovite	Garnet	Spinel	Sillimanite	Unidentified	% transparent to total heavies
SU801	25-													
258	300	46	7		2	3	18	18	7					30
SU801	60-													
258	120	22	13	3	1	7	22	20	9					
1,100	60-													
1,101	120	47	8	4		5	18	17	2	1				
1,102	120													
1,103	120													
1,104	120													
1,105	120													
Davies														
1915-16														
SU841	25-	/	/	/	/		/	/		/				
242	300	60	2	/	/	3	9	5	14	1		6		45
Wood		/	/	/	/		/	/		/				
1956		85	2	1			6	6						
1954		/	/	/	/		/	/	/	/				
Wood		/	/	/	/		/	/	/	/				
1956		92	/	1			2	5						
Davies														
1915-16		/	/	/	/	/	/	/		/				
Wood		/	/	/	/		/	/		/				
1956		82	2	1		/	5	10		/				
Wood		/	/	/	/		/	/		/				
1956		80	/	/			8	8						
Wood		/	/	/	/		/	/	/	/				
1956		73	3	2	/		9	11		1			/	
Wood		/	/	/	/		/	/		/				
1956		78	3	2	/		8	15						
Wood		/	/	/	/		/	/		/				
1956		83	1	1			7	8						
Wood		/	/	/	/		/	/	/	/				
1956		81	/	1		/	9	7		1				

Table 6. Heavy mineral assemblage by percent, Hythe beds.

Location	Mesh	Zircon	Kyanite	Rutile	Amphibole	Anatase	Tourmaline	Staurolite	Muscovite	Garnet	Spinel	Sillimanite	Unidentified	% transparent to total heavies
SU801	25-													
258	300	57	3	6	2	3	7	11	7	✓			4	44
SU801	25-													
258	300	45	7		2	3	16	16	7				4	30
SU801	60-													
258	120	22	13	3	1	7	22	20	9				3	21
1,100	60-													
& 101	120	47	8	4	2	5	13	17	2	1			1	31
SU801	120-													
258	300	69	7	4		6	4	5	4	1			2	37
1,100	120-													
& 101	300	83	2	1	2	2	3	4	1	✓			✓	45
Davies	150-													
1915-16	300	✓	✓	✓			✓	✓		✓				42
Hayward	120-													
1932	300	✓	✓	✓			✓	✓	✓	✓			1	44
Worrall														
1954		✓	✓	✓	✓		✓	✓	✓	✓				
Wood														
1956		64	5	2			13	15						
Wood														
1956		71	4	2			8	15		✓				
Wood														
1956		82	2	1		✓	5	10		✓				
Wood														
1956		89	✓	✓			3	8						
Wood														
1956		73	3	2	✓		9	11		1			✓	
Wood														
1956		74	3	2	✓		8	13						
Wood														
1956		83	1	1			7	8						
Wood														
1956		81	✓	1		✓	9	7		1				

Table 6. Heavy mineral assemblage by percent, Sandgate Beds.

Table 7. Heavy mineral assemblage by percent, Bargate Beds.

Location	Mesh	Zircon	Kyanite	Rutile	Amphibole	Anatase	Tourmaline	Staurolite	Muscovite	Garnet	Spinel	Sillimanite	Unidentified	% transparent to total heavies
SU844	25-	13	4			7	13	16	51				2	37
234	300	60	4	2	2	6	9	5	8	1			4	46
142 &	60-	9	10	1		6	21	7	40	✓			3	26
143	120	64	3	✓	✓	2	15	9	4	1			✓	43
SU844	60-	75	5	✓		5	8	8	1	✓		✓	1	31
234	120	6	3	2	2	15	34	9	25	1	1		2	29
SU844	120-	76	4	1		5	7	3	2	✓			1	35
234	300	60	4	2	3	5	11	8	5	1	✓		2	42
142 &	120-	77	7	2			7	12						
143	300	75	1	✓	✓	2	11	7	1	1			1	44
Wood		80	✓	2			8	10		✓				
1956		76	3	1		✓	7	11		✓				
Wood		88	✓	1			8	3		✓				
1956		85	2	1			3	9		✓				
Wood		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	
1956		90	1	2			1	6						
Wood		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	
1956		78	1	1	1		7	12						

Table 8. Heavy mineral assemblage by percent, Sandgate Beds.

Types of Sandgate Bed samples are in reasonable agreement with Wood's (1956) data. A higher proportion of kyanite was observed, and Wood's samples were lacking in muscovite. Worrall (1954) however did observe kyanite in his samples from the Sandgate Beds.

Location	Mesh	Zircon	Kyanite	Rutile	Amphibole	Anatase	Tourmaline	Staurolite	Muscovite	Garnet	Spinel	Sillimanite	Unidentified	% transparent to total heavies
SU808	25-													
229	300	53	9	2		3	12	6	14	✓			2	25
SU808	25-													
229	300	69	5	1		3	4	7	6	✓			4	40
SU808	60-													
229	120	13	4			7	13	10	51				2	37
6,21,22, 23 & 24	60-													
	120	9	10	1		6	21	7	44	✓			3	26
SU808	120-													
229	300	74	5	✓		5	8	6	1	✓	✓	1	31	
6,21,22, 23 & 24	120-													
	300	76	4	1		5	7	3	2	✓			1	35
Wood														
1956		77	2	2			7	12						
Wood														
1956		80	✓	2			8	10		✓				
Wood														
1956		88	✓	1			4	7		✓				
Worrall														
1954		✓	✓	✓		✓	✓	✓	✓	✓				
Davies														
1915-16		✓	✓	✓			✓	✓				✓	✓	

The fraction analysis indicated that kyanite was in greater abundance than zircon in the fine sand range whereas in the very fine sand range the converse was true. Tourmaline and staurolite were seen to have a greater proportion in the fine sand than in the very fine sand range. Spinel was present in trace amounts in the very fine sand range.

Table 8. Heavy mineral assemblage by percent, Folkestone Beds. range of Sandgate Bed samples are in reasonable agreement with Wood except that a higher proportion of kyanite was observed, and Wood's samples were lacking in muscovite. Worrall (1954) however did observe muscovite in his samples from the Sandgate Beds.

Fraction analysis showed zircon to be dominant in abundance in the very fine sand range, while muscovite dominated the fine sand size range. Indeed, the high muscovite content of this size range is mainly responsible for the relatively high proportion of this mineral in the total size range. Also, tourmaline and staurolite are slightly more abundant in the fine sand range than in the very fine sand range.

Folkestone Beds (Table 9)

The mineralogy of the total size range of Folkestone samples collected from within the study catchment are again in agreement with Wood (1956) except that his data do not indicate the presence of any anatase or muscovite; both of which were observed by Worrall (1954). Also, Wood's samples collected from within the present study area show 34% and 35% of kyanite while the present author had results of 19% and 15%. Also, Wood did not observe any garnet or spinel, but these were indicated by the fraction analysis.

The fraction analysis indicated that kyanite was in greater abundance than zircon in the fine sand range whereas in the very fine sand range the converse was true. Tourmaline and staurolite were seen to have a greater proportion in the fine sand than in the very fine sand range. Spinel was present in trace amounts in the very fine sand range.

Table 9. Heavy mineral assemblage by percent, Folkestone Beds.

Location	Mesh	Zircon	Kyanite	Rutile	Amphibole	Anatase	Tourmaline	Staurolite	Muscovite	Garnet	Spinel	Sillimanite	Unidentified	% transparent to total heavies
SU806	25- 224 300	45	19	2		1	6	9	15				3	36
SU806	25- 224 300	51	15	2		2	8	3	20				2	34
SU806	60- 224 120	17	24	1		7	25	11	10	1			4	29
32, 33 & 34	60- 120	22	29	2		5	19	14	6	/			3	24
SU806	120- 224 300	57	12	2		4	14	7	2	/	/		1	30
32, 33 & 34	120- 300	44	14	3		7	15	7	5	/	/		4	26
Worrall 1954		/	/	/		/	/	/	/	/				
Davies 1915-16		/	/	/		/	/	/	/	/				
Hayward 1932		/	/	/		/	/	/	/					
Wood 1956		70	18	2		3	7							
Wood 1956		63	24	1		4	8							
Wood 1956		42	34	1		6	17							
Wood 1956		43	35	2		6	14							
Wood 1956		61	25	1		4	9							
Wood 1956		45	36	4		3	12							

Table 10. Heavy mineral assemblage by percent, Gault.
Gault (Table 10)

As with the Weald Clay and Atherfield Clay the results of this analysis refer only to material larger than 300 mesh. The sample from the study catchment indicated a predominance of muscovite and zircon.

Upper Greensand (Table 11)

The sample of the Upper Greensand from the catchment which includes the total size range differs from those samples of Groves (1931) in that muscovite was dominant and zircon was more abundant than tourmaline. Grove's samples indicated that tourmaline is dominant, and that zircon is less abundant than muscovite, which is less abundant than tourmaline.

The samples upon which the fraction analysis was carried out were collected from the bed of streams that drained only from the Upper Greensand. These samples were originally considered to be representative for determining the mineralogy of the Upper Greensand as a source of rock. The validity of this assumption however is discussed later. Reasons for the collection of a river bed sample and not a sample from a rock exposure included the easier laboratory procedure for the former sample. The sample of rock for the size range analysis had to be disrupted in sodium sulphate prior to the heavy mineral separation.

Fraction analysis indicated a greater proportion of kyanite, tourmaline, anatase and staurolite in the fine sand size range, and a greater proportion of muscovite and zircon in the very fine sand size range.

Davies
1915-16

Table 10. Heavy mineral assemblage by percent, Gault.

Chalk (Table 12)

Work by Veit and Gatt (1965) on the Upper Chalk of the Antrim

of a indicated that zircon, rutile, tourmaline, sillimanite

may be present in the same as that of the

Location	Mesh	Zircon	Kyanite	Rutile	Amphibole	Anatase	Tourmaline	Staurolite	Muscovite	Garnet	Spinel	Sillimanite	Unidentified	% transparent to total heavies
SU800	25-													
217	300	23	2	✓		3	7	3	57	✓			4	40
Groves														
1931		✓			✓			✓		✓				

author has checked his results and is of the opinion that the

accuracy is due to the former explanation.

Table 11. Heavy mineral assemblage by percent, Upper Greensand.

in the heavy mineral data obtained by the author was with

reasonable agreement of other workers, and as little background

variation occurs (Veit, 1956) it was felt that the

Location	Mesh	Zircon	Kyanite	Rutile	Amphibole	Anatase	Tourmaline	Staurolite	Muscovite	Garnet	Spinel	Sillimanite	Unidentified	% transparent to total heavies
SU791	25-													
205	300	11	✓	✓	3	1	3	2	75	1		✓	3	68
River	120-													
Bed	300	27	✓	✓	✓	1	2	1	66	✓			1	55
River	60-													
Bed	120	20	10	4	10	14	12	12	6	✓			10	41
Groves														
1931		✓		✓		✓	✓		✓					
Groves														
1931		✓		✓			✓		✓	✓				
Davies														
1915-16		✓		✓			✓	✓		✓				

Chalk (Table 12)

Work by Weir and Catt (1965) on the Upper Chalk of the Arundel area indicated that zircon, rutile, tourmaline, sillimanite and muscovite were present in the sand sized detritus of the Chalk.

Davies (1915-1916) also detected some staurolite in Chalk detritus.

Throughout the study the proportion of anatase obtained was often higher than that of previous workers. This could be a real difference or due to the mis-identification of other minerals as anatase. The author has checked his results and is of the opinion that much of the discrepancy is due to the former explanation.

VARIATION OF MINERALOGY BETWEEN ROCK TYPES

As the heavy mineral data obtained by the author were within reasonable agreement of other workers, and as little horizontal variation occurs (Wood, 1956) it was decided that the present samples would be sufficient to determine whether or not diagnostic minerals could be determined. Other analyses could be undertaken as required.

At first appearance it seems doubtful if any significant difference in the mineralogy could be determined between the source rocks. The mineralogical assemblages are basically the same consisting of zircon, muscovite, kyanite, rutile, anatase, tourmaline and staurolite, often with garnet and amphibole and occasionally with spinel and sillimanite. However, some comparative features include:

1. A higher proportion of kyanite in the total size range, and

the fine and very fine sand range of the Folkstone Beds.

Amphibole is absent from the Chalk, the Folkstone Beds and

the Sandgate Beds.

Muscovite occurs in high proportions in the South Clay, the

Upper Greensand and the Gault.

Table 12. Heavy mineral assemblage by percent, Chalk.

Spinel is confined to the Folkstone and Sandgate Beds. However,

the percentage of spinel is very low and the error of counting

is consequently large.

Sillimanite is confined to the Chalk, Upper Greensand and to

Sandgate Beds. However, here again the number of grains

involved is low and the error is high.

Location	Mesh	Zircon	Kyanite	Rutile	Amphibole	Anatase	Tourmaline	Staurolite	Muscovite	Garnet	Spinel	Sillimanite	Unidentified	% transparent to total heavies
----------	------	--------	---------	--------	-----------	---------	------------	------------	-----------	--------	--------	-------------	--------------	--------------------------------

Weir &
Catt
1965

✓

✓

✓

✓

✓

Davies
1915-16

✓

✓

The specific gravity of muscovite (2.75-3.0) illustrates the effect of broadness (2.5) and consequently causes some problems during the separation of heavy minerals. What is more important, however, is that muscovite also has peculiar hydraulic properties, due in the main to its occurrence as thin platy grains. These tend not to settle out in flowing water when other mineral species of the same size and specific gravity would. The consequence of this is that grains of muscovite in a sediment tend to be up to four times larger than the average grain-size of distributed minerals. The effect of crystal shape on the settling rate is present in all mineral grains, but of all the heavy minerals this effect is probably at its greatest in

reducing the fine and very fine sand range of the Folkestone Beds.

2. Amphibole is absent from the Chalk, the Folkestone Beds and the Sandgate Beds.

3. Muscovite occurs in high proportions in the Weald Clay, the Upper Greensand and the Gault.

4. Spinel is confined to the Folkestone and Bargate Beds. However, the percentage of spinel is very low and the error of counting is consequently large.

5. Sillimanite is confined to the Chalk, Upper Greensand and Sandgate Beds. However, here again the number of grains involved is low and the probable error high.

The usefulness of the data for the purpose of this study is extremely restricted. The mineralogical assemblages are characteristic but not very diagnostic. One of the major differences in the present data and that of previous workers is the proportion of muscovite. The specific gravity of muscovite (2.76-3.0) fluctuates around that of bromoform (2.9) and consequently causes some problem during the separation of heavy minerals. What is more important, however, is that muscovite also has peculiar hydraulic properties, due in the main to its occurrence as thin platy grains. These tend not to settle out in flowing water when other mineral species of the same size and specific gravity would. The consequence of this is that grains of muscovite in a sediment tend to be up to four times larger than the average grain-size of associated minerals. The effect of crystal shape on the settling rate is present in all mineral grains, but of all the heavy minerals this effect is probably at its greatest in

reducing the settling rate with muscovite grains.

Table 13. Heavy mineral assemblage by percent, excluding Muscovite, then, is problematical, and if it was omitted from the heavy mineral data perhaps variations in the assemblages would be enhanced. These revised data are presented in Tables 13-15, but once again the usefulness is restricted.

A further stage of the study was a detailed examination of particular mineral species. Emphasis was on the Lower Greensand and the Upper Greensand.

	Zircon	Kyanite	Rutile	Amphibole	Anatase	Tourmaline	Staurolite	Calcite	Spinel	Sillimanite
<u>Zircon</u>										
Upper Greensand	50	3	1	16	6	12	8	5		/
Beds	55	23	2	2	8	11				
Beds	64	18	2	2	10	3				
Sandgate	61	11	2	2	10	11				
Sandgate	61	11	2	2	10	11				
Beds	61	11	2	2	10	11				

An analysis of the shape of zircon grains (Table 16) did not provide any diagnostic features. Similarly, various other characteristics (Table 17) of zircon grains proved not to be diagnostic. Zoned grains are very infrequent and consequently unreliable. Zircon grains with overgrowths were also very restricted but did appear to be confined to the very fine sand size of the Sandgate and Hythe Beds.

	Zircon	Kyanite	Rutile	Amphibole	Anatase	Tourmaline	Staurolite	Calcite	Spinel	Sillimanite
<u>Amphibole</u>										
Beds	68	4	2	2	6	11	5	2		
Beds	64	3	6	2	3	8	13			
Beds	51	8	2	2	3	18	18			
Atherfield	51	8	2	2	3	18	18			
Clay	36	60				14				

A survey of the type of amphiboles (tremolite, actinolite or hornblende) found in the Hythe, and Bargate Beds and in the Upper Greensand proved unlikely to contribute any diagnostic features. The data concerning the relative abundance of amphibole types in these beds have not been presented as ^{are} they considered extremely unreliable due to the small number of grains involved.

Kyanite, Staurolite, Tourmaline and Anatase

Colour variation of these mineral species occurring in the source rocks did not provide any diagnostic features.

Table 16. Analysis of zircon shape, (by percent).

Formation	Location	Fine Sand		Very Fine Sand	
		Prismatic	Rolled	Prismatic	Rolled
Upper Greensand	River Bed	✓	100	3	97
Felkestone Beds	32, 33 & 34	1	99	5	95
Felkestone Beds	SU806224			7	93
Sandgate Beds	6, 21, 22, 23 & 24	✓	100	4.5	95.5
Sandgate Beds	SU808229			5	95
Bargate Beds	142 & 143	3	97	1	99
Bargate Beds	SU844234	✓	100	6	94
Hythe Beds	1, 100 & 101	1	99	4	96
Hythe Beds	SU801258			4	96

There was no evidence in support of the kyanite of the Folkestone Beds. The Bargate Beds are pale yellowish in colour (Wood, 1956).

Table 17. Analysis of some zircon characteristics, (by percent).

Opaque Minerals with Overgrowths

The occurrence of opaque minerals with overgrowths was examined and the relative abundance of the red-brown overgrowths and zirconless overgrowth did not vary significantly between rock types. Opaques with overgrowths do however appear to be absent from the Folkestone Beds and are most abundant in the Hythe Greensand.

Formation	Location	Fine Sand				Very Fine Sand			
		Zoned	Inclusions	Overgrowth	Pink	Zoned	Inclusions	Overgrowth	Pink
Upper Greensand	River Bed		16			20			
Folkestone Beds	32, 33 & 34		17			✓ 23			
Folkestone Beds	SU806224					34			
Sandgate Beds	6, 21, 22, 23 & 24		22			21	✓		
Sandgate Beds	SU808229					28	✓		
Bargate Beds	142 & 143		21			36			
Bargate Beds	SU844234					41			
Hythe Beds	1, 100 & 101		27			30	✓		
Hythe Beds	SU801 258					29			

The Bargate Beds are characterized by the presence of amphibole and the absence of zircons with overgrowths.

There was no evidence in support of the kyanites of the Folkestone Beds being dominated by more angular reddish-brown grains whereas those of the Hythe and Sandgate Beds are pale yellowish in colour (Wood, 1956).

Opaque Minerals with Overgrowths

The occurrence of opaque minerals with overgrowths was examined more closely. However, the total amount of opaques with overgrowths, and the relative abundance of the red-brown overgrowth to the colourless overgrowth did not vary significantly between rock types. Opaques with overgrowths do however appear to be absent in samples from the Folkestone Beds and are most abundant in the Upper Greensand.

The author is of the opinion that he is able to distinguish between samples from the Lower Greensand members and the Upper Greensand using the characteristics described below.

The Upper Greensand is characterised by a relatively high proportion of opaques with overgrowths, and by a higher proportion of amphibole in the total and fine sand range.

The Folkestone Beds are characterised by a relatively high proportion of kyanite and an absence of amphiboles and opaques with overgrowths.

The Sandgate Beds are characterised by an absence of amphibole, and the presence of zircons with overgrowths, but these appear to be confined to the very fine sand size.

The Bargate Beds are characterised by the presence of amphibole and the absence of zircons with overgrowths.

The Hythe Beds are characterised by the presence of amphiboles and of zircons with overgrowths.

USEFULNESS OF THE DATA AS A PERCENTAGE

Some consideration was given to the method of comparison of the heavy mineral data of source rocks. As the purpose of the study is to determine diagnostic features that can be used as indicators in river sediment the presentation of the data as relative percentages of the total is not very useful. A better comparison would be obtained using the relative proportions that occur in a known volume or weight of source rock, i.e. the relative availability from the source rocks. The advantage of this can be shown theoretically: for example, Kyanite may form 20% of the heavies of the Folkestone Beds and 8% in the Sandgate Beds. But 100 grams of Folkestone Beds may only yield 400 grains of kyanite, while 100 grams of Sandgate Beds may yield 500 grains of kyanite, i.e. the total amount of heavies per unit weight is greater in the Sandgate Beds than in the Folkestone Beds.

For the present problem, the yield of heavy minerals per unit weight, or per unit volume, must be considered when determining the proportions of sediment from each rock type. Comparison of data of source rocks in this way may serve to enhance or perhaps mask the characteristics of the different formations, e.g. samples having the same ratios by number but with different absolute amounts may be differentiated. This method of presentation is similar to the "hydraulic ratio" of Rittenhouse (1943). He defines the hydraulic ratio as "100 times the weight of a heavy mineral in a known range of

sizes, divided by the weight of light minerals of hydraulic equivalent size". That is the percentage by weight of a heavy mineral species to the total weight of light minerals of hydraulic equivalent size. The present method of comparison can be defined as the relative weight of each heavy mineral species in a known weight of the total sample (lights and heavies) of the same grain size.

The present method of comparison involving the ratios of each heavy mineral species in a known weight of total sample was determined:

a) The percentage by weight of heavy minerals to the total grains of the fraction was determined (Table 18, Column 1); e.g. Upper Greensand fine sand has 0.387% heavies to total grains in this size range. These determinations would have high errors that would be reflected in the final data.

b) This was multiplied to give the total weight of heavy minerals in 100,000 grams (Table 18, Column 3); e.g. Upper Greensand fine sand = $0.387 \times 100,000 = 387.0$ g.

c) The percentage of transparent grains to total heavies was determined (Table 18, Column 2); e.g. Upper Greensand fine sand, transparent grains for 41.4% of total heavies.

d) Using this percentage it is possible to determine the weight of total transparent heavy minerals in 100,000 grams of total sample (Table 18, Column 4); e.g. Upper Greensand fine sand, = $387 \times 41.4 = 160.2$ g. of transparent heavies

100

e) The percentage figures of relative abundance of heavy minerals in the Tables 14 and 15 were taken and used to determine the weight of

each transparent heavy mineral species in the total transparent heavy mineral fraction. The data are presented up to four decimal places; their accuracy beyond two places in column 1, and beyond one place in columns 2, 3, and 4 is dubious.

		Percentage heavies of fraction	Percentage non- opaque to total	Weight total heavy minerals in 100,000g	Weight non-opaques in 100,000g
		1	2	3	4
Upper Greensand	Fine Sand	0.3875	41.3793	387.5	160.34
Upper Greensand	Very Fine	0.3365	54.5171	336.3	183.34
Folkestone Beds	Fine Sand	0.0746	26.5927	74.6	19.83
Folkestone Beds	Very Fine	0.3683	28.1062	368.3	103.51
Sandgate Beds	Fine Sand	0.1851	31.5220	185.1	58.34
Sandgate Beds	Very Fine	1.3358	33.1613	1335.8	442.96
Bargate Beds	Fine Sand	0.0909	35.8841	90.9	32.61
Bargate Beds	Very Fine	0.3624	42.9276	362.4	155.56
Hythe Beds	Fine Sand	0.2353	26.0538	235.3	61.30
Hythe Beds	Very Fine	1.6761	41.0110	1676.1	687.38

It seemed unlikely that, without a detailed study of individual mineral species, the abundance of the various minerals for a successful estimate of the total heavy mineral content of the useful minerals from very low percentages of the total minerals.

each transparent heavy mineral species in the total transparent heavy mineral weight.

This last stage (stage e) however, assumes that the specific gravity of each heavy mineral species is the same. This obviously is not so (Table 23) and the specific gravity of the grains vary from 2.93-3.20 for tourmaline to 4.5-4.7 for zircon. It was decided that for a preliminary treatment of the data the error involved would be insignificant if the resulting data showed sufficient variation between different source rocks. If necessary a specific gravity correction could be applied. The specific gravity correction assumes that all the heavy minerals involved have equal volumes. This has been discussed at length by Rittenhouse (1943) who explains a compensating effect caused by variation in mineral shape, which counteracts the effect of variation in specific gravity.

Table 19 represents the weight of each mineral species in grams in 100,000 grams of the same size fraction of source rocks. These values have been obtained by taking a mean value of the percentages of the various transparent grains to the total transparent minerals (Table 14-15) eg. if in the Folkestone Beds very fine sand size range one sample had a kyanite percentage of 12% and another sample had 16%, then the mean value used would be 14%. The data for each rock type in Table 19 is a measure of the relative availability of heavy minerals from the source rocks within the two size grades involved.

It seemed unlikely that, despite a detailed study of individual mineral species, the assemblages are sufficiently variable for a successful outcome of the study, partly because some of the useful minerals form very low percentages of the total minerals.

Table 19. Weight of heavy mineral species in 100,000g. of sample of the same grade size. Figures in grams.

Formation	Mesh	Zircon	Kyanite	Rutile	Amphibole	Anatase	Tourmaline	Staurolite	Garnet	Spinel	Sillimanite
Upper Greensand	60-120	38	19	8	20	27	24	24	1		
Folkestone Beds	60-120	4	6	✓		2	5	3	✓		
Sandgate Beds	60-120	13	8	1		7	19	10	✓		
Bargate Beds	60-120	13	1	✓	✓	3	9	3	✓	✓	
Hythe Beds	60-120	23	7	2	1	4	12	12	✓		
Upper Greensand	120-300	149	2	1	2	7	13	6	4		
Folkestone Beds	120-300	56	14	3		7	16	8	1	✓	
Sandgate Beds	120-300	341	20	5		21	33	20	2		✓
Bargate Beds	120-300	109	4	1	2	6	18	12	2	✓	
Hythe Beds	120-300	543	31	17	6	29	27	32	1		

1973), the more important of which can be found in Russell (1937).

However, some analysis of sand-sized river bed sediment was undertaken.

The important factors are threefold:

1. Those due to abrasion and weathering. This is of limited extent.

COLLECTION OF SAMPLES FROM THE RIVER BED AND LABORATORY TREATMENT

2. Those due to the sorting action of the river. This sorting

Samples of the river bed material were collected from a number of localities with a form of scoop sample, and occasionally with a Peterson grab in deeper water. The scoop samples were taken across the entire width of the channel and care was taken to keep the loss of fines to a minimum. Samples taken with the Peterson grab were also to be representative of the entire channel width and so several spot samples were taken in a traverse and these were compiled into a single compound sample. The location of samples from the stream bed (Fig.2) can, in the main, be defined as a point just upstream of the intersection of the stream course with a geological boundary, or just above the confluence of two streams (sampling both streams) and below the confluence with sufficient distance downstream for mixing of the two sediments supplied by the streams to occur.

The samples were boiled in hydrochloric acid and the heavies were separated in bromoform as before. Mounting and the method of counting were also as for the source rocks. The size ranges separated comprised of either the total size range, or the very fine sand and the fine sand size range.

FACTORS AFFECTING HEAVY MINERAL OCCURRENCE IN STREAMS

Much discussion has been given to the factors affecting the distribution and occurrence of heavy minerals (e.g. Swift and others, 1971), the more important of which can be found in Russell (1937),

Rittenhouse (1943) and Van Andel (1950).

The important factors are threefold:

1. Those due to abrasion and weathering. This is of limited extent.
2. Those due to the sorting action of the river. This sorting

can be on the basis of specific gravity, basis of grain shape,

or basis of grain size. Also important is the relationship

of a grain with the surrounding grains, and size of these grains. The results of the heavy mineral analysis of the river bed sediment samples whose locations are given in Fig. 2 are presented in Table 20-32. For example, generally a heavy mineral of a certain size will settle out with light grains of a larger size. Consequently, the heavy grain will be

surrounded by grains of a larger size. This factor is

important for renewed pick-up and movement of that grain, because

because

a) there is a greater chance for the smaller heavy grain to

become "trapped" between the larger light grains;

b) the surface area for the forces of bed load movement to act upon is smaller for a heavy grain than it is for a light grain of the same weight.

3. The relative availability of mineral grains from each of the

source rocks. Here, heavy mineral variation with grain size

within the source rocks is also important.

It is not necessary to elaborate further on these factors at

present, although some further discussion occurs below.

be reasonable to expect that the heavy mineral assemblage of the

river bed sediment and the Nye beds should be comparable.

RESULTS OF THE HEAVY MINERAL ANALYSIS OF RIVER SEDIMENT

The comparison of the heavy mineral assemblage of the Nye beds

A full description of the heavy minerals is not necessary as the

variety and characteristics are essentially the same as the source rocks. Noteworthy, however, is the reduction in the occurrence of the fragile frayed ends of some grains such as kyanite and amphibole. This reduction is presumably the result of erosional processes breaking and rounding off these fragile projections.

The results of the heavy mineral analysis of the river bed sediment samples whose locations are given in Fig.2 are presented in Tables 20-22. Muscovite was omitted from the analysis for reasons explained earlier. These data are presented in the form of percentages of the total transparent heavy minerals. It is not necessary for the data of the river bed samples to be presented as weight per unit weight unless quantitative evaluations are to be made.

When considering the importance of the various source rocks for the heavy minerals of the river sediment, the assemblage of the Bargate Beds may be omitted from consideration for the samples upstream of, and including, river bed samples 71 and 72. This is because the Bargate Beds are absent from the drainage basin at, and upstream of, this location.

57 83 3

INTERPRETATION OF RESULTS

Samples 50, 51 and 32. These samples were collected from a stream bed which only drains from the Hythe Beds, and consequently it would be reasonable to expect that the heavy mineral assemblages of the river bed sediment and the Hythe Beds should be comparable.

The comparison of the heavy mineral assemblage of the fine sand

Table 20. Heavy mineral analysis by percent of river bed samples - mesh 60-120.
River bed samples - total size range.

Sample	Zircon	Kyanite	Rutile	Amphibole	Anatase	Tourmaline	Staurolite	Garnet	Spinel	Sillimanite
38	82	✓	✓	✓	1	5	2	10		
34	64	12	1	✓	3	12	8	✓		
35	75	5	1	✓	3	9	3	3		
32	85	3	3		2	2	5		✓	
36	91	3	1	✓	1	2	2	✓	✓	
33	77	8	1	✓	2	5	6	1		
39	71	10	1		4	8	4	1	✓	
37	82	3		✓	2	6	3	5		
54	73	8	1	✓	2	11	4	2		
	77	50	15	✓	✓	2	20	12		

Aug. '71

Dec. '71

Aug. '72

Table 21. Heavy mineral analysis by percent of river bed samples - mesh 120-300.

Table 21. Heavy mineral analysis by percent of river bed samples - mesh 60-120.

Sample	Zircon	Kyanite	Rutile	Amphibole	Anatase	Tourmaline	Staurolite	Garnet	Spinel	Sillimanite	Date of collection
50	75	3	6		2	4	9	1			
52	52	13	2	✓	2	10	19	2			
48	24	29	1	✓	4	19	22	1			
62	24	12	5	13	17	15	15	✓			
72	66	12	1		2	6	13	✓			
69	34	11	1		3	36	15				
74	30	16	1	1	4	27	20	1			
65	61	10	✓	✓	3	14	10	1			Aug. '71
75	65	10	1		1	11	9	2			Dec. '71
77	50	15	✓	✓	2	20	12				Aug. '72
66	74	5	1	✓	2	10	5	1	✓		Aug. '71
76	70	6	1	✓	1	13	8	✓			Dec. '71
78	72	5	✓	✓	4	13	6	✓			Aug. '72

Table 22. Heavy mineral analysis by percent of river size grade of the river sediment (Table 21, sample 50) with the same bed samples - mesh 120-300.

size grade of the river sediment (Table 21, sample 50) with the same bed samples - mesh 120-300. The river bed sample has a larger proportion of zircon and a lower proportion of kyanite, tourmaline and staurolite.

The heavy mineral assemblage of the very fine sand size grade (Table 22, sample 51) when compared with the mean values of the same size grade of the Hythe beds (mean of two values, Table 14) shows an increased proportion of zircon and staurolite, and a decreased proportion of kyanite and tourmaline.

The heavy mineral assemblage of the total size range of the river bed (Table 23, sample 5) when compared with the similar size range of the Hythe beds (mean values of the two samples, Table 13) again shows an increase in zircon and staurolite, and a decrease in kyanite and tourmaline.

Sample	Zircon	Kyanite	Rutile	Amphibole	Anatase	Tourmaline	Staurolite	Garnet	Spinel	Sillimanite	Date of collection
51	83	2	4	✓	1	2	8	✓			
53	85	3	1	✓	2	5	3	1			
49	76	6	1		5	7	3	2			
61	82	1	✓	2	3	7	3	2			
71	86	3	1		1	5	4	✓			
70	66	2	2	1	2	17	9	✓			
73	71	6	1	✓	1	12	8	✓			
66	74	5	1	✓	2	10	6	1	✓		Aug. '71
76	70	6	1	✓	1	13	8	✓			Dec. '71
78	72	5	✓	✓	4	13	6	✓			Aug. '72

(Table 21) is considered it because obvious that the three heavy mineral assemblages from the river bed show a relative increase of the

size grade of the river sediment (Table 21, sample 50) with the same size grade of the Hythe Beds (mean of the two values in Table 15) shows some similarity, but it is not good. The river bed sample has a larger proportion of zircon and a lower proportion of kyanite, tourmaline and staurolite.

The heavy mineral assemblage of the very fine sand size grade (Table 22, sample 51) when compared with the mean values of the same size grade of the Hythe Beds (mean of two values, Table 14) shows an increased proportion of zircon and staurolite, and a decrease in kyanite and tourmaline. However, the percentage differences used here are becoming low so that the variation is possibly within the limits of the accuracy of counting.

The mineral assemblage of the total size range of the river bed sample (Table 20, sample 32) when compared with the similar size range of the Hythe Beds (mean values of the two samples, Table 13) again shows a relative increase in zircon and a decrease in staurolite, kyanite and tourmaline.

All these variations observed could be partly accounted for by inaccuracies of sampling and counting, or by the data for the Hythe Beds recorded in Tables 13, 14 and 15 not being representative of the Hythe Beds in the locality in question. However, it is unlikely that all of this variation is due to these causes. It is also unlikely that the change is due to the action of weathering and erosion. When the specific gravity of each of these four minerals (Table 23) is considered it becomes obvious that the three heavy mineral assemblages from the river bed show a relative increase of the

Table 23. Specific gravity of selected heavy minerals .
 when compared with the Hyla Beds (Table 24 shows the percentage of
 the original amount of each mineral). In other words, there is a
 strong indication that sorting on the basis of specific gravity is
 occurring.

Zircon	4.5 - 4.7
Rutile	4.18 - 4.25
Anatase	3.82 - 3.95
Staurolite	3.65 - 3.77
Kyanite	3.61 - 3.68
Spinel	3.6
Garnet	3.4 - 4.3
Amphibole	3.0 - 3.3
Tourmaline	2.98 - 3.2
Muscovite	2.76 - 3.0
Bromoform	2.88 - 2.91
Quartz	2.66

It could be argued that the sorting effect is not one on a specific gravity basis but on another basis and that the mineralogy has changed from that of the source rocks because the grains of the mineral species that show a decrease have not reached the sample location yet. This is obviously unlikely on two accounts:

1. The limited length of channel upstream of the sample location is indicative that it is more likely that the change is the result of selective removal rather than selective introduction.
2. The only other reasonable sorting feature is on a basis of shape and this is unlikely to account for smooth grains, which

Table 24. Percentage of original content of selected minerals from river bed sample compared with mean original percentage in the Hythe Beds source rock.

heavier heavy minerals and a decrease of the lighter heavy minerals when compared with the Hythe Beds (Table 24 shows the percentage of the original amount of each mineral). In other words, there is a strong indication that sorting on the basis of specific gravity is occurring.

Even if the accuracy of the data is poor, this sorting on the basis of specific gravity must occur. Some change may also be occurring as a result of sorting by shape; this may be adverse, or complementary, to the sorting by specific gravity. Sorting on the basis of specific gravity is perhaps emphasized in the present samples because, due to their location, they have a very limited upstream stretch of channel. Consequently, the sample location will not be receiving as great a proportion of the lighter heavies being washed in from more upstream areas to replace those being removed, as would a location more downstream.

It could be argued that the sorting effect is not one on a specific gravity basis but on another basis and that the mineralogy has changed from that of the source rocks because the grains of the mineral species that show a decrease have not reached the sample location yet. This is obviously unlikely on two accounts:

1. The limited length of channel upstream of the sample location is indicative that it is more likely that the change is the result of selective removal rather than selective introduction.
2. The only other reasonable sorting feature is on a basis of shape and this is unlikely to account for zircon grains, which

Table 24. Percentage of original content of selected minerals from river bed sample compared with mean original percentage in the Hythe Beds source rock.

Total Size			Fine Sand			Very Fine			
% Hythe Beds	Sample %	Original content %	% Hythe Beds	Sample %	Original content %	% Hythe Beds	Sample %	original content %	
57.5	85	148	36.5	75	205	79	83	105	Zircon
15.5	5	32	20	9	45	4.5	8	178	Staurelite
5.5	3	55	12	3	25	4.5	2	44	Kyanite
13.0	2	15	19.5	4	21	4	2	50	Tourmaline

Table 25. Percentage of original content of selected minerals from river bed sample compared with mean original percentage in the Gault and Felkestone Beds source rock.

Total Size Range			Total Size Range			
Felkestone Beds	Sample %	Original content %	Gault Beds	Sample %	Original content %	
59.5	71	119	58	82	141	Zircon
7	4	57	8	2	25	Staurelite
20.5	10	49	5	trace	trace	Kyanite
9	8	89	19	5	26	Tourmaline

removed are generally more rounded and more spherical, to be selectively introduced at the expense of grains such as staurolite, kyanite and tourmaline. If anything, it is more likely that sorting on the basis of shape will act conversely and, like sorting on a basis of specific gravity, is more likely to cause an increase in zircon by selective removal of staurolite, kyanite and tourmaline. Lighter heavy minerals.

This sorting of heavy minerals of the same size range on the basis of specific gravity and possibly shape brings up two major points:

1. Are the 3 river bed samples taken from streams draining only the Upper Greensand representative for the heavy mineral assemblage of the Upper Greensand?
2. Is the hydraulic ratio method (Rittenhouse, 1943) of comparing heavy mineral assemblages valid?

The samples (50, 51 and 32) from the river bed indicate a certain percentage or amount of tourmaline. However, the percentage of tourmaline in the source rocks, and hence the percentage originally available for transport was greater. Consequently, more tourmaline has been removed from the location than would have been determined from these samples using the hydraulic ratio simply because there is less tourmaline in the bed material than in the source rock. In other words, the samples are indicative of what is left, not of what has been removed. Now if a tourmaline rich deposit occurred downstream, determination of its source using the hydraulic ratio method would be difficult.

It could be argued that these lighter heavy minerals may be

removed completely from the river system and consequently do not occur in a more downstream sample. However, this is unlikely, as the hydraulic properties of a stream (mainly the turbulence and velocity) will vary with changes in channel profile and size. For example, a quieter stretch of water on the same source rocks and downstream of the location of samples 32, 50 and 51 may have a mineral assemblage with a greater proportion of the lighter heavy minerals. Conversely, a stretch with greater velocities may have even less of the lighter heavy minerals.

The sample taken from a river bed can only be considered representative for determination of the heavy minerals supplied by the stream at this location if it is known that:

- a) the relative proportion and amounts of the minerals in the sediment arriving at the sample location are the same as that leaving it, and
- b) that there is interchange and replacement of mobile grains with resting grains on the bed at the sampling location.

These conditions apply also, in essence, to a study of grain size supplied by rivers. For example, determining the grain size of a river bed sample, and then stating that this is the range and proportion of sizes that are supplied by the river bed, is generally erroneous. It is folly to consider that, after observing a lag cobble deposit in a relatively narrow channel, it can be used to determine the range and proportion of sizes moved as bed load over this stretch without considering material entering the stretch under consideration. It could perhaps be argued that most material finer

than the lag cobbles would be transported as suspended material over this stretch which indeed they might. However, the principle still holds, and the hydraulic properties of the sample location are important considerations. The lag deposit is primarily the result of sorting on the basis of size (minor effects being specific gravity and shape) but the mineral assemblage within any size range is the result of sorting by specific gravity and shape.

The computation of the mineralogy of the sediment that has been removed, by considering the assemblages in the source rocks, and of the remaining bed sediment is not straightforward. However, the mineralogy of the sediment being removed could be determined by taking a sample of the moving sediment during the passage of a storm hydrograph. This, however, involves all the well known problems of successfully sampling mobile sediment on the stream bed. Sampling this moving sediment for the purpose of mineral determination however is perhaps not as problematical as sampling for the estimation of the total amount of bed load sediment discharge. For the latter no sediment should be lost, but for the former it is only the ratio of the relative minerals that is needed and so only a representative sample is required. However, any method of sampling moving sediment on the river bed is going to upset the flow field, generally by reducing the velocity, and this in itself may affect the representative nature of the sample. It is unlikely that grains of different specific gravity will be equally affected by this change in the flow field and the resulting sample will be non-representative for the determination of the heavy mineral assemblage. *(see assemblage of the sample (Table 20))*

Sample 39. This sample was collected from the bed of a stream that drains only from the Folkestone Beds, consequently it would be expected that the sediment is derived from the Folkestone Beds. Comparison of the heavy mineral data of this sample (Table 20) with those of the Folkestone Beds (Table 13) shows similar changes to those exhibited by samples 50, 51 and 32. The percentage of zircon has increased from a mean value of 59.5% to a value of 71%, while staurolite, kyanite, and tourmaline has decreased (staurolite from 7% to 4%, kyanite from 20.5% to 10%, and tourmaline from 9% to 8%). The percentage for each mineral of the original amounts in the source rocks are given in Table 25.

As the total size range of heavy minerals is being considered all or part of this change from the original source rock may be the result of a change in the grain size distribution of the river bed sample. However, comparison of the mechanical size analyses of the river bed sample and the Folkestone Beds indicated that the river bed material was generally coarser than the Folkestone Beds. So, as an increase in zircon would be explained by an increased proportion of the finer size ranges it is unlikely that the change in percentages between the river bed sample and the Folkestone Beds is due to a change in the grain size distribution.

Sample 38. This sample was collected from the bed of a stream that drains only from the Gault and so it is reasonable to assume that most of its sediment is derived from the Gault.

Comparison of the heavy mineral assemblage of the sample (Table 20)

with that of the Gault Clay (Table 13) again shows some indication of a change in the relative proportions of the heavy minerals. The river sample shows an increase in zircon of 24%, and a decrease in kyanite of about 5%, in staurolite of 6% and in tourmaline of 14%. Table 25 gives these changes as a percentage of the original percentage within the Gault.

Some of this variation could again be partly explained by a change in the grain size of the river sediment. However, the assemblage as determined for the Gault and for sample 33 was restricted to material larger than 300 mesh. So once again very little of the increased zircon content can be explained by an increased proportion of finer grades. Indeed, again the river bed sample was coarser than the source rock sample.

Again there appears to be a real change due to the sorting effect based on specific gravity, perhaps with a minor effect from sorting on the basis of shape. The kyanite content of 12% is probably Samples 61 and 62. These samples were taken from the bed of a stream which drains only from the Upper Greensand and so the sediment is derived only from the Upper Greensand. However, the data for the Upper Greensand as a source rock on Tables 14 and 15 were determined from the same samples as explained earlier. But as it has been shown that some variation from the original mineral assemblage of the source rocks occurs, the value of the data from the Upper Greensand as a source rock is limited.

These samples from the river bed, however, do show an increase in

the zircon content in comparison to the Upper Greensand as determined in the total size range (Table 13).

There is also a reduction in tourmaline and staurolite, although the Sample 36. This sample is taken from the river bed of a stream that drains only from the Hythe Beds and Sandgate Beds. Once again the zircon content (91%) of the total size range is greater than either of the zircon contents of the Hythe Beds (mean value of 57.5%) or Sandgate Beds (mean value of 70%). There is also an associated smaller proportion of kyanite, staurolite and tourmaline than in the two source rocks. This sample was collected from a stream draining similar

A comparison of the grain size of sample 36 with that of the two source rocks again showed that there was an indication of coarser material in the river bed sample. content and like sample 37 has a

kyanite and staurolite content similar to that of the Folkestone Sample 34. This sample is taken from the bed of a stream that drains only the Gault and the Folkestone Beds. The zircon content of this sample gives an indication of being greater than both that of the Gault and the Folkestone Beds. The kyanite content of 12% is probably indicative that at least some of the sediment of the sample is derived from the Folkestone Beds (kyanite content of 20.5%). Originally it may have been considered that the dilution of kyanite from 20.5% in the Folkestone Beds to 12% in the river sample was due to mixing with relatively kyanite poor sediment derived from the Gault. However, it is likely that some of the reduction in kyanite is due to the sorting effect of the stream.

Sample 37. This sample is from the bed of a stream draining Upper grain

Greensand, Gault, and Folkestone Beds. Again there is a higher zircon content in the sediment than in any of the source rocks. There is also a reduction in tourmaline and staurolite, although the percentage of these two minerals is close to that of the Folkestone Beds. However, the value of kyanite from the stream bed is contrary to this and is in more agreement with the values for the Gault and Upper Greensand. There is also a garnet content of 5% in the river bed sample and the Upper Greensand. (Table 21) has a heavy mineral assemblage almost identical with that of the Folkestone Beds Sample 35. This sample was collected from a stream draining similar formations as the stream of sample 37, but it also drains for a very short distance of the Lower Chalk.

The sample has a high zircon content and like sample 37 has a tourmaline and staurolite content similar to that of the Folkestone Beds. The kyanite content again resembles that of the Upper Greensand and Gault (i.e. a lower kyanite content than for the Folkestone Beds).

Both samples 35 and 37 were collected where the stream flows over the Folkestone Beds, and as this formation is possibly the most readily available source of sand (due to its grain size and less indurated nature) of all the formations drained by the streams in question, it is possible that a high proportion of the sediment is derived from the Folkestone Beds. If this is so, does the reduced kyanite content indicate that these grains are more readily removed than tourmaline and staurolite? If so, this may be indicative of sorting on the basis of shape.

The reduction in kyanite is not explained by a change in the grain

size distribution as, although a total size range is being considered, kyanite is more common in the larger grain size, and so should form a higher percentage in the coarser river sediment.

content of source rocks cause some problem in this estimation.

Samples 48 and 49. These samples, like sample 37, were collected from a stream draining only the Upper Greensand, Gault and Folkestone Beds.

decrease in kyanite.

The fine sand size range (sample 48, Table 21) has a heavy mineral assemblage almost identical with that of the Folkestone Beds fine sand (Table 14). The very fine sand size range (sample 49, Table 22) however does not resemble that of the Folkestone very fine sand size range (Table 15).

Samples 33, 52 and 53. These samples were collected from a river bed which drains the Chalk, Upper Greensand, Gault, Folkestone Beds, Sandgate Beds and Hythe Beds.

The zircon content of the total size range (sample 33, Table 20) is greater than that of the total size range of all the source rocks, with possibly the exception of the Sandgate Beds. Even here, the zircon content of the stream sample is greater than the mean value for zircon of the Sandgate Beds (Table 13). The increased zircon is again not explained by an increased proportion of the very fine sand size range as the sediment is generally coarser than the source rocks. variable (Table 14) and a comparison of mean values with the river bed

The fine sand (sample 52, Table 21) again has a much higher zircon content than any of the source rocks drained by the stream.

There is also an increase in the proportion of the next heaviest

Discussion regarding the cause of a decrease in zircon occurs later. would assume that the sediment derived from the river bed of the

heavy mineral - staurolite. A decrease occurs in the proportion of kyanite and tourmaline and this decrease is probably greater for the tourmaline than for kyanite, but the variability of the original content of source rocks causes some problem in this estimation.

The very fine sand sample (sample 53, Table 22) ^{has} also an increase in zircon, a decrease in tourmaline and staurolite, and a possible decrease in kyanite. There is also a decrease in staurolite and

perhaps kyanite.

Samples 69 and 70. These samples were collected from the bed of the Hammer Stream, which drains from the Weald Clay areas of the catchment and over the Hythe Beds and some very restricted areas of Bargate Beds. It also collects water issuing from springs and seepages above the Atherfield Clay.

The very fine sand sample (sample 70, Table 22) contrary to all other samples so far mentioned, shows a decrease in the zircon content from that of the source rocks. There is also an increase in the tourmaline content and a possible increase in the staurolite content. The sample location is sufficiently downstream of the Hammer tributary

The fine sand sample (sample 69, Table 21) has a zircon content of 34% and this is probably a decrease when compared with the zircon

content of the Hythe Beds and Bargate Beds, which would be the main

sources of this sized sediment to this location. However, the zircon content of the Bargate and Hythe Beds fine sand size range appears to be

variable (Table 14) and a comparison of mean values with the river bed

samples involves values that are becoming close to the limit of accuracy of the method involved.

Discussion regarding the cause of a decrease in zircon occurs later.

would assume that the sediment sampled from the river bed of the main

Samples 71 and 72. This sample was collected from the bed of the main stream just above the Hammer tributary and so it drains over all the source rocks of the catchment except the Weald Clay, Atherfield Clay and the Bargate Beds.

The fine sand size sample (sample 72, Table 21) has a much greater zircon content than any of the source rocks (Table 14) and a definite decrease in tourmaline. There is also a decrease in staurolite and perhaps kyanite.

The very fine sand sample (sample 71, Table 22) again has an increased zircon content over that of the source rocks (Table 15).

This is accompanied by a decrease in tourmaline and staurolite, and perhaps kyanite.

Samples 73 and 74. The upstream network of the location of this sample includes the Hammer tributary and consequently potential sources of sediment include all of the rock types within the study catchment.

The sample location is sufficiently downstream of the Hammer tributary for complete mixing of sediment supplied by this stream with the sediment of the main-stream to occur.

Both samples 73 and 74 have a mineral assemblage that is not sufficiently different from that of the source rocks to warrant any further description.

These assemblages would probably be explained by a mixing of zircon rich sediment from the main stream (sample 71 and 72) with zircon poor sediment from the Hammer catchment (samples 69 and 70). This however would assume that the sediment sampled from the river bed of the main

stream (samples 71 and 72) and from the river bed of the Hammer stream (samples 69 and 70) was representative of what was being removed from them. This is possible if the sample locations are sufficiently downstream for the sorting by specific gravity to become less pronounced.

There is generally a related decrease in zircon content in Samples 54, 65, 75, 76, 77, and 78. These samples were taken from the bed of the main stream near to the downstream limit of the study catchment. There is little change if any between the total size range mineral assemblage of sample 54 (Table 20) and that of the source rocks (Table 13).

Samples 66, 76 and 78 (Table 22) are of the very fine sand size range, and these, taken at different times, show very little indication of a change in the mineral assemblage with the period of time covered by the samples. Any variation is within the limits of accuracy of the method. These assemblages also are very similar to the assemblages of the source rocks (Table 15).

Samples 65, 75 and 77 (Table 21) also give little indication of any variation through time in the mineralogy of the fine sand size range. The zircon content of these assemblages is perhaps a little above the general zircon content of the source rocks (Table 14). There is possibly a related decrease in the kyanite, staurolite and tourmaline levels, but again this is difficult to ascertain due to the variability in content within the different source rocks.

the basis of specific gravity, with a possible complementary effect of sorting on the basis of shape. The heaviest heavy minerals (zircon,

DISCUSSION

The river bed samples, the fine sand, very fine sand, and total size ranges, when compared with the mineral assemblages of the source rocks may be divided into three categories:

1. Those samples with a greater proportion of zircon than the source rocks. There is generally a related decrease in kyanite, staurolite and tourmaline. In some samples (51 and 52) there is a slight increase in the proportion of staurolite as well as zircon.
2. Those samples with a smaller proportion of zircon than the source rocks (samples 69 and 70). This is accompanied by an increase in the proportion of kyanite, staurolite and tourmaline.
3. Those samples (73, 74, 54, 65, 66, 75, 76, 77, and 78) that have a mineral assemblage in proportions similar to the general proportions of the assemblages of the source rocks.

Category 1. Much discussion regarding the formation of the first type of assemblage has been set out previously. The discussion has been confined to these four minerals (zircon, staurolite, tourmaline and kyanite) because these occur in sufficient quantity for the data to be reasonably accurate. Grain size variation, sampling and counting errors, and weathering and erosion do not suitably explain the increased zircon content. It appears that the mineral assemblage is the result of selective removal of the grains of some mineral species on the basis of specific gravity, with a possible complementary effect of sorting on the basis of shape. The heaviest heavy minerals (zircon,

geological formation B. Each of these formations has a hypothetical or sircon and staurolite) increase in percentage while the lighter (not distinguishable heavy mineral assemblage, and as formation A is heavy minerals (tourmaline, kyanite and staurolite, or tourmaline and kyanite) decrease in percentage. It has been suggested that the heavy minerals derived from formation A. Upstream of this position effects of the sorting on this basis becomes less obvious downstream, however sorting of the minerals from A will have occurred and it is but is in fact present.

It is likely that the assemblage as it passes into formation B will be stable in quality and quantity through time, if the upstream distance material is confined to periods of high flow, i.e. during the passage of a storm hydrograph. This would be the period of time during which formation B will be influenced by the sorting also, but the effects of this sorting occurs. In the channel reach above the location of the sorting in the channel at this point (just downstream of the samples 50, 51 and 32, sediment would be introduced into the channel by run-off processes. Indeed, there may be selective sorting processes occurring on the sediment derived from the Hythe Beds during these run-off processes prior to sediment even reaching the river channel.

Once in the channel however the sediment will be sorted by the flow, and with all other things being equal, the heavier heavy minerals will be transported at a slower rate than the lighter heavy minerals. Now, as bed load movement occurs at a much slower rate than the velocity of the water, it is unlikely that even the more readily transported grains of the bed load will be removed completely from the river system during the passage of the storm hydrograph. This results in an upstream concentration of the heavier heavy minerals and a downstream concentration of lighter heavy minerals. However, as run-off processes introduce sediment all along the length of a stream the situation is more complex and will probably become obscured more depend on the mineral assemblage of the sediment supplied to the

lakes. Now, if the selective processes described had been occurring,

Consider the passage of a channel from geological formation A to

geological formation B. Each of these formations has a hypothetical upstream of the lake, than the sediment supplied to it would probably be richer in the lighter heavy minerals than the sediment on the upstream of formation B, the channel as it passes onto B will have heavy minerals derived from formation A. Upstream of this position in the lake, deposition of sediment particles of the same size would however sorting of the minerals from A will have occurred and it is more likely that the assemblage as it passes onto formation B will be stable in quality and quantity through time, if the upstream distance is sufficiently lengthy. Now, material entering the channel from

In the presence or absence of a lake, the mineralogy of the formation B will be influenced by the sorting also, but the effects of sediment leaving the catchment as a whole probably have a richer the sorting in the channel at this point (just downstream of the intersection of the channel with the boundary between formations A and the source rocks. This is indicated also by the lack of these minerals B) may be more easily seen on the assemblage from formation B, than in the smaller streams and tributaries upstream, from formation A.

The question of the fate of the lighter heavy grains is ultimately a question of time. On the long term the majority of grains will be removed from the catchment, but on the short term many of the grains will be retained in the catchment. It is likely that the stream gradient and average velocity decreases downstream and consequently some deposition (as a temporary store) will occur within the channel in quiet areas of low velocities, e.g. inside bends, wider channel areas, ponds, etc. Obviously, such deposition will also be influenced by the sorting on the basis of specific gravity and shape. But, assuming that all the sand size sediment is deposited, for example in a lake, the mineral assemblage of that deposit would depend on the mineral assemblage of the sediment supplied to the lake. Now, if the selective processes described had been occurring sorting would not cause a reduction in the percentage of zircon.

upstream of the lake, then the sediment supplied to it would probably be richer in the lighter heavy minerals than the sediment on the river bed upstream. Now, if only part of the sediment was deposited in the lake, deposition of sediment particles of the same size would be influenced by specific gravity and shape. Would this mean that sediment being washed through the lake would be rich in the lighter heavy minerals?

In the presence or absence of a lake, the mineralogy of the sediment leaving the catchment as a whole probably ^{would} have a richer proportion of the lighter heavy minerals than would be indicated by the source rocks. This is indicated also by the lack of these minerals in the smaller streams and tributaries upstream.

Category 2. Samples 69 and 70 are those samples that are deficient in zircon. Their location is the Hammer Stream downstream of the Hammer Pond. Explanations of why there is a relatively low zircon content could perhaps be limited to the following:

- A. The sediment is carried through the Hammer Pond and the mineral assemblage is the result of sorting as described above.
- B. The hydrological regime of the Hammer sub-catchment differs from that of the main stream. It has a more flashy character with more rapid run-off and storm events of less duration. Now, as it is during the storm event that bed load transport and sorting occurs, a more limited duration may result in poorer sorting. If this is the real cause then the actual reduction in the zircon content may be the result of inaccuracies of the method, as poorer sorting would not cause a reduction in the percentage of zircon.

C. The sample location is at the downstream end of what is probably the largest inter-confluence reach of river in the study catchment. Consequently the masking of the effects of sorting along the channel by mineral assemblage being introduced by tributaries etc. will be at a minimum. The assemblage observed in the samples 69 and 70 then may be the result of material being supplied to the location being rich in these minerals due to selective transport.

D. The zircon is preferentially removed from the sample location by some unknown process. study catchment is needed to complete the story. There is no evidence as to which, if any, of these factors is more important. A, B and C may all be occurring as complementary processes. More work would probably enlighten the problem. It is improbable that D is occurring, and no reasonable process known to the author would easily account for a preferential removal of zircon.

inherited from underlying deposits and may not be due to sorting.
Category 3. The samples downstream of the junction of the Hammer also, slower rates of movement for grains of greater specific gravity tributary with the main stream are those that have a mineral assemblage have been reported (Rathbun and others, 1971). that is within reasonable agreement of that of the source rocks.

These assemblages could be accounted for by the following:

- CONCLUSIONS**
- A. There is no sorting on the basis of specific gravity or shape and the results of the heavy mineral analysis of the sand sized the assemblage is similar to that of sediment introduced into the material of river bed sediment, and of source rocks have led to the river.
 - B. There is sorting on the basis of specific gravity or shape, but it is very small and/or masked by the introduction of sediment from sufficiently variable for samples from the Rythe Beds, Barygate tributaries and the length of the upstream river network.
 - C. It is a result of mixing of zircon rich sediment from the mainstream distinguished from each other by a detailed study of their mineralogy.

with zircon poor sediment from the Hammer tributary.

- D. This stretch of river could possibly be a transition zone between upstream areas of zircon rich sediment, and more downstream areas of zircon poor sediment. With the present river however, if such a zircon poor sediment occurs it is possibly within the Arun estuary: the "ultimate" depositional area.

The author is of the opinion that factors B, C and D are all contributing and complementary, and further study with more samples from outside the present study catchment is needed to complete the story.

4. It is tentatively suggested that sorting on the basis of similar down current heavy mineral variations have been reported from Ceder Spit on Lake Eire (Pettijohn and Ridge, 1933) and from the coast between Cape Hatteras and Cape Henry (Swift and others, 1971). However, the mineral distribution in the latter area may possibly be inherited from underlying deposits and may not be due to sorting. Also, slower rates of movement for grains of greater specific gravity have been reported (Rathbun and others, 1971).

Zone A. An upstream zone that has a relatively greater proportion of the heavier heavy minerals than zone B.
Zone B. A downstream zone that has a relatively greater proportion of the lighter heavy minerals than zone A.
Zone C. A transitional zone between A and B that has a reasonable proportion of the heavier and lighter heavy minerals.

CONCLUSION

The results of the heavy mineral analysis of the sand sized material of river bed sediment, and of source rocks have led to the following conclusions:

1. The heavy mineral assemblages of the source rocks are not sufficiently variable for samples from the Hythe Beds, Bargate Beds, Sandgate Beds, Folkestone Beds and Upper Greensand to be distinguished from each other by a detailed study of their mineralogy.

2. The presence of large masses of quiet water, particularly along or near the river, may serve to accelerate the development of these three zones, or cause local development of similar indicators of the rocks occurring in river sediment.
3. For such a study, in any catchment, it appears that sufficient understanding of the processes of sorting and transportation is lacking. The methods of sampling and use of samples needs some revision. A comparison of two river bed samples is best confined to samples from identical hydrological regimes.
4. It is tentatively suggested that sorting on the basis of specific gravity and to a lesser degree, basis of shape, will result in the formation of three zones of different mineral assemblages that are transitional with each other:
- Zone A. An upstream zone that has a relatively greater proportion of the heavier heavy minerals than zone B.
- Zone B. A downstream zone that has a relatively greater proportion of the lighter heavy minerals than zone A.
- Zone C. A transitional zone between A and B that has a reasonable proportion of the heavier and lighter heavy minerals. "A reasonable proportion" could be defined as a proportion that is within reasonable agreement with the mineralogy of the source rocks.

Further work is necessary to confirm the presence and extent of these three zones, and their presence in other streams. Such work would be better conducted in a catchment with a uniform heavy mineral distribution so that the sorting effects would be better seen.

5. The presence of large expanses of quiet water, particularly lakes or ponds may serve to accelerate the development of these three zones, or cause local development of similar but subsidiary zoning.

6. Such zoning could possibly be indicative of zones of tectonic source degradation (Zone A) and aggradation (Zone B). The ranges were subjected to X-ray diffraction to determine their mineralogy. Soils developed upon the various rock types, and river alluvium were also subjected to analysis as the possibility of a change in mineralogy due to weathering and chemical reaction is present (whereas little or no change would occur in the heavy minerals of the sand sized fraction). The possibility of diagnostic minerals or mineral assemblages being determined was indicated by a provisional survey. The results of the petrological size analysis (Appendix I) of the source rocks indicates that the principal sources of this sized sediment are the Weald Clay, the Atherfield Clay, and the Gault, with subsidiary amounts from the Sandgate Beds, Hyatt Greensand and Rythe Beds. Obviously, however, all of the formations within the area are potential although limited suppliers of detritus of this size.

COLLECTION OF SAMPLES OF SOURCE ROCKS AND SEDIMENT

Samples of rock and of stream alluvium were carried where possible by the channel sampling method, and were collected from river bank exposures. Soil samples were of the compound sample type formed from several spot samples collected over a few metres.

The X-ray diffraction was carried out using a Siemens Crystalloflex 4 fitted with a copper tube and nickel filter. X-ray

CHAPTER 2

MINERALOGY OF THE CLAY AND SILT SIZED FRACTION

INTRODUCTION

Rocks occurring within the study catchment that are a potential source of clay (finer than $+8\phi$) and silt ($+4$ to $+8\phi$) size ranges were subjected to X-ray diffraction to determine their mineralogy. Soils developed upon the various rock types, and river alluvium were also subjected to analysis as the possibility of a change in mineralogy due to weathering and chemical reaction is present (whereas little or no change would occur in the heavy minerals of the sand sized fraction). The possibility of diagnostic minerals or mineral assemblages being determined was indicated by a provisional survey. The results of the mechanical size analysis (Appendix I) of the source rocks indicates that the principle sources of this sized sediment are the Weald Clay, the Atherfield Clay, and the Gault, with subsidiary amounts from the Sandgate Beds, Upper Greensand and Hythe Beds. Obviously, however, all of the formations within the catchment are potential although limited suppliers of detritus of this size.

COLLECTION OF SAMPLES OF SOURCE MATERIAL AND TREATMENT

Samples of rock and of river alluvium were sampled where possible by the channel sampling method, and were collected from river bank exposures. Soil samples were of the compound sample type formed from several spot samples collected over a few metres.

The X-ray diffraction was carried out using a Siemens Crystalloflex 4 fitted with a copper tube and nickel filter. X-ray

diffraction patterns were run through a variety of degree ranges, the maximum being from 4° through to 38° . As many samples included sand sized material this had to be removed as the mineralogy of this sized material was not required. This size of material could not be removed by grinding as this would affect the mineralogy of the finer size ranges of the sample. Consequently the slide preparations were as follows. A small representative portion of the sample was placed in a small glass tube and was agitated with a small amount of water for some time. This was then set down and the larger grains allowed to settle for 5-10 seconds. Then some liquid and suspended material was taken off with a dropper and placed onto a slide to be slowly dried, with occasional tapping to encourage suitable orientation of grains, in an oven set at $15-20^{\circ}\text{C}$. After some experience a good slide preparation could be obtained free of material coarser than 4ϕ .

The peaks occurring on the X-ray diffraction patterns were measured by height and not by peak area. The highest peak of each diffraction pattern was taken as a strength 10 peak and all other peaks were measured against this standard.

Tables 26, 27 and 28 give the results of the X-ray diffraction analysis of the source rocks, soils and alluvium. The location of

The mineralogy of the soil, alluvium and source rocks within the study catchment was limited to seven minerals, one of which remains unidentified.

Quartz. Quartz was identified on the diffraction patterns by a strong peak at 4.3\AA , 1.32\AA and 36.5\AA . Kaolinite. This mineral was identified by a strong peak at 7.1\AA and a

Table 26. Mineralogy of the clay and silt sized material of source rocks.

subsidiary peak at 3.6Å.

Illite. Illite was identified by a strong peak at 10Å and weaker peaks at 5Å, at 3.7Å and at 3.3Å.

Montmorillonite. Identification of montmorillonite was based on a strong peak at 15Å.

Calcite. Calcite was identified by the presence of a strong peak at 3.0Å and subsidiary peaks at 2.09Å and 3.46Å.

Apatite. The identification of this uncommon mineral was based on a strong peak at 2.78Å and minor peaks at 2.68Å and 3.46Å.

Unidentified Mineral. The unidentified mineral was detected by the presence of a strong peak at 4.06Å. Any subsidiary peaks for this mineral were obscured by the peaks of other minerals. The occurrence of a main peak at this position is within reasonable agreement with the occurrence of the main peak for cristobalite. However, the presence of this high temperature silicate in the study catchment is unlikely. The position of this peak does not agree with the position of peaks for gypsum, vermiculite, muscovite, glauconite and goethite.

Tables 26, 27 and 28 give the results of the X-ray diffraction analysis of the source rocks, soils and alluvium. The location of samples of source rocks are given in Fig.2.

Weald Clay.

Samples from the Weald Clay showed a predominance of quartz with subsidiary amounts of kaolinite and illite. Soils developed on the Clay had a similar mineralogy, as did the alluvium sampled from stream courses on the Weald Clay.

Sandgate Beds
Sandgate Beds
Sandgate Beds

Table 26. Mineralogy of the clay and silt sized material of source rocks.

Table 26 contd.,

Formation Sample	Height of strongest peak (1-10)						
	Montmorillonite	Illite	Kaolinite	Quartz	Calcite	Apatite	Unidentified
Upper Chalk					10		
Upper Chalk- non-calc. residue	8	2		10		2	
Lower Chalk- non-calc. residue		½	1	10			
Upper Greensand		½		10			2
Gault 123	2	½		10			1
Gault 122	½	½	½	10			
Gault 121	1	1	1	10			
Marehill Clay 26	½	1	2	10			
Sandgate Beds 118		½	½	10			
Sandgate Beds 120	1½	½	½	10			
Sandgate Beds 117							
116	½	½	½	10			
25							
Sandgate Beds 3							
35	1	1	1	10			
Sandgate Beds 115	½		½	10			
Sandgate Beds 38		½		10			
Sandgate Beds 37			½	10			
Sandgate Beds 36	½		1	10			
Sandgate Beds 21		1	½	10			
Sandgate Beds 4	1		½	10			
Sandgate Beds 145	1			10			

contd.

Table 27. Mineralogy of the clay and silt sized material of soil samples.

Table 26 contd..

Formation upon which soil is developed	Sample location	Height of strongest peak (1-10)						
		Mentmorillonite	Illite	Kaolinite	Quartz	Calcite	Apatite	Unidentified
Head	SU 841273							
Upper Chalk	SU 841173							
Upper Chalk	SU 841173							
Middle Chalk	SU 782184				1	10		
Hythe Beds	SU 141 93	½	½	½	10	2	10	
Hythe Beds	SU 141 110	½		10	1½	10		
Atherfield Clay	SU 152 07	½	1	½	10	10		
Weald Clay	SU 131 93	½	½	½	10	10		
Weald Clay	SU 132 93	½	½	1	10	10	½	
Weald Clay	SU 153 19	½	½	½	10	10		
7ef Sandstone	SU 130 54	½	½		10	10		
Sargate Beds	SU 769288							
Sargate Beds	SU 842234							
Sargate Beds	SU 861284							
Hythe Beds	SU 830241					10	½	
Hythe Beds	SU 766244					10		
Atherfield Clay	SU 833249					10		
7ef Sandstone	SU 824266					1	10	
Weald Clay	SU 843288						10	

Table 27. Mineralogy of the clay and silt sized material of soil samples. The clay and silt sized material of river alluvium.

Formation upon which soil is developed	Sample location	Height of strongest peak (1-10)						
		Montmorillonite	Illite	Kaolinite	Quartz	Calcite	Apatite	Unidentified
Head alluvium	SU 841273		½	½	10			
Upper Chalk	SU 821173				10	½		
Upper Chalk	SU 821173				10	½		
Middle Chalk	SU 782184				1	10		
Lower Chalk	SU 777198	½	½	½	4	10		
Upper Greensand	SU 764210	½			10			2
Gault	SU 834207		1		10			
Gault	SU 767303	½			10			
Folkestone Beds	SU 772290		½		10	½		
Folkestone Beds	SU 823219		½		10			
Sandgate Beds	SU 808232				10			½
Sandgate Beds	SU 769268		½	½	10			
Bargate Beds	SU 842234		½	½	10			
Bargate Beds	SU 883224		½		10			
Hythe Beds	SU 830241		½		10	½		
Hythe Beds	SU 766244		½	½	10			
Atherfield Clay	SU 835249		½	½	10			
7ef Sandstone	SU 824264		½	1	10			
Weald Clay	SU 843280		½		10			

Table 28. Mineralogy of the clay and silt sized material of river alluvium.

This alluvium also had a preponderance of quartz with an admixture of very fine kaolinite and illite. The soil developed on the alluvium was similar but also indicated the presence of kaolinite.

Height of strongest peak (1-10)

Formation upon which alluvium is developed	Sample location	Montmorillonite	Illite	Kaolinite	Quartz	Calcite	Apatite	Unidentified
Upper Greensand	SU 739212	½			10	1		2
Upper Greensand	SU 766210	1½	½		10			1
Gault	SU 767303	1	½	½	10			1
Gault	SU 843205	1	½	½	10			½
Folkestone Beds	SU 771291	1½	½	½	10			1
Folkestone Beds	SU 826218	½	½		10			
Sandgate Beds	SU 804228	1	½	½	10			½
Sandgate Beds	SU 808229			½	10	½		
Sandgate Beds	SU 770268	½			10			
Bargate Beds	SU 887223		½		10			½
Hythe Beds	SU 847234		½	1	10	½		
Hythe Beds	SU 761244	½		½	10			
Atherfield Clay	SU 842241		½	½	10			
7ef Sandstone	SU 836267		½		10			
Weald Clay	SU 843279	½		½	10			

The soil developed on the alluvium was similar but also indicated the presence of kaolinite.

7ef Sandstone

This sandstone also had a predominance of quartz with an indication of some montmorillonite and illite. The soil developed on the sandstone was similar but also indicated the presence of kaolinite.

Atherfield Clay

A predominance of quartz in the Atherfield Clay is possibly accompanied by some kaolinite and illite. Soil samples and alluvium samples collected from areas of the Clay are again similar.

Hythe Beds

A sample from the Hythe Beds showed a predominance of quartz and some illite. Another sample, however, taken from a very clayey horizon indicated a predominance of kaolinite (Force 10) and subsidiary amounts of quartz. Samples from soils developed on the Hythe Beds, and of river alluvium collected from channels crossing the formation show a predominance of quartz with some illite and kaolinite.

Sandgate Beds

Many samples collected from the Sandgate Beds had sufficient clay and silt sized material to warrant analysis. The results all showed a predominance of quartz with varying subsidiary amounts of illite, kaolinite and montmorillonite. (A sample from the Marehill Clay at the top of the Sandgate Beds gave a higher proportion of kaolinite than the rest of the samples). Alluvium and soil samples collected from areas of Sandgate Beds gave similar results.

Folkestone Beds

No samples of the Folkestone Beds were subjected to X-ray diffraction analysis as they were considered too coarse and quartz is likely to be the predominant constituent of the clay and silt sizes. Samples of soil and alluvium collected from areas of Folkestone Beds were analysed and these did have a high proportion of quartz with subsidiary amounts of illite, montmorillonite and kaolinite.

Gault

Samples of the Gault also gave a force 10 peak for quartz with subsidiary proportions of montmorillonite, kaolinite and illite. There is also a subsidiary peak for the unidentified mineral. Samples of soil and alluvium from areas of the Gault had a similar mineralogy again with an indication of the unidentified mineral in the alluvium but not in the soil.

Upper Greensand

Samples of the Upper Greensand indicated quartz as most abundant with the unidentified mineral as being the second most abundant.

There are also minor amounts of illite. Samples of alluvium and soils from areas of Upper Greensand give a similar mineral assemblage with the unidentified mineral being the second most abundant after quartz.

Chalk

Two preparations of Upper Chalk were subjected to X-ray diffraction. The preparation of non-calcareous residue only gave a high proportion of quartz and montmorillonite with smaller proportions

of illite and apatite. The preparation from which the calcareous material was not removed showed only the presence of calcite.

Samples of the soil developed on the Lower and Middle Chalk gave a predominance of calcite with smaller amounts of quartz. However, samples of Upper Chalk (two from very close localities), gave a high proportion of quartz and very small amounts of calcite and virtually nothing else. The small proportion of calcite is unexpected especially as fragments of chalk are abundant in the soil. The sample locality is not an area of clay with flints, and due to the presence of chalk fragments in the soil it is difficult to explain the absence of calcite in the finer sizes. Perhaps, due to a high proportion of quartz, the calcite was masked. Some of the quartz is possibly of loess origin.

Head

A single soil sample collected from the soil developed on head deposits within the Hammer Catchment was analysed. This gave a high quantity of quartz with very small amounts of illite and kaolinite.

VARIATION BETWEEN ROCK TYPES

Analysis of the samples indicated very little variation between the mineralogy of clay and silt sized material of a source rock and the soil and alluvium developed on areas of the source rock. The variation between the mineralogy of different source rocks is somewhat restricted but the following features occur:

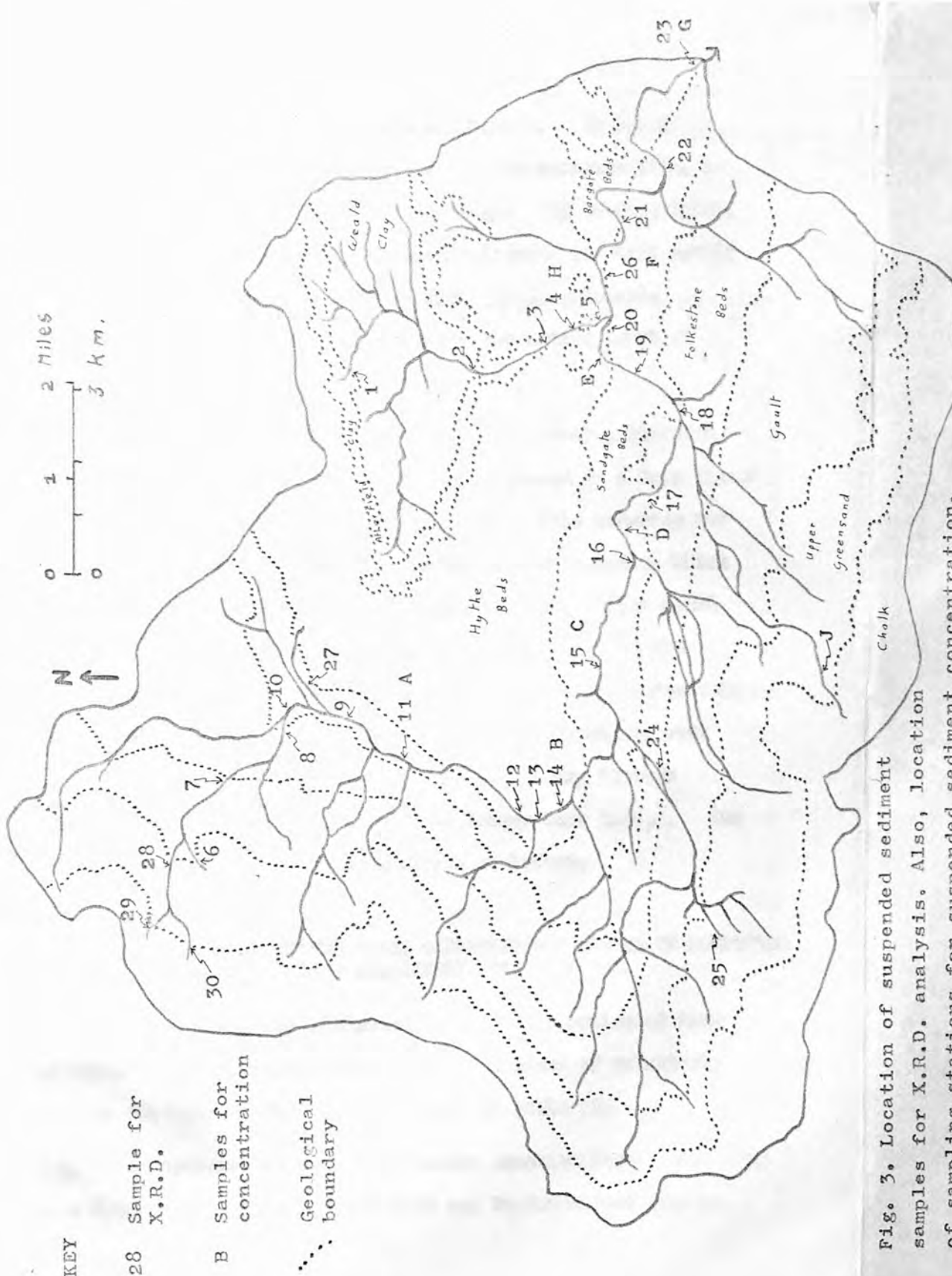
1. Quartz is generally the dominant mineral species.

2. Chalk has a predominance of calcite in untreated samples while samples without calcareous material have a predominance of quartz and montmorillonite.
3. A clay from within the Hythe Beds has a predominance of kaolinite.
4. The unidentified mineral appears to be confined to the Upper Greensand and the Gault.
5. The Weald Clay assemblage is principally quartz and minor amounts of illite and kaolinite while the Gault assemblage has mainly quartz, with some montmorillonite, illite and kaolinite, and possibly a proportion of the unidentified mineral.

Despite the simplifying factor of similarity between the mineralogy of soils and rock types, it was considered that the mineralogy of the source rocks was probably insufficiently variable for determination of the source of the suspended sediment. However, some samples of suspended sediment were collected and analysed for their mineralogy.

COLLECTION OF SAMPLES OF SUSPENDED SEDIMENT AND TREATMENT

The sampling locations (Fig. 3) of suspended sediment were generally positions just upstream of a change in the geological formation, or just upstream or downstream of a confluence. The dates on which some of the samples were collected are indicated in the Tables 29 and 30 with the results. As the samples of suspended sediment were required for mineralogy and not for suspended sediment



KEY

28 Sample for X.R.D.

B Samples for concentration

..... Geological boundary

Fig. 3. Location of suspended sediment samples for X.R.D. analysis. Also, location of sampling stations for suspended sediment concentration.

Table 29. Mineralogy of suspended sediment samples

concentration the sampling procedure was simplified. It was of no concern if the samples were not representative for concentration, as long as they were representative for mineralogy. Up to five litres of river water with suspended sediment were collected for each sample by introducing a plastic bottle into the flow (neck upstream). During collection attempts were made to cover the entire depth of flow.

The samples were filtered as soon as possible after collection but as this is a long process some samples were stored in a deep freeze to prevent excessive growth of organic material. This freezing may have caused the precipitation out of solution of some calcite, which upon thawing may not all have gone back into solution. This would result in a higher proportion of calcite being registered in the suspended sediment than is really present. No tests were undertaken to determine this however, and the error involved is probably very small. The samples were filtered, using filter pumps, through membrane filters that retained all material larger than 0.45μ . The residue was then prepared for X-ray analysis as before.

RESULTS AND INTERPRETATION OF THE X-RAY DIFFRACTION ANALYSES OF SUSPENDED SEDIMENT SAMPLES COLLECTED DURING RELATIVELY HIGH FLOW

The results of the X-ray analyses of 24 samples collected from various points within the catchment during conditions of relatively high flow on 4th February 1972 are presented in Table 29.

Sample 6. The upstream areas of this sample location drains only over the Upper Greensand, but some of the flow may be drawn from springs

Table 29. Mineralogy of suspended sediment samples collected during conditions of non-base flow. Discharge at Iping Mill - 5.6 m³/sec..

Sample Location	Height of strongest peak (1-10)						
	Montmorillonite	Illite	Kaolinite	Quartz	Calcite	Apatite	Unidentified
6	½			6	3		10
7				4	10		2
8	½			10	10		4½
9	½	½	½	10	½		3½
11	½	½		10			4
12	1		1	10	6		4
13	½			10	5		1
14	½		½	10			1½
25				5	1½		10
24				10	1		4
15	1	½		10			2
16				10	3		1
17	1		½	10	½		1½
18				10			1
19			½	10	1½		2
20	1			10			1

contd.

and fragments issuing from the base of the Gault. The sample has a high proportion of the mineral which is in general agreement with a source rock of Upper Devonian. However, it is unexpected that a trace 10 peak occurs in the suspended sediment when only a trace 2 peak occurs in the source rock. Perhaps the mineral is more easily held in suspension.

Table 29 contd..

Height of strongest peak (1-10)
of some suspended sediment derived from the Gault, whereas the bulk of the quartz (trace 6) is probably derived from the Upper Devonian.

Sample 7.

Sample Location	Montmorillonite	Illite	Kaolinite	Quartz	Calcite	Apatite	Unidentified
-----------------	-----------------	--------	-----------	--------	---------	---------	--------------

The channel above this sample is a... developed chalk springs. This is reflected in the suspended sediment which has a trace 10 peak for calcite. The high content of the unidentified mineral in sample 5 (optimum of trace 7) has been divided by the calcite and is now only 1/2 trace 2 peak. Quartz (trace 4) is also present...
 1 10
 2 10
 3 10
 4 10
 5 10

Sample 8.

21	1/2			10	1		1
22				10			1
23	1	1/2		10			1/2

This sample location is... over visible formations but includes the Folkstone beds which are a potential source of quartz. This is again reflected in the suspended sediment where both quartz and calcite have trace 10 peaks. The unidentified mineral is again present but has increased in trace from sample 7; this may be the result of a tributary entering upstream and joining from the Gault which is also a possible source of this mineral (Table 27).

Sample 9.

The mineralogy of this sample shows a drastic reduction in the amount of calcite present when compared with sample 8, but the location only flows over the...
 10

and seepages issuing from the base of the Chalk. The sample has a high proportion of the unidentified mineral which is in partial agreement with a source rock of Upper Greensand. However, it is unexpected that a force 10 peak occurs in the suspended sediment when only a force 2 peak occurs in the source rocks. Perhaps the mineral is more easily held in suspension. Calcite (force 3) is indicative of some suspended sediment derived from the Chalk, whereas the bulk of the quartz (force 6) is probably derived from the Upper Greensand.

Sample 7. The channel above this sample location drains over the Gault, the Upper Greensand and the Chalk, and includes two well developed Chalk springs. This is reflected in the suspended sediment which has a force 10 peak for calcite. The high content of the unidentified mineral in sample 6 (upstream of sample 7) has been diluted by the calcite and is now only a force 2 peak. Quartz (force 4) is also somewhat overwhelmed by the calcite.

Sample 8. This sample location is downstream of sample 7 and drains over similar formations but includes the Folkestone Beds which are a potential source of quartz. This is again reflected in the suspended sediment where both quartz and calcite form force 10 peaks. The unidentified mineral is again present but has increased in force from sample 7; this may be the result of a tributary entering upstream and draining from the Gault which is also a possible source of this mineral (Table 27).

Sample 9. The mineralogy of this sample shows a drastic reduction in the amount of calcite present when compared with sample 8, but the

location only flows over the Upper Greensand.

quartz remains unaffected. This is due to the influx of quartz rich sediment deficient in calcite being introduced by tributaries draining from the Lower Greensand formations. However, the unidentified mineral shows a surprisingly small decrease in importance.

Sample 11. This again has a high quantity of quartz, and the unidentified mineral (force 4) is still present. Calcite is completely absent from the diffractogram.

Sample 12. The mineralogy here is similar to sample 11 except for a considerable increase in calcite. This increase cannot readily be explained as the only tributary joining the main stream between the location of samples 11 and 12 does not drain from the Chalk but only just reaches onto the Upper Greensand. It is unlikely that ground water discharges can account for the increased calcite. An increase in calcite would be more expected to occur between samples 9 and 11 as a tributary between these two locations does drain from the Chalk, but when these two samples are compared this is not the case.

Sample 13. Very little change from the mineralogy of sample 12 is found in this sample, except for a decrease of the unidentified mineral from force 4 to force 1.

Sample 14. There is very little change between this sample and sample 13 except that there is a marked decrease in the amount of calcite.

Sample 25. Sample 25 has a very similar mineralogy to that of sample 6. Similarly too, the main river channel upstream of the sample location only flows over the Upper Greensand.

Sample 24. Sample 24 is downstream of sample 25 and has a similar mineralogy to that of sample 9 which is downstream of sample 6. Similarly the channel upstream of sample 9 and the channel upstream of sample 24 drains similar formations (Chalk, Upper Greensand, the Gault and Lower Greensand). However, the amount of channel over Lower Greensand is very much restricted for the sample location 24. In sample 24 the force 10 peak of sample 25 has become diluted by quartz (force 10).

Samples 15, 16, 17, 18, 19, and 20. These samples have a very similar mineralogy and are all dominated by quartz with fluctuating amounts of calcite and the unidentified mineral. These assemblages are also similar to sample 14 and they probably represent a fairly stable mineral assemblage of the main stream which is the result of mixing of suspended sediments supplied by the different tributary streams and of quartz rich sediment being supplied by the Lower Greensand over which the main stream flows. There is some fluctuation in the calcite content, particularly in sample 13 (force 3) which could be the result of quantities of calcite being brought in by the tributary just upstream of this sample location.

Samples 1, 2, 3, 4 and 5. These samples have been collected from various locations on the Hammer Stream drainage network and they contrast to most of the other samples by not having any of the unidentified mineral or calcite. They all have a predominance of quartz with some kaolinite and illite but no montmorillonite. The kaolinite is more abundant in the two samples downstream of the Hammer Pond (samples 4 and 5). Perhaps this is indicative of some quartz settling out in the

Hammer Pond in preference to the more platy clay minerals. These samples (4 and 5) have the highest kaolinite levels of all the samples collected on 4th February 1972.

The variations discussed here are spatial variations and little or no variation in time can be deduced from them. Samples 21, 22 and 23. These are similar to samples 15, 16, 17, 18, 19 and 20 but perhaps have a smaller proportion of the unidentified mineral and calcite. Quartz still dominates the assemblage while kaolinite is absent from all three samples which is probably indicative of only a small proportion of the total *suspended* sediment being supplied by the Hammer Catchment.

Analysis of the samples collected on 4th February 1972 indicates the existence of three types of suspended sediment mineral assemblage whose distribution is primarily controlled by the mineralogy and distribution of source rocks:

1. The variable assemblage of the tributaries and the upper part of the main stream. Here calcite, quartz, or the unidentified mineral may be dominant and the assemblage varies as different geological formations are crossed.
2. The more constant assemblage of the main stream. This assemblage is the result of mixing of suspended sediments supplied by the tributaries and of quartz rich sediment derived from the Lower Greensand. In this assemblage quartz predominates and calcite and the unidentified mineral are less important than in the tributaries. The assemblage varies very little downstream and minor variations may result from the influx of sediment from tributaries.
3. The assemblage of the Hammer Catchment differs from that of other

tributaries by being without calcite, montmorillonite and the unidentified mineral, and by having a higher proportion of kaolinite.

on 27/8/72, (discharge at Spring Hill of 0.7 m³/sec.).

The variations discussed here are spatial variations only: little or no variation in time can be deduced from them.

RESULTS AND INTERPRETATION OF THE X-RAY DIFFRACTION ANALYSES OF SUSPENDED SEDIMENT SAMPLES COLLECTED DURING RELATIVELY LOW FLOW

The samples collected during conditions of low flow are really samples of colloidal sediment, but will here be referred to as suspended sediment.

In order to determine any variation in suspended sediment mineralogy with conditions of flow ten samples were collected at low flow on 22nd August 1972 and their mineralogy (Table 30) compared with that of samples collected at high flow (Table 29). In all of the samples except 29 quartz predominates and was the only mineral recorded in all samples except 7, 28 and 29.

Sample 7. This sample was collected at the same locality as sample 7 of 4th February 1972. However, it differs from the sample collected at high flow by having a force 10 peak for quartz and not for calcite, and by having a lower peak strength for the unidentified mineral. This can be explained, as during periods of low flow, run off is absent and so most calcite would be removed in the dissolved form. Any solid calcite being introduced by ground water springs and seepages may soon become diluted by quartz picked up from the channel sides and bed.

Table 30. Mineralogy of suspended sediment
 samples collected during conditions of low flow
 on 22/8/72, (discharge at Iping Mill of 0.7 m³/sec.).
 Only the strongest peak for each mineral plotted.

The sample has a quartz and calcite ratio which is
 transitional between that of sample 29 and 26. The
 sample has low concentrations of the unidentified mineral which is
 probably derived from the alluvium transported along the channel.

Sample	Montmorillonite	Illite	Kaolinite	Quartz	Calcite	Apatite	Unidentified
29				10	10		
28				10	2		2½
7		½		10	1		½
8				10			
10				10			
9				10			
27				10			
20				10			
4				10			
26				10			

Five alluvial samples of suspended sediment were collected
 at Iping Mill (sample location 26) during the course of a river
 hydrograph. This location was chosen for the reasons...

Sample 29. This sample was collected from a locality just a little downstream of a chalk spring, and upstream of sample 7. The sample gave a force 10 peak for calcite and a force 6 peak for quartz. The high proportion of calcite in this sample is explainable by the explanation under sample 7 above.

Sample 28. This sample has a quartz and calcite ratio which is transitional between that of samples 29 and 7. This is acceptable as the sample location is between these two sample locations. This sample also has a reasonable amount of the unidentified mineral which is presumably derived from the alluvium developed along the channel length and derived originally from the Upper Greensand.

A sample from location 6 was not possible due to the discharge of the stream being reduced to a small trickle.

These samples, although limited in number and assemblage, indicate little change in suspended sediment mineralogy between conditions of high and low flow at particular localities. The only variation appears to be confined to the head waters and tributaries where fluctuations in calcite, quartz and the unidentified mineral may occur due to a variation in the ratio between the amount of run-off and amount of ground water seepage.

AT-A-STATION SAMPLES COLLECTED DURING THE PASSAGE OF A STORM EVENT TO DETERMINE ANY VARIATION

Five at-a-station samples of suspended sediment were collected at Iping Hill (sample location 26) during the passage of a storm hydrograph. This location was chosen for two reasons: it appears to

1. The discharge is continuously gauged by the River Authority.
2. It was hoped that an increase in kaolinite might be detected in the early period of the hydrograph due to the more flashy nature of the Hammer Catchment. It was then expected that the kaolinite would become overwhelmed by other minerals as the main catchment reacted to the rainfall.

The results of these samples are presented in Table 31.

Kaolinite possibly forms the highest proportion in the first two samples collected but the strength of the peaks is very low. All of the samples have force 10 peaks for quartz.

From these few samples there appears to be very little variation in the mineralogy of suspended sediment during the passage of a storm hydrograph at Iping Kill.

Date	Time	Stage	Peak Strength
6-2-75	16.30	0.81	10

MINERALOGY OF SUSPENDED SEDIMENT SAMPLES COLLECTED FROM THE UPPER CATCHMENT AT DIFFERENT TIMES AND CONDITIONS OF FLOW

6-1-75	21.05	0.75	10
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A comparison of the samples from locations 7 and 8 on Tables 29 and 30 suggests that there may be some variation in the mineralogy of the suspended sediment of the upper catchment due to a variation in conditions of flow. To investigate this more fully more samples were collected at different conditions of flow and their results are presented with the other data in Table 32. Samples were not collected through an entire flood hydrograph as the work load involved is high and this aspect is only marginal to the original problems of the study.

The data presented in Table 32 indicate that some variation in the mineralogy of the suspended sediment does occur and it appears to

Table 32. Mineralogy of suspended sediment samples collected from the upper catchment at different times and conditions of flow.

Table 31. Mineralogy of at-a-station samples collected from Iping Mill.

Sample Location	Collection Date	River Stage	Peak Strength					Unidentified
			Montmorillonite	Illite	Kaolinite	Calcite	Quartz	
29	22-8-72		0.7			10		
"	7-3-73		1.1			10		
"	4-2-72		5.6					
30	22-8-72		0.7					
6-2-72	14.30	0.80	1.1	1/2	1/2	10		
6-2-72	16.30	0.81	5.1	1/2	1/2	10		
6-2-72	17.50	0.79	6.1			10		
6-2-72	21.05	0.73	0.7			10	25	
6-2-72	23.05	0.67	1.1			10	1	
"	4-2-72		5.6					
"	2-4-73		6.1			10	25	
6	22-8-72		0.7					
"	7-3-73		1.1			10	25	
"	4-2-72		5.6		6	3	10	
"	2-4-73		6.1				1	
7	22-8-72		0.7			10	1	
"	7-3-73		1.1			10	2	
"	4-2-72		5.6		4	10	2	
"	2-4-73		6.1			10	1	

Table 32. Mineralogy of suspended sediment samples collected from the upper catchment at different times and conditions of flow.

Sample Location	Collection Date	Discharge at Iping Mill m ³ /sec	Height of strongest peak (1-10)		
			Quartz	Calcite	Unidentified
29	22-8-72	0.7	6	10	
"	7-3-73	1.1	4	10	
"	4-2-72	5.6			
"	2-4-73	6.1	4	10	
30	22-8-72	0.7			
"	7-3-73	1.1	6	10	
"	4-2-72	5.6			
"	2-4-73	6.1	10	4	
28	22-8-72	0.7	10	2	2½
"	7-3-73	1.1	10	10	1
"	4-2-72	5.6			
"	2-4-73	6.1	10	3½	2½
6	22-8-72	0.7			
"	7-3-73	1.1	10	10	2½
"	4-2-72	5.6	6	3	10
"	2-4-73	6.1	10		1
7	22-8-72	0.7	10	1	½
"	7-3-73	1.1	10	2	2
"	4-2-72	5.6	4	10	2
"	2-4-73	6.1	10	1	½

Table 32 contd..

be more dominant in sample locations 30, 28, 5, 7 and 11. However, the data are too restricted for any conclusions to be drawn. The conclusion is probably the result of factors including amount of water seepage, the amount and intensity of rainfall, and varying permeability of the rock types. There is no definite relationship.

One Sample Location	Collection Date	Discharge at Iping Mill m ³ /sec.	Height of strongest peak (1-10)		
			Quartz	Calcite	Unidentified
8	22-8-72	0.7	10		
"	7-3-73	1.1	10	½	½
"	4-2-72	5.6	10	10	4½
"	2-4-73	6.1	10	½	
10	22-8-72	0.7	10		
"	7-3-73	1.1	10	½	
"	4-2-72	5.6			
"	2-4-73	6.1	10		
9	22-8-72	0.7	10		
"	7-3-73	1.1	10	4	
"	4-2-72	5.6	10	½	3½
"	2-4-73	6.1	10		
11	22-8-72	0.7			
"	7-3-73	1.1	10		
"	4-2-72	5.6	10	4	
"	2-4-73	6.1	10		

1. There is a close relationship between the quantity of clay and silt sized material of source rocks and that of the soil and alluvium developed from them.

2. (i) The Shalk is characterized by a preponderance of calcite, (ii) The Upper Gressend is characterized by a preponderance of quartz, and the presence of the unidentified mineral.

be more dominant in sample locations 30, 28, 6, 7 and 3. However, the data are too restricted for any conclusions to be drawn. The variation is probably the result of factors including the amount of ground water seepage, the amount and intensity of rainfall, and the relative permeability of the rock types. More work is necessary to ascertain a more definite relationship.

One problem arising from this study is the quartz peak for sample 10 for 7/3/73. Here the force 10 peak is in the 4.26 \AA position and not the usual 3.34 \AA position. This has not been found within any of the samples of source rock, soils or alluvium. However, it has been found to occur in the fine sand range of the Hythe Beds. But due to the sample location it is unlikely that a high proportion of sediment for this location is derived from the Hythe Beds. Whether this peak is for quartz, or if it is indeed another mineral the problem of its origin still arises.

the Lower Greensand, which is dominated by quartz.

CONCLUSIONS

(i) The mineralogy of the Haxton Stream which is characterised by Despite the limited data the author considers that the results of the absence of montmorillonite, calcite, and the unidentified the X-ray diffraction analyses of the clay and silt sized material of mineral. suspended sediment and of source rocks, soil and alluvium lead to the following conclusions:

1. There is a close relationship between the mineralogy of clay and silt sized material of source rocks and that of the soil and alluvium developed upon them.
2. (i) The Chalk is characterised by a predominance of calcite.
 - (ii) The Upper Greensand is characterised by a predominance of quartz, and the presence of the unidentified mineral.

(iii) The Gault is characterised by the predominance of quartz, and the presence of clay minerals, particularly montmorillonite.

(iv) The Lower Greensand is characterised by the predominance of quartz.

(v) The Weald Clay is characterised by the predominance of quartz and the absence of montmorillonite.

3. The mineralogy of the source rocks is reflected to an extent in the suspended sediment of streams draining over them.

4. When considering the spatial variation of suspended sediment three types of assemblage are apparent:

(i) The variable mineralogy of the tributaries due to a change in the formation, and hence mineralogy, being crossed by the channel. Dominant minerals are either quartz, calcite or the unidentified mineral.

(ii) The more constant mineralogy of the main stream flowing over the Lower Greensand, which is dominated by quartz.

(iii) The assemblage of the Hammer Stream which is characterised by the absence of montmorillonite, calcite, and the unidentified mineral.

5. A quantitative assessment of the source of the suspended sediment is not possible for the catchment as a whole as the mineralogy is dominated by quartz which is the dominant mineral of most rock types within the catchment. It may prove possible for a quantitative assessment to be made on a much more restricted catchment, for example, limited to a single tributary.

6. Variation in time appears to be restricted to the tributaries and complicates the variation in space occurring here. More work is necessary to determine the exact relationship of involved factors.

7. The suspended sediment lost from the catchment as a whole is dominated by quartz and clay minerals from only a small proportion of the total.

The source rocks for particles of pebble sized material would be confined to the coarse grained elastic rocks, and to the more indurated sedimentary rocks that could be broken up to rock fragments. The soft Weald Clay, Aikensfield Clay and the Chalk would not produce any material of this size. The Chalk is, however, a potential source of fragments of pebble size but the weight, and distance of transport, of particles of this size would be very limited.

COLLECTION OF SAMPLES FROM RIVER BED AND LABORATORY PROCEDURES

Sampling locations were restricted to four areas:

1. The lower end of the catchment. Several samples were collected from here at different times, and it is this stretch where bed load transport rates were determined (Section II). Consequently, it was hoped that the data of this study could be referred to the transport data of the appropriate sized sediment particles.
2. The Hamner tributary just upstream of its confluence with the main stream.
3. The main stream just upstream of its confluence with the Hamner

CHAPTER 3

IDENTIFICATION OF THE PEBBLE SIZED FRACTION

INTRODUCTION

The pebble sized fraction of river bed samples was studied and individual particles were identified into one of several categories in an attempt to relate them directly to one of the source rocks within the study catchment. The source rocks for particles of pebble sized material would be confined to the coarser grained elastic rocks, and to the more indurated sedimentary rocks that could be broken up to provide rock fragments. The soft Weald Clay, Atherfield Clay and the Gault would not produce any material of this size. The Chalk is, however, a potential source of fragments of pebble size but the resistance, and distance of transport, of particles of this soluble rock would be very limited.

COLLECTION OF SAMPLES FROM RIVER BED AND LABORATORY PROCEDURE

Sampling locations were restricted to four areas:

1. The lower end of the catchment. Several samples were collected from here at different times, and it is this stretch where bed load transport rates were determined (Section II). Consequently, it was hoped that the data of this study could be referred to the transport data of the appropriate sized sediment particles.
2. The Hammer tributary just upstream of its confluence with the main stream.
3. The main stream just upstream of its confluence with the Hammer

tributary. The source of these is possibly the Folkestone Beds, although some of the fragments within the Folkestone Beds may have come from this area.

4. The main stream at a sufficient distance downstream of the confluence with the Hammer for mixing of the two sediments supplied to occur.

Sample locations 2, 3 and 4 were chosen as it was hoped that any difference in 2 and 3 would be reflected in 4.

Samples from the river bed were collected using a scoop type sampler and attempts were made to sample the entire width of the channel. Some of the samples were compound samples of several spot samples collected at intervals both across and along the river channel. The samples were then dried and material larger than -1ϕ separated out by dry sieving. The material was then washed to remove clay and clay/silt aggregates produced by the drying procedure. The remaining material was again dried, and divided by sieving into material between -1ϕ to -2ϕ , and -2ϕ to -4ϕ .

The individual particles were then identified to the appropriate category and the percentage in each category was determined for each sample. The categories used were:

Quartz Grains: individual quartz grains within these size ranges do occur. The most likely source of this size of quartz grain is the coarse Folkestone Beds.

Flint Fragments: the primary source of fragments of flint in the catchment are the flints within the Chalk. However, also occurring within the catchment are areas of flint gravels which are sources of reworked flint fragments.

Other Mineral Grains: the source of these is possibly the Folkestone Beds, although grains of authigenic minerals within the Hythe and Sandgate Beds may reach this size.

Chalk Fragments: hydrochloric acid was used on some grains to determine the presence of a high Ca CO_3 content.

Fine Sandstone Fragments: these fragments of fine sandstone are pale yellow to white in colour and they consist of aggregates of fine sand sized grains. They are considered to be derived from the Upper Greensand formation.

Medium and Coarse Sandstone Fragments: these sandstone fragments are dark yellow to brown in colour and consist of quartz grains of medium and coarse sand size cemented by an iron or silica cement. They are considered to have been derived from the Hythe, Sandgate and Bargate Beds.

Iron Rich Sandstone Fragments: these fragments are much more iron rich than the other sandstone fragments. Possible sources are iron stones and iron pans developed in the Sandgate, Hythe and Bargate Beds. A very few may be derived from iron pans developed in the Folkestone Beds.

Calcareous Organic Material: this consists entirely of present day lamellibranch valves.

Shale or Slate Fragments: this material is considered to be secondary worked fragments derived from the coarser Folkestone Beds. Fragments of these rocks have been observed in this formation by the author although it is possible that some of these fragments in the river sediment are alien to the study catchment.

Usually all of the particles of each size range were identified as the accuracy of the data is increased with the number of particles identified.

RESULTS OF SAMPLES COLLECTED AT THE LOWER END OF THE CATCHMENT

The results of the study of pebble sized material from samples collected from the lower end of the catchment are presented in Table 33.

Several features become evident from these results:

1. Sandstone fragments and flint fragments are the most common elements in both the size ranges considered. This is not surprising as flints and cemented sandstones are the major source of this sized material within the catchment. Clays and poorly consolidated sandstones will provide smaller sized material. Medium and coarse sandstone fragments form a higher proportion than the fine sandstone fragments which is easily explained: the Lower Greensand formations (source of medium and coarse sandstone) are more easily eroded than the Upper Greensand Formation (source of fine sandstone fragments) and the former also has a much more extensive outcrop area and length of drainage network (Table 1).
2. Quartz grains are slightly more abundant in the very fine pebbles than in the medium and fine pebbles. This is due to individual grains of quartz in the source rocks, and in rocks generally, being more abundant in the very fine pebble size than in the medium and coarse pebble size, just as individual mineral grains in general are more abundant in the sand sized ranges than in the pebble sized ranges.

Table 33. Analysis of pebble sized fraction of samples collected from the lower end of the catchment, by percent.

Date	Mesh	Quartz Grains	Flint Fragments	Other mineral Grains	Chalk Fragments	Fine Sandstone Fragments	Med. & coarse sandstone frags.	Iron impregnated sandstone	Calcareous organic debris	Shale or slate fragments
Aug. 71	>5		16	2		7	65	5		5
Dec. 71	>5	5	19	3		5	62	3		3
Feb. 72	>5	4	21			4	67	2		2
Aug. 72	>5	5	10			8	72	5		
Apr. 73	>5	3	25			4	61	5		2
Aug. 71	5-8	4	14	4		9	63	4		2
Dec. 71	5-8	10	25	3		7	51	2		2
Feb. 72	5-8	10	27	4	/	5	50	3	/	1
Aug. 72	5-8	9	21	5		6	53	4	/	1
Apr. 73	5-8	9	22	6		6	53	2		2

3. The percentage within each category is fairly stable through time (at least two years). Much if not all of the fluctuation collected upstream and downstream of the Hammer / Rother confluence, by percent.

RESULTS OF SAMPLES COLLECTED UPSTREAM AND DOWNSTREAM OF THE HAMMER AND ROTHER CONFLUENCE

The results of the study of the pebble sized fractions of the two samples collected upstream of the Hammer and Rother confluence (one from each river), and of the sample collected downstream of the confluence are presented in Table 34.

The most significant feature of these results is the absence of quartz grains and flint fragments in this sized material from the Hammer tributary sample. Instead, there is a very high proportion of medium and coarse sandstone fragments. It would be expected that a mixing of this sized material from the Hammer Stream with this sized sediment of the main stream would result in a dilution of the percentage of quartz grains and flint fragments of the main stream. However, a comparison of samples taken from the main stream above and below the Hammer tributary shows no dilution, and if anything, shows an increase of the percentage of quartz grains and flint fragments. This, accompanied by a reduction in the percentage of medium and coarse sandstone fragments probably indicates that very little sediment of this size is supplied to the main stream by the Hammer tributary.

The cause of the increase in quartz grains and flint fragments below the Hammer tributary is not clear. It is probably the result of sorting processes on the basis of specific gravity and shape. For

example, a solid quartz grain is likely to have a greater weight than

Table 34. Analysis of pebble sized fraction of samples collected upstream and downstream of the Hammer / Rother confluence, by percent. Another factor which may be

contributory to these processes is the distribution of aggregates of pebbles and coarse sandstone in the channel stretch between the sample locations. This would cause an associated increase in the proportion of quartz grains and flint fragments.

DISCUSSION

The data here considered seem that a much larger volume of material

Rother above confluence

Hammer above confluence

Rother below confluence

sediment is not represented.

Also, a consideration of how representative the material sampled is of the material moved by the river is necessary. If all categories of material are being removed from the sample location, the processes of sorting will cause the removal of more of the more easily transported materials than would be indicated by the data in Tables 33 and 34.

example, a solid quartz grain is likely to have a greater weight than an aggregate of quartz grains the same size. Also, the shape of the flint fragments is much more angular than the shape of the quartz grains or sandstone fragments. Another factor which may be complementary to these processes is the disruption of aggregates of medium and coarse sandstone in the channel stretch between the sample locations. This would cause an associated increase in the proportion of quartz grains and flint fragments.

DISCUSSION

A consideration of the data presented in Tables 33 and 34 requires some thought of the implications involved. Each grain or fragment of the size range considered means that a much larger volume of material from the relevant source rock has been introduced into the system. Generally, the majority of this material is of a finer size and has therefore been transported farther downstream than has the coarser material sampled. However, determination of the total sediment load removed cannot be determined from consideration of this information as it is obvious that some material of the size range being considered here has been removed and consequently an unknown amount of finer sediment is not represented.

Also, a consideration of how representative the material sampled is of the material moved by the river is necessary. If all categories of material are being removed from the sample location, the processes of sorting will cause the removal of more of the more easily transported materials than would be indicated by the data in Tables 33 and 34.

For example, the Rother above the confluence with the Hammer Stream has 25% of flint fragments, 8% of quartz grains, and 36% of coarse and medium sandstone fragments. But if flint fragments are more readily set in motion on the river bed than are quartz grains, and if the coarse and medium sandstone fragments are the most readily moved of all, it is possible that the proportions of these in the material that is actually moved is (using arbitrary values) 50% for the coarse and medium sandstone fragments, 30% for the flint fragments, and only 4% for the quartz grains. However, how much effect the processes of sorting will have on changing the composition of sampled material and material removed is not at present known. More work, including flume studies, would provide information.

Another fluvial process that could be complicating or complementing the sorting process is the breaking up of fragments during transport. The most vulnerable fragments are the coarse and medium sandstone fragments. These are poorly consolidated and may break up during transport. This process is probably much more important in eliminating material of this size in the present river than reduction of grain size by rounding processes.

If the understanding of sorting and other fluvial processes involved with this sized sediment was adequate the data of relative proportions of sediment from each rock type was to be related to the sediment transport data for this sized material expected to be obtained from field experiments (Section II).

CONCLUSIONS OF THE STUDY OF THE PEBBLE SIZED FRACTION OF RIVER
SEDIMENT

If the material of pebble size in the samples collected from the river bed are reasonably representative of the material of this size range removed from the location the following conclusions can be drawn:

1. The majority of the material of these sizes removed from the study catchment as a whole consists of medium and coarse sandstone fragments (about 65% for medium and fine pebbles and about 53% for very fine pebbles) derived from the Lower Greensand (Hythe, Sandgate and Bargate Beds in particular).
2. Flint fragments are also an important constituent of the material of this size. The majority of these flint fragments are probably the result of reworking of flint gravels and other superficial deposits and are therefore not indicative of the rate of present day erosion of the Chalk.
3. The proportion of constituents of the medium and fine pebbles, and the very fine pebbles seems to fluctuate very little during the sampling period (two years).
4. Very little material of this size range appears to be contributed by the Hammer Stream.
5. The results of the samples collected upstream and downstream of the Hammer confluence with the main stream are confusing and probably indicate that some sorting processes are present.

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SECTION II

RATE OF SEDIMENT LOSS

... of the ...

... of the ...

1. The area of the source region
2. The rate of sediment loss from that region
3. The duration of the process

... of the ...
... of the ...

... of the ...

in the United States and SECTION II indicates the rate of denudation for the country as a whole to be about twice that of previous estimates. This difference in their data and the previous data may

INTRODUCTION

The movement of river sediment (bed load and suspended load) in alluvial channels has long been a real problem to the geologist and engineer alike. Present knowledge of rates of removal of material, by rivers and streams is restricted to a few study catchments, and these studies have provided a general understanding of processes involved, but for a complete understanding the present author believes that many more intensive studies of various sized rivers with different geomorphological, lithological and land use characteristics are necessary. The knowledge of sediment transport rates is required if proper development of river control structures and river management is proposed. Knowledge of fluvial processes are also important if the estimation of average rates at which regions are lowered is to be attempted.

Monard (1961) explains ^{that} the average rate of regional erosion for a particular time period can be estimated from:

1. the area of the source region;
2. the volume of sediment derived from that region, and
3. the duration of the erosion.

He does not consider the dissolved load in his calculations, and Judson and Ritter (1964) acknowledge that the dissolved load contributes very little to the rate of lowering of the present surface as most solution occurs at depth.

Judson and Ritter (1964) determined rates of regional denudation for different positions along the entire length of a river and its

in the United States and their calculations indicate the rate of denudation for the country as a whole to be about twice that of previous estimates. This difference in their data and the previous data may be the result of a change in sampling technique and accuracy of methods involved, or it could be a real difference due to a change in some fundamental control of erosion between the two periods of observation. For whatever the reason, the results of older studies may therefore be inaccurate for present day requirements, and consequently more studies are needed of present erosion rates.

Data for the sediment yields of the world's major rivers (Holeman, 1968) suggest that Africa, Europe and Australia have very low sediment yields, South America's yield is low, North America's is moderate, and Asia's is high and yields up to 80% of the sediment reaching the oceans annually. Holeman also draws attention to the fact that, in most rivers, only a very low percentage (about 5% for the Potomac River Basin) of the products of erosion in a water shed reach tide water. In other words there is a storage of material between the areas of erosion and the areas of tide water deposition. This immediately questions the usefulness of determining sediment transport rates for rivers! Should such data be obtained for small upland catchments or headwater tributaries where erosion rates are higher but the proportion of sediment reaching tide water is limited, or should the data be for larger catchments or entire river catchments where all sediment reaching tide water is determined but the total erosion is not known? Perhaps a position between these two extremes is a suitable alternative for some purposes; the best study obviously involves a comparison of data for different positions along the entire length of a river and its

tributaries. Associated with this would be the change in grain size of any particular sediment type (bed load or suspended load) that is likely to occur with position of channel traverse and distance from source.

Erosion and introduction of sediment into a river system can occur by one of two processes: sheet erosion and channel erosion. The controls and factors affecting the rate of these processes are well explained in a summary by Colby (1963). Once elastic sediment has been introduced into a river channel it may be transported as suspended load or as bed load. The definitions of these terms are discussed in the introduction to this thesis. The total load removed from the Rother Catchment has been sub-divided into the dissolved load, the suspended load, and the bed load, and estimation of transport rates for each of these sub-divisions were attempted. Particular emphasis was placed on the bed load as this is probably the least well studied division, and the estimations of bed load are more problematical.

DISSOLVED LOAD

Two important constituents of the dissolved load within the present study catchment will be Ca^{2+} and HCO_3^- . Most of this will be the result of the solution of the Chalk and it should prove possible to obtain information of the rate of solution and removal of CaCO_3 by the waters entering the Rother. (The purpose of this part of the study was to determine the rate of Chalk solution). Much work has been done on the dissolved load and chemistry of river waters (including Starkey and others, 1971; Slatt, 1972; Edwards and Thorne, 1970;

Miller, 1961; Jacobson and Langmuir, 1972; and Canberra, 1964), but studies on waters draining from limestone areas are somewhat more limited but include Back and Hanshaw, 1970; Shuster and White, 1971; and Edwards, 1973 (two papers).

Back and Hanshaw (1970) compared the chemical hydrogeology of two carbonate peninsulas (Florida and Yucatan) and concluded that differences between these two areas are due to, in the main, the absence of an upper confining bed in Yucatan that is present in Florida. A difference in elevation between the two peninsulas may be a secondary cause of hydrologic and chemical difference.

A study of 14 carbonate springs in the Appalachians (Shuster and White, 1971) indicated that aquifer systems with different flow mechanisms can and do exist in the same hydrogeological environment, and that they can be distinguished by the behaviour of their dissolved constituents. A diffuse flow feeder system type of spring (when the flow is governed principally by "Darcy's" Law) is characterised by a more constant hardness of water, whereas a conduit feeder system type of spring (where pipe flow occurs along a system of fractures, pipes and conduits) is characterised by a very variable hardness throughout the year.

Edwards (1973a) estimated CaCO_3 erosion rates of 58.0 tonnes/km² (River Yar) and 39.2 tonnes/km² (River Tud) for two rivers draining from the Chalk in Norfolk. In his other paper Edwards states that calcium/discharge correlation coefficients are low and that large storms have little effect on calcium concentrations. This is explained by two sources of calcium being present in the catchment. One source

is calcium carbonate which is transported in the bicarbonate form and which decreases in concentration with increased discharge, and calcium sulphate, which increases in concentration with increased discharge. This results, in the Norfolk Rivers, according to Edwards, in a compensation of reduced calcium from CaCO_3 with increased discharge.

Pitty (1971, p.368) indicates values of CaCO_3 in solution of over 220p.p.m. for streams draining over chalk.

SUSPENDED LOAD

The suspended load will be the major agent of removal from the study catchment, of material of clay ($> + 8\phi$) and silt ($+ 8\phi$ to $+ 4\phi$) size ranges. Data on suspended sediment load of streams are widespread in the literature and recent studies include Wolman (1955), Hall (1967), Douglas (1967), Arnberg and others (1967), Holeman (1968), Rodolfo (1970), Walling and Teed (1971), and Brown III and Ritter (1971).

Suspended sediment concentrations are very variable, both between rivers and within any given river, and studies of the suspended load are usually concerned with one or more of three distinct aspects:

1. the actual quantity of material per unit volume of water;
2. the total quantity of material transported in a given period of time; and
3. the size of the particles moved in suspension.

With any given river, these three aspects generally correlate, as an increased load per unit volume will cause an increase in the total load carried, and this is generally accompanied by an increase in the medium

grain size of material being carried. Also, these aspects in general show a positive correlation with the river's discharge. Hjulström (1935) however has shown that in temperate regions the major exception to this relationship occurs during spring flooding when the maximum load per unit volume of water generally precedes the peak of the flood hydrograph. This is because the rate at which the sediment reaches the river from the catchment increases more rapidly than the rate of increase in river stage. Another reason, proposed by Arnborg and others (1967) is that the first sediment entrained during the rising stage is that which was last deposited during the falling stage of the previous flood hydrograph. This material lies loosely on the channel bed and is readily eroded. By the time the flood hydrograph reaches its peak, the channel floor may be paved with sediment that is less easily entrained. Arnborg and others show that the relationship between suspended sediment and river stage is somewhat different in Arctic rivers because of the presence of other physical controls such as permafrost, snow and ice cover, and the nature of river-ice breakup, precipitation and type of vegetation. This very interesting report includes four graphs (op.cit., Fig.6, p.136) with curves showing suspended load plotted against stage, for four different periods of time. Three of the four curves take on the form of loops, exhibiting a hysteresis effect so that suspended sediment concentrations are greater for any given discharge on the ascending limb than on the descending limb.

Walling and Teed (1971), after analysis of several samples collected through the passage of a storm hydrograph on a small stream

in Devon, also produced a hysteresis loop when suspended sediment concentrations were plotted against discharge. It is these hysteresis loops that should be regarded as rating curves, and not the simple line relationship produced by some workers (Hall, 1967; Leopold and Maddock, 1953; Wolman, 1955; Brown III and Ritter, 1971). Also, any particular hysteresis loop is only really applicable to a particular storm hydrograph as a similar hydrograph may produce a different suspended sediment concentration for the same discharge. However, the formation and analysis of all the necessary rating loops in this way is a great time consumer. However, it is worthwhile, for greater accuracy is obtained, as can be imagined when comparing the hysteresis plot, and the diagram of all sediment concentrations obtained plotted against discharge (Walling and Teed, 1971, Fig.40, p.332 with Fig.5, p.334). In the latter there is a considerable degree of scatter which also emphasises the lack of accuracy when using a simple line relationship as a rating curve.

Hall (1967) working on the River Tyne of North East England produced three rating curves for a single station (op.cit., Fig.7, p.128). One line describes samples taken during low flow, while the other two lines describe samples collected at different conditions of flow during summer and winter respectively. Indeed, his line for the summer period indicates higher suspended sediment concentrations for a given discharge than for the winter period. This, he explains, is a function of two characteristics: the change in vegetation from summer to winter, and the characteristics of rainfall intensity:

"Rainfall intensities are highest during thunder storms which are

suspended sediment discharge of 110 million tons was computed

almost entirely confined to the summer months. High intensity falls cause a high percentage of run-off with consequent heavy erosion of the ground surface. During winter months, however, most precipitation is of a frontal nature and is less intensive." (Hall, 1967, p.129).

However, this relates concentration to discharge, and does not fully explain a difference in concentration with time. (It is the present author's opinion that an important factor is the frequency of successive flood hydrographs. If the interval between successive floods is short, it is likely that material of a size suitable to be carried in suspension is limited and may become somewhat exhausted, and so rapidly successive flood hydrographs may have significantly smaller sediment concentrations for a given discharge. As the frequency of hydrographs is greater in winter than in summer it is likely that suspended sediment values for winter are lower than in summer.

Brown III and Ritter (1971) working on the Bel River, California, also produced two curves (op.cit., Fig.12, p.32) to describe the relationship of suspended sediment discharge to water discharge for a single station. These two lines, however, referred to a much larger time scale with higher suspended sediment values for a given discharge being obtained from samples collected during 1965-1967 than for the samples collected during the six previous years.

The importance of high flows on suspended sediment transport rate is well documented (Douglas, 1967; Arnborg and others, 1967, etc.). Of these, an example that well illustrates the point is the Bel River of California (Brown III and Ritter, 1971). During the 1964 flood, for example, a

suspended sediment discharge of 116 million tons was computed

for the Bel River at Scotia, for a 3-day period beginning December 22nd, 1964. The total suspended sediment load at this station for the previous 8 years amounted to 94 million tons, (Brown and Ritter, 1971, p. 25).

Work on the correlation of suspended sediment load with other parameters includes that of Leopold and Maddock (1953) who have shown that the quantity and concentration of suspended sediment are related to the channel shape. Also, Vanoni (1941) and Schnackenberg (1951) have shown that bed roughness may be influenced by suspended sediment concentration. Vanoni suggests that high sediment values will reduce energy loss by friction due to the dampening effect of turbulent eddies.

Wolman (1955), after a study of the Brandywine Creek, Pennsylvania, shows that the channel cross-section and gradient are approaching a state of dynamic equilibrium. This is indicated from measurements of discharge, width, depth, velocity, slope and suspended sediment load, and the computation of a roughness factor. The gradient and shape of the channel at any given reach are assumed to be primarily a function of the discharge and load supplied to it, and of the material supplied to the bed of the stream, both within the reach and from upstream.

So, the exact controls of suspended sediment concentrations in streams, and its effects on other parameters such as bed roughness, channel gradient and shape are not fully understood. However, estimates of suspended sediment discharge have been obtained for many rivers, and the author is of the opinion that one of the major controlling factors of concentration, the time period between successive hydrographs, has somewhat been overlooked.

BED LOAD *Measuring indicative of fluvio-sediment transport. Such transport*

Methods of determining amounts of material transported as bed load have mainly been approached from two main aspects:

1. The more practical approach mainly involving field sampling of moving sediment.
2. The more theoretical approach mainly concerning the construction of sediment transport equations (often for the total load) based on such characteristics as river velocity, grain size distribution, bed roughness, and hydraulic parameters etc., but possibly involving some field sampling.

The first approach is hampered by the much discussed practical problem associated with bed load studies: that is the actual sampling of moving material on the river bed. Hubbel (1964) and Painter (1972) have reviewed and summarised most of the post- and out-dated sampling methods, and described in some detail their limitations. They also give some consideration to more recently developed ideas. The problem of bed load sampling has occasionally been overcome by the use of the turbulence flume (Colby and Hembree, 1955; Benedict and others, 1955; and Hubbel and Matejka, 1959). Here, turbulence is increased sufficiently to cause suspension of the bed load particles, so that samples can be collected by the ordinary method of sampling for suspended sediment. However, this method only provides information of the total sediment load, and the bed load can only be estimated if suspended loads are determined for a stretch just upstream of the turbulence flume. This is supported by Hubbel and Matejka (1959) working on the main river, who state that "the suspended

More recent methods for studying the bed load include tracer

techniques involving radioactive or fluorescent tracers. Such tracers were first used for coastal studies, but have more recently been applied to streams. A literature survey of these methods (see Section II, Chapter 3) suggests that they have some potential for the accurate determination of bed load.

The second and more theoretical approach involves the many sediment transport equations that have been developed, often on the basis of flume studies. The accuracy of these methods is somewhat variable, and many of these are again concerned with the total sediment load. They include: e.g. Douglas, 1957; Rinaldo, 1970; 1,646). It is

Du Boys Procedure	activities are usually associated with
Straub Procedure	(Straub, 1935)
Schoklitsch Formula	and generally as in (Shulits, 1935)
Meyer-Peter and Muller Formula	(Meyer-Peter and Muller, 1948)
Einstein Procedure	time period of the (Einstein, 1950)
Modified Einstein Procedure	(Colby and Hembree, 1965)
Bagnold Transport Equation	(Bagnold, 1946)
Laursen Method	(Laursen, 1958)

Similar and more recent formulae are presented by Einstein and Abdel-Aal (1972), Bishop and others (1965) and Simons and others (1965).

Reliable data of bed load are somewhat limited but is generally accepted to be only a minor percentage of the total sediment load. Fisk and others (1954) estimated that between 7-10% of the detrital load issuing from the Mississippi is transported as bed load. However, Serr (1950) reports that, at times, up to 50% of the total sediment load of the Niobrara River may be transported as bed load. Also, Vice and Serr (1950) estimated bed loads of up to 55% of the total load for the Middle Loup River, Nebraska. This is supported by Hubbell and Matejka (1959) working on the same river, who state that "the suspended

sediment discharge...averages about one half of the total sediment discharge," (Hubbell and Matejka, 1951, p.1).

THE DISSOLVED LOAD

The bed load, then, probably forms a variable percentage of the total sediment load, depending on the conditions of flow, turbulence, etc. It appears also that in some rivers the bed load can be as important as the suspended load in the removal of clastic sediment.

EFFECTS OF MAN

The effects of man on the total load of rivers have also been documented (e.g. Douglas, 1967; Rodolfo, 1970, p.668). It is sufficient to say that man's activities are usually associated with increased sediment discharges, and generally an increased amount of run-off and reduction in the time period of the basin-lag of the flood hydrograph.

THE DISSOLVED LOAD

The source of dissolved calcium for the waters of the River was 1. Point 12: the calcium content of rainfall is negligible and may be neglected when dealing with the dissolved load of streams draining chalk or limestone areas (Hallsforth and Cornford, 1953, and Edwards, personal communication). Stoverson (1963) shows that the calcium content of rain water falling on the study area for the years 1957-1964 was between 1.5 and 2.0 mg/l. The importance

CHAPTER 1

THE DISSOLVED LOAD

INTRODUCTION

The dissolved load of a stream or river is that part of the total sediment load that is characterised by the absence of solid clastic material and it consists only of substances in solution. As the purpose of this study is a determination of the source rock and rate of removal of material from the source rock, the obvious and most important constituents present in the dissolved load will be calcium and bicarbonate ions. The majority of these ions in the Rother would be derived from the solution of the Chalk and so determination of their content in the dissolved load will provide information on the rate of solution of the Chalk by the waters flowing in the Rother. The author has done very little work concerning the dissolved load of the River Rother, and for the methodology and data presented here is indebted to Dr. A.M.C. Edwards.

SOURCES OF CALCIUM FOR THE DISSOLVED LOAD

The sources of dissolved calcium for the waters of the Rother are:

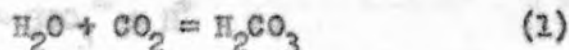
1. Rainfall: the calcium content of rainfall is negligible and may be neglected when dealing with the dissolved load of streams draining chalk or limestone areas (Hallsworth and Crawford, 1965; and Edwards, personal communication). Stevenson (1963) shows that the calcium content of rain water falling on the study area for the years 1959-1964 was between 1.5 and 2.0 mg/l. The importance

of the calcium in the rainfall upon the calcium in the river water is dependent not only on the original concentration but also on the amount of concentration in the river water due to evaporation of water from the ground surface.

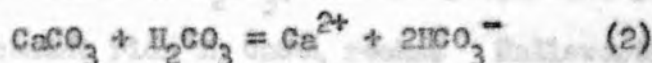
2. Soils: some calcium may be derived from solution of compounds of the soil. However, as much of the soil developed on the Chalk within the study area is derived from the Chalk then dissolved calcium from these soils may be regarded as having an origin from the Chalk. Some soils developed on the Chalk, but of limited extent, may not be entirely formed from the underlying Chalk, but include a component of loess-like drift or is a clay-with-flints soil. Relatively little calcium will be derived from these soils. The amount of calcium that will be derived from the soils developed on other rocks in the catchment, and from fertilisers and any lime that is spread onto them is not known. It is likely that the amount involved is negligible compared to that derived from the Chalk. The effects of animals and plants is again considered negligible and any calcium supplied by these would be originally derived from the calcium of the soil or the rainfall.

3. Chalk: the majority of the dissolved calcium and bicarbonate in the water will be derived directly from the solution of the calcium carbonate of the Chalk (Edwards, personal communication). Calcium carbonate is almost insoluble in pure water, but if carbon dioxide is present it becomes converted to the more soluble calcium bicarbonate. So, rainwater containing carbon dioxide (from the

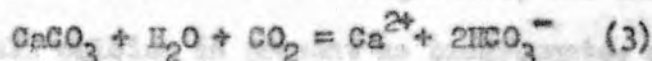
atmosphere or soil air) will behave as carbonic acid (equation 1) which is a widely and naturally occurring weak acid:



This rain water containing carbon dioxide is now capable of dissolving the calcium carbonate of the Chalk (equation 2) which is then removed in solution by the river:



Equations (1) and (2) can be represented:

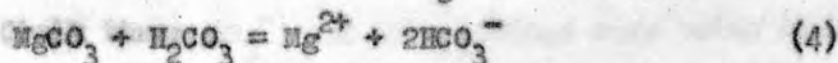


4. Other rocks: the Upper and Lower Greensands may provide some calcium and are probably a secondary source.

VALUE OF THE DETERMINATION OF THE Ca^{2+} CONTENT

Determination of the Ca^{2+} content of the dissolved load however is not sufficient to provide information concerning the rate of Chalk solution. This is because of the presence of other minor Ca^{2+} sources, such as other calcium compounds, e.g. sulphates, nitrates and chlorides. Of these calcium sulphate is possibly a significant source of Ca^{2+} (Edwards, personal communication); for example, gypsum (Ca SO_4) is present in the Gault (Cowan, personal communication).

In order to determine the rate of removal of dissolved Chalk it is also necessary to determine the HCO_3^- content of the dissolved load. Virtually all the HCO_3^- comes from solution of CaCO_3 of the Chalk (Edwards, personal communication). There is little or no magnesium carbonate present to provide HCO_3^- (equation 4):

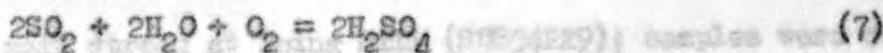


However, carbonic acid is a potential supplier of HCO_3^- as it dissociates in two stages thus:



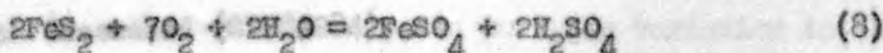
Thus it is possible for some HCO_3^- to be present due to the first stage of the dissociation of H_2CO_3 , but the proportion present will be small in a catchment rich in CaCO_3 rocks. Hallsworth and Crawford (1965) state that on the Chalk in Cambridgeshire, the error involved in assuming that all calcium is present as bicarbonate, and consequently ignoring sulphate, and nitrate, is negligible. Similarly therefore the assumption that all the HCO_3^- is from the Chalk, and that all the carbonate from the Chalk is present as HCO_3^- is probably valid for the present study area. It is possible however that a small amount of the CaCO_3 of the Chalk is removed by solution by sulphuric acid and not carbonic acid. The sources of this sulphuric acid are twofold:

1. sulphur dioxide in the atmosphere:

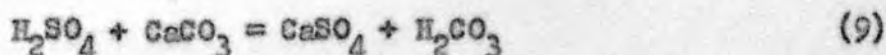


The amount of sulphuric acid produced by this method is small and only significant in areas of great industrial activity.

2. By the oxidation and hydrolysis of FeS_2 minerals: pyrite and marcasite. These minerals are both present in the rocks of the catchment: marcasite decomposing more readily than pyrite.



The sulphuric acid is then able to react on the CaCO_3 of the Chalk thus:



Then:



The H_2CO_3 (equation 9) is then available for solution of more CaCO_3 (equation 2). The amount of CaCO_3 removed as Ca^{2+} and SO_4^{2-} is considered very small.

So, in an attempt to determine the rate of removal of CaCO_3 from the catchment the bicarbonate content of the river waters was determined. The calcium content was also determined and by balancing the charge of anions and cations this will provide an estimate of calcium derived from sources other than CaCO_3 .

COLLECTION OF SAMPLES, TREATMENT AND ANALYSIS

The samples of river water for dissolved load were collected during the 1971-1972 water year from four types of location:

1. Chalk springs: several springs within the catchment were sampled so that values could be determined for waters issuing from the Chalk aquifer.
2. The main stream at Iping Mill (SU854229); samples were collected here so that values for waters leaving the catchment as a whole could be determined.
3. The Hammer Stream; low values were expected here due to the lack of carbonate rich rocks in the Hammer sub-catchment.
4. The Rother in the upper catchment where it drains only the Lower Greensand (SU783284).

Water samples were collected in polythene bottles (inert as regards Ca^{2+} and HCO_3^-) and when springs were being sampled attempts

were made to get as close to the actual spring as was possible. The samples were filtered, as soon as possible after collection, through Whatman GF/C filter pads to remove solids and then diluted five times in 1% lanthanum chloride solution. If any storage was necessary the samples were stored in this solution. Deep freeze storage is not recommended as CaCO_3 may precipitate out upon thawing from an originally supersaturated solution.

The Ca^{2+} concentration values were measured on a Pye Unicam S.P.90 Atomic Absorption Spectrophotometer. HCO_3^- concentrations were determined by the method of Mackereth (1963). 25.0 ml. of sample was titrated with 0.05N HCl (standardised against NaCO_3) to an end point at pH 4.5 (as shown by the "B.D.H." 4.5 pH indicator). Concentration of HCO_3^- was then determined thus:

$$\frac{\text{mg/l } \text{HCO}_3^- = \text{vol. titrated in ml.} \times N \times 1,000 \times \text{molecular weight of } \text{HCO}_3^-}{\text{vol. of sample in ml.}} \quad (11)$$

RESULTS AND INTERPRETATION

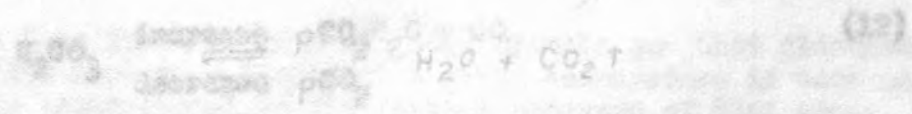
The Ca^{2+} and HCO_3^- values for the dissolved load of samples collected from the four localities during the 1971-1972 water year are presented in Table 35.

The samples collected from the Hammer Stream and the River Rother draining only from the lower Greensand have the lowest values, and the concentration is apparently more stable during a variation in conditions of flow. The low values are easily explained due to the absence of calcium rich rocks in their catchments. These values may be considered

Table 35. Ca^{2+} and HCO_3^- concentrations in the River Rother for the 1971-72 water year. (Edwards, personal communication).

	mg/l			
	Ca^{2+}	HCO_3^-	Ca^{2+}	HCO_3^-
	Low Flow	High Flow	Low Flow	High Flow
Chalk Springs	75-80	60+	205-326	170-270
Iping Mill	30-60 typically 55	35-50	180	70-140
Hammer Stream	15-20	15-20	40-60	40-60
Rother above SU 783284	15-20	15-20	---	---

As low flow the bicarbonate values for Chalk springs are between 205-326 mg/l. The high values are due to the presence of the Chalk providing Ca^{2+} and HCO_3^- rich groundwaters. As low flow the dilution of HCO_3^- rich water from the Chalk is the result of the super-saturated water from the Chalk aquifer equilibrating with the atmosphere. As saturation of $CaCO_3$ in water is controlled by the partial pressure of carbon dioxide, (the higher the partial pressure the higher the amount of CO_2 in solution), and as the partial pressure of CO_2 is probably higher in the pores of the Chalk than in the free atmosphere (Edwards, personal communication), it would be expected that some CO_2 would be lost from solution after the waters have issued from the aquifer:



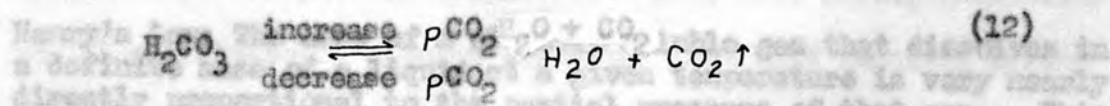
For this to occur, the following must also occur:



indicative of the rate of removal of Ca^{2+} from rocks in the catchment other than Chalk.

Samples from locations near to Chalk Springs and at Iping Mill give higher values for both Ca^{2+} and HCO_3^- at conditions of low flow which become somewhat diluted by storm run-off waters during conditions of high flow. The high values are due to the presence of the Chalk aquifer providing Ca^{2+} and HCO_3^- rich ground-waters.

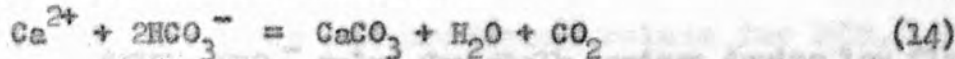
At low flow the bicarbonate values for Chalk springs is between 205-326 mg/l whereas the values at Iping Mill are 130 mg/l. This difference may be due to the dilution of HCO_3^- rich water from the Chalk aquifer by HCO_3^- poor water from the Lower Greensand aquifer, or it may be the result of the super-saturated water from the Chalk aquifer equilibrating with the atmosphere. As saturation of CaCO_3 in water at 18°C occurs at 13 mg/l, water issuing from the Chalk springs is supersaturated with calcium (in respect to CaCO_3). Now, as one of the controlling factors for the solution of CaCO_3 in water is the partial pressure of carbon dioxide, (the higher the partial pressure the higher the amount of CO_2 in solution), and as the partial pressure of CO_2 is probably higher in the pores of the Chalk than in the free atmosphere (Edwards, personal communication), it would be expected that some CO_2 would be lost from solution after the waters have issued from the aquifer:



For this to occur, the following must also occur:



Equations (12) and (13) may be combined:



So, if on exposure to the free atmosphere, the spring waters equilibrate to the partial pressure of the atmospheric carbon dioxide (as controlled by Henry's Law¹) the solubility of CaCO_3 will decline as CO_2 falls as long as no other acids are involved. This will result in the precipitation of CaCO_3 . Indeed, CaCO_3 is being precipitated in Buriton Pond (SU739209) (Edwards, personal communication). This precipitate in Buriton Pond has been subjected to X-ray diffraction analysis and has been found to be calcite. Also, this precipitation of CaCO_3 as calcite from waters issuing from Chalk springs would account for the presence of calcite as suspended sediment in streams even at conditions of low flow (Section I).

The Rother at Iping Mill is slightly supersaturated with respect to CaCO_3 during low flow, and the presence of phosphate from sewage effluents may inhibit CaCO_3 nucleation and hence prevent the precipitation of calcite (Edwards, personal communication).

It is possible to predict, from the HCO_3^- values, approximately how much of the Ca^{2+} has its source from the solution of CaCO_3 , and how much is from other sources. This can be done using the atomic

Similarly, the predicted and observed Ca^{2+} concentrations are in good

agreement for the water collected from Iping Mill during conditions of

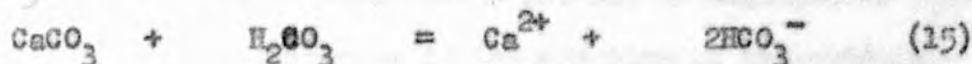
¹ Henry's Law: The mass of a slightly soluble gas that dissolves in a definite mass of a liquid at a given temperature is very nearly directly proportional to the partial pressure of that gas. This holds for gases which do not unite chemically with the solvent.

and measured values for Ca^{2+} . Predicted values are approximately

14 mg/l while observed values are 15-30 mg/l. This means that up to

weights of the elements involved:

Table 36. Measured and predicted values for HCO_3^- , Ca^{2+} and CaCO_3 .
 GIVEN: HCO_3^- value for chalk springs during low flow of 265 mg/l



Atomic Weight	$40+12+16_3$	+	$1_2+12+16_3$	=	40	+	$2(1+12+16_3)$
Molecular Weight	100	+	HCO_3^- 62	=	40	+	Ca^{2+} 122
mg/l	217	+	mg/l 135	=	mg/l 87	+	mg/l 265

So, for a concentration of 265 mg/l HCO_3^- , 87 mg/l of Ca^{2+} derived from the solution of CaCO_3 should be present. This represents 217 mg/l CaCO_3 being dissolved in one litre of spring water. The predicted values of Ca^{2+} obtained in this way, and the actual measured values are represented in Table 36 along with the predicted values of CaCO_3 in solution. These values are comparable to Pitty's data (1971, p.368) for streams on Chalk.

The predicted concentrations of Ca^{2+} are in good agreement with the observed concentrations for water issuing from the Chalk springs both at low flow and during high flow. This indicates that most of the calcium in the waters issuing from springs is derived from the solution of CaCO_3 and that very little is derived from other sources. Similarly, the predicted and observed Ca^{2+} concentrations are in good agreement for samples collected from Iping Mill during conditions of low flow. However, samples collected from this locality during conditions of high flow show a relatively poor agreement of predicted and measured values for Ca^{2+} . Predicted values are approximately 34 mg/l while observed values are 35-50 mg/l. This means that up to

Table 36. Measured and predicted values for HCO_3^- , Ca^{2+} , and CaCO_3 .

	Measured HCO_3^- mg/l	Predicted Ca^{2+} mg/l	Measured Ca^{2+} mg/l	Predicted CaCO_3 mg/l
Chalk Spring				
Low Flow	265	87	75-85	217
Chalk Spring				
High Flow	220	72	60+	180
Iping Mill				
Low Flow	180	59	30-60 typically 55	148
Iping Mill				
High Flow	105	34	35-50	86

As aquifers on the Chalk are more likely to be controlled by a diffuse-flow feeder system to springs the hardness of waters issuing from them may be fairly constant (Shuster and White, 1971). Minor fluctuations in values may occur due to a variation in other controlling factors, but with the assumption that these have only a negligible effect the amount of CaCO_3 removed in solution during the 1971-1972 water year is approximately 6,120.6 tonnes. Of this 4,273.6 tonnes is removed during conditions of low flow and 1,846.9 tonnes is removed

16 mg/l of the observed Ca^{2+} is derived from sources other than the solution of CaCO_3 . This assumes that the proportion of CaCO_3 that is removed as Ca^{2+} and SO_4^{2-} (equations 9 and 10) is negligible. The most likely other source of calcium is the solution of pre-existing CaSO_4 within the catchment with a small but unknown proportion from the rainfall. No determinations of SO_4^{2-} concentrations were made but values predicted by the method used to predict Ca^{2+} are in the range of up to 38 mg/l. This gives a figure of CaSO_4 concentration of up to 54 mg/l.

CaCO_3 erosion rate for the Chalk areas. However, the determination of this rate would also require the groundwater
DETERMINATION OF THE CALCIUM CARBONATE EROSION RATE

The total amount of any constituent of the dissolved load removed from a catchment is the product of its concentration and the river's discharge. If the data for CaCO_3 in solution at Iping Hill presented in Table 36 are assumed representative of water leaving the catchment during conditions of high and low flow it is possible to determine the rate of removal of CaCO_3 in solution with a knowledge of the discharge data (obtainable from the Sussex River Authority).

As aquifers on the Chalk are more likely to be controlled by a diffuse-flow feeder-system to springs the hardness of waters issuing from them may be fairly constant (Shuster and White, 1971). Minor fluctuations in values may occur due to a variation in other controlling factors, but with the assumption that these have only a negligible effect the amount of CaCO_3 removed in solution during the 1971-1972 water year is approximately 6,128.6 tonnes. Of this 4,273.8 tonnes is removed during conditions of low flow and 1,854.8 tonnes is removed

3. The Ca^{2+} and HCO_3^- concentrations of water passing over the Iping

during conditions of high flow. This gives an erosion rate of CaCO_3 in solution for the 1971-1972 water year, for the catchment above Iping Mill as a whole, of 39.8 tonnes/km^2 . This compares well with erosion rates of 58.0 tonnes/km^2 (River Yare) and 39.2 tonnes/km^2 (River Tud) obtained by Edwards working on catchments that included Chalk as a bed-rock (1973a).

However, if most of the CaCO_3 is assumed to be derived from the Chalk, and as the area of Chalk outcrop is very restricted, this will give a much higher CaCO_3 erosion rate for the Chalk areas. However, the determination of this rate would also assume that the groundwater divide is coincident with the topographic divide. If only 50% of the CaCO_3 in solution passing Iping Mill is derived from solution of the Chalk this will give an erosion rate for the area of Chalk outcrop of $141.5 \text{ tonnes/km}^2/\text{year}$.

CONCLUSIONS

Despite limited data, and the necessity for several assumptions it seems that the following conclusions can be made from the study of the Ca^{2+} and HCO_3^- concentrations of the dissolved load:

1. Most of the Ca^{2+} and HCO_3^- of the dissolved load is derived from the solution of CaCO_3 from the Chalk.
2. The Ca^{2+} and HCO_3^- concentrations of water issuing from Chalk springs fluctuates by only small amounts ($220-265 \text{ mg/l}$ for HCO_3^- and $60-85 \text{ mg/l}$ for Ca^{2+}) with a variation in discharge, and all of the Ca^{2+} seems to be from the solution of CaCO_3 .
3. The Ca^{2+} and HCO_3^- concentrations of water passing over the Iping

SECTION II

Mill crump weir is more variable (105-130 mg/l for HCO_3^- and 30-60 mg/l for Ca^{2+}) and appears to be controlled by discharge, lower values during conditions of higher flow being the result of dilution by run-off waters.

4. Waters issuing from the springs and waters passing Iping Mill are saturated in Ca^{2+} with respect to CaCO_3 .

5. Most of the Ca^{2+} of the water passing Iping Mill is derived from the solution of CaCO_3 , but some (up to 16 mg/l) is possibly

derived from the solution of CaSO_4 . The amount from sources other than the solution of CaCO_3 is higher during conditions of high flow and will be introduced by overland flow and run-off.

6. Values of 15-20 mg/l Ca^{2+} and 40-60 mg/l HCO_3^- are found in waters draining from the Lower Greensand and Weald Clay.

7. The erosion rate of CaCO_3 for the catchment above Iping Mill as a whole for the 1971-1972 water year is approximately 39.8 tonnes/ km^2 . However the erosion rate for the area of the Chalk outcrop is probably much greater.

8. Some CaCO_3 is probably removed as calcite in the suspended load.

Suspension is generally viewed as the major transporting mechanism in streams, and sediment yields of streams are often based on data concerning the suspended load only. In the present stream suspension is still the major method of elastic sediment removal, but, due to the extensive occurrence of poorly consolidated sandstone within the catchment, it is possible that bed load transport removes a greater

SECTION II

CHAPTER 2

THE SUSPENDED LOAD

INTRODUCTION

The suspended load of a stream is that part of the total sediment load that is composed of clastic particles that move entirely surrounded by, and at essentially the same velocity as the river water.

In the present study catchment this method of transport was considered responsible for the removal of the majority of the sediment of the clay and silt size that is lost. It is also likely that some of the finer sand sizes are transported in suspension. The source rocks for the sizes of material carried in suspension are, potentially, all of the rocks of the catchment. However, as many of these rocks include sandstones, it is likely that the majority of the suspended sediment is derived from the finer grained rocks, particularly the Gault and Weald Clay. However, mineralogical analysis of source rocks, of soils, and of suspended sediment and river alluvium provided very little information regarding the source rocks of the suspended sediment (Section I).

Suspension is generally viewed as the major transporting mechanism in streams, and sediment yields of streams are often based on data concerning the suspended load only. In the present stream suspension is doubtless the major method of clastic sediment removal, but, due to the extensive occurrence of poorly consolidated sandstones within the catchment, it is possible that bed load transport removes a greater

proportion of total clastic load than it would in other streams.

Samples of water were collected with a view to determining the suspended sediment concentration at different localities on the river network, and to determining the total suspended sediment discharge at Iping Mill gauging station (sample location F, Table 37). This locality was chosen due to the presence there of a continuously recording stage recorder and crump weir to provide river discharge data.

COLLECTION OF SAMPLES AND LABORATORY TREATMENT

Samples of water for the determination of the suspended sediment concentrations were collected from various sampling localities. These localities, and the method of instrumentation are listed in Table 37, and their position indicated on Fig. 3.

Samples were collected by a variety of sampler types and sampling methods: one-point samples, multi-point samples. A comparison and discussion on the concentrations in the samples obtained by the different methods is given later in this chapter. The volume of samples was generally 1 litre, and these were collected at a variety of flow conditions during the passage of storm hydrographs, and at conditions of base flow.

After collection, 1,000 cc of sample (or 500 cc if concentrations were high) were filtered, as soon as possible, through leached, dried and pre-weighed Whatman GF/C Filter Circles using a Buchner Funnel and filter pump. Care was taken that no sediment adhered to the side of vessels involved, and to the side of the Buchner Funnel. The filter

Table 37. Sample location and instrumentation for collection of samples for suspended sediment concentration.

Station	Location	Instrumentation
A	main channel	Stage post
B	main channel	Continuous stage recorder
C	main channel	Stage post
D	main channel	Stage post
E	main channel	Stage post
F	main channel	Continuous recording gauging station & 3 crump weir
G	main channel	Stage post
H	Hammer Stream	Stage post
J	Chalk spring	Continuous recording gauging station & single crump weir

DEFINITION AND COMPARISON OF SUSPENDED SEDIMENT SAMPLES AND METHODS USED

One point samples were collected using a sampler similar to that described by Hall (1967, p.127). Other one point samples were collected by introducing a wide necked open bottle into the flow. This would sample water by the principle described by Redolfo (1970, p.667).

A multi-point sampler was also used to collect samples. This consisted of 5 sample containers whose height above the river bed could be adjusted according to desired height for sample collection, depth

circles were then carefully removed and dried in an oven, allowed to cool in a desiccator, allowed to equilibrate with the atmosphere and then reweighed. Concentrations could then be determined as mg/l for each sample involved.

Determination of the percentage by weight of the organic material in the samples was more complex and followed on from the determination of suspended sediment concentrations. After the second weighing of the filter circles, the sediment on them was sprayed with ethanol and ignited. They were then placed in an oven at 500°C for 24 hours. They were then removed, cooled in a desiccator, allowed to equilibrate with the atmosphere and weighed for a third time. The resultant loss in weight, after the application of a correction factor, was considered to be due to the loss of organic material. It was found that a correction factor of 4mg for each filter was necessary as the circle would lose this amount during the treatment, even if no suspended sediment was present.

DESCRIPTION AND COMPARISON OF SUSPENDED SEDIMENT SAMPLES AND METHODS USED

One point samples were collected using a sampler similar to that described by Hall (1967, p.127). Other one point samples were collected by introducing a wide necked open bottle into the flow. This would sample water by the principle described by Rodolfo (1970, p.667).

A multi-point sampler was also used to collect samples. This consisted of 5 sample containers whose height above the river bed could be adjusted according to desired height for sample collection, depth

of flow etc. Then, a trigger mechanism allowed 5 instantaneous samples to be collected along a vertical. There were some practical difficulties involved in using this apparatus, but it was able to provide information on the vertical distribution of suspended sediment concentration. The device was used at sample localities F and G.

A depth integration sampler was also used, and this provided a basis for determination of the accuracy of the spot samples collected.

A rising stage sampler was also constructed and installed at Iping Mill (sample location F) to sample automatically at pre-determined conditions of stage on the rising limb of the flood hydrograph. There were some problems associated with this sampling device, and these culminated in the whole apparatus being swept away during the flood of 1st-2nd December, 1972. The sampler was recovered, but not re-installed.

The results of the analysis of suspended sediment concentrations collected by the multi-point sampler described are presented in Table 38. These samples were collected from Iping Mill (location F) during the passage of a broad peaked hydrograph and at a discharge of $3.9\text{m}^3/\text{sec}$. The results show that there is very little vertical variation in the suspended sediment concentration, and in each vertical sampled the difference between the highest and lowest concentrations is no more than $20\text{mg}/\text{l}$. As the lowest sample location does tend to have a higher concentration than the highest sample location this may represent a real vertical concentration gradient. However, if it does exist, this vertical concentration gradient is of a low value and due to the very turbulent nature of the flow at this location.

These results indicated that a one-point sample taken from a position

Table 38. Suspended sediment concentrations of samples collected with a multi-point sampler at location F on 10-5-72.

Height of sample above river bed	Time of sample		
	15.45	16.15	16.20
50cm	121 mg/l	89 mg/l	78 mg/l
39cm	135 "	107 "	80 "
29cm	126 "	91 "	85 "
19cm	122 "	87 "	85 "
4cm	141 "	96 "	98 "
Depth of water at sampling location	56 cm	56 cm	56 cm

RESULTS OF THE SUSPENDED SEDIMENT DETERMINATIONS.

The results of samples collected during conditions of medium flow and of base-flow will be considered in turn. Organic content and detritus variation is also considered.

approximately in the middle of the depth of flow would be a representative sample for the determination of suspended sediment concentrations as turbulent flow ensures thorough mixing of the waters and suspended sediment. To test this, six samples were collected by the one-point sample technique during conditions of low flow, when turbulence would be at a minimum. These gave a suspended sediment concentration ranging from 3mg/l to 5mg/l. Due to the close agreement of these values, samples collected from Iping Mill (location F) were generally collected by a one-point sample method, but occasionally using the depth integration sampler. The latter proved more difficult to operate during conditions of high flow.

Samples obtained by the rising stage sampler gave suspended sediment concentrations that were extremely high (occasionally over 2,500mg/l). The reason for this is not quite certain. Although the apparatus was fitted with a device to prevent entry of any solid sediment and river water after the sample bottle was filled, it is possible that some suspended sediment entered into the already filled bottle, and on settling out would provide an erroneous high concentration. Consequently, all concentration values obtained from the samples collected by the rising stage sampler have been omitted from the data given below, and will not be considered.

RESULTS OF THE SUSPENDED SEDIMENT DETERMINATIONS.

The results of samples collected during conditions of non-base flow, and of base-flow will be considered in turn. Organic content and downstream variation is also considered. The maximum flows are reached. Suspended sediment concentrations

1,000-
TOTAL SEDIMENT LOST FROM CATCHMENT ABOVE IPING MILL (LOCATION F)
DURING NON-BASE FLOW

Fig.4 represents all the suspended sediment concentrations determined, plotted against discharge. Despite the plot being on log-log scales the scatter of points is still quite considerable and any rating curve drawn through these points would be somewhat unreliable. Also, during the plotting of the points on Fig4 it was apparent that, for a similar discharge value, earlier storms of water year had higher concentrations of suspended sediment.

Consequently, rating 'loops' (Walling and Teed, 1971) were constructed, and are displayed (Figs. 5-19) for individual flood events that were sampled during 1972. These comprise almost all of the floods of that year except those that could not be sampled due to bed load transport experiments being conducted. However, for those floods that were not sampled, estimated values of suspended sediment lost have been set out.

Figure 5 (11th-12th January 1972)

This represents a simple flood event that occurred on the 11th-12th January 1972 reaching a peak discharge of approximately $15.5\text{m}^3/\text{sec}$. It was the fourth flood with a peak flow of over $3.5\text{m}^3/\text{sec}$ to occur in the 1971-1972 water year (the others were in November [two] and December [one]), but it had a much greater peak flow than the previous three which had peak flows of less than $9\text{m}^3/\text{sec}$.

Fig.5 indicates a rapid rise in the suspended sediment concentration with an increase in the flow, but the suspended sediment concentration reaches its peak before the discharge and even drops off a little before the maximum flows are reached. Suspended sediment concentrations

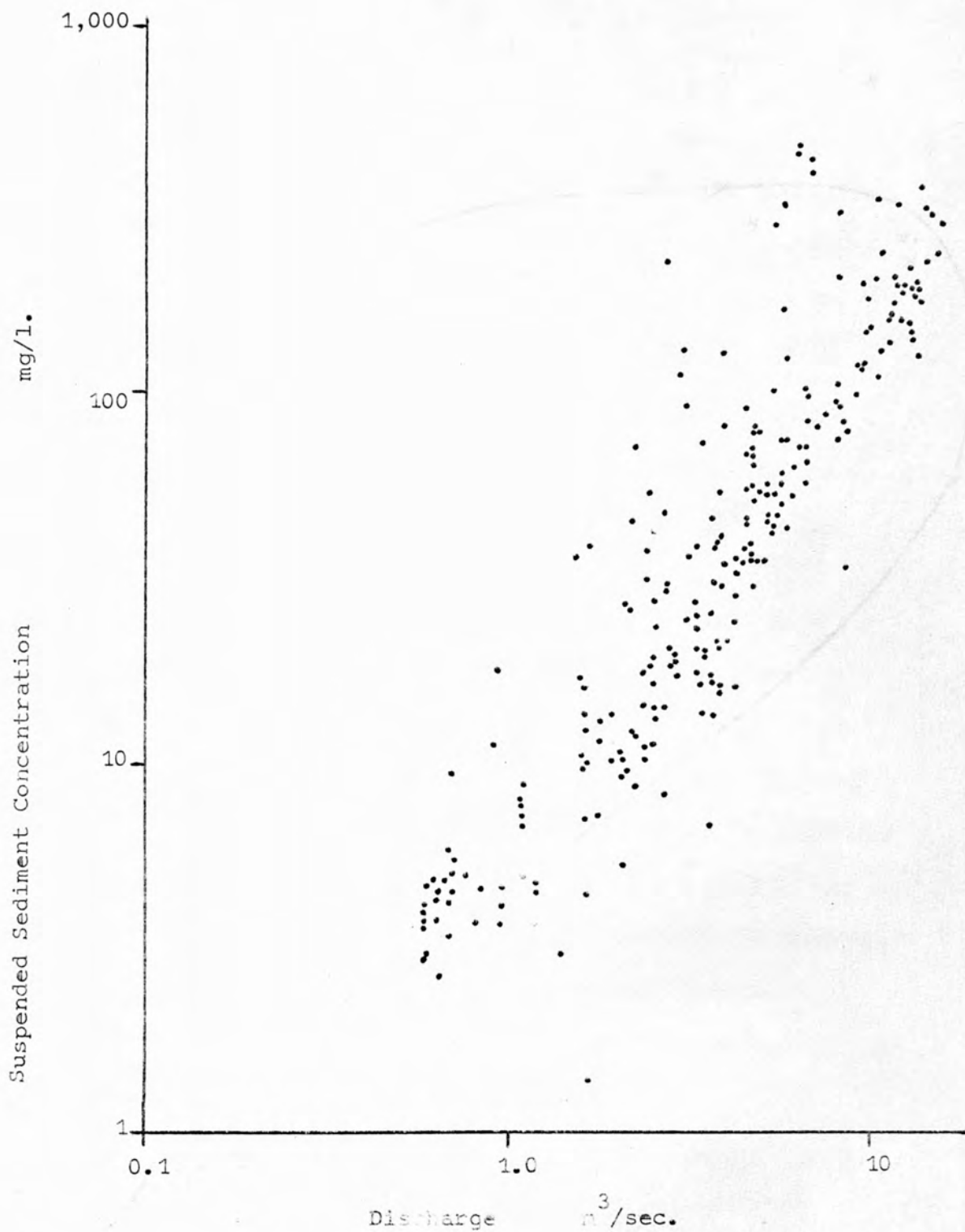


Fig. 4. Relationship between suspended sediment concentration and discharge, Location F, Iping Mill.

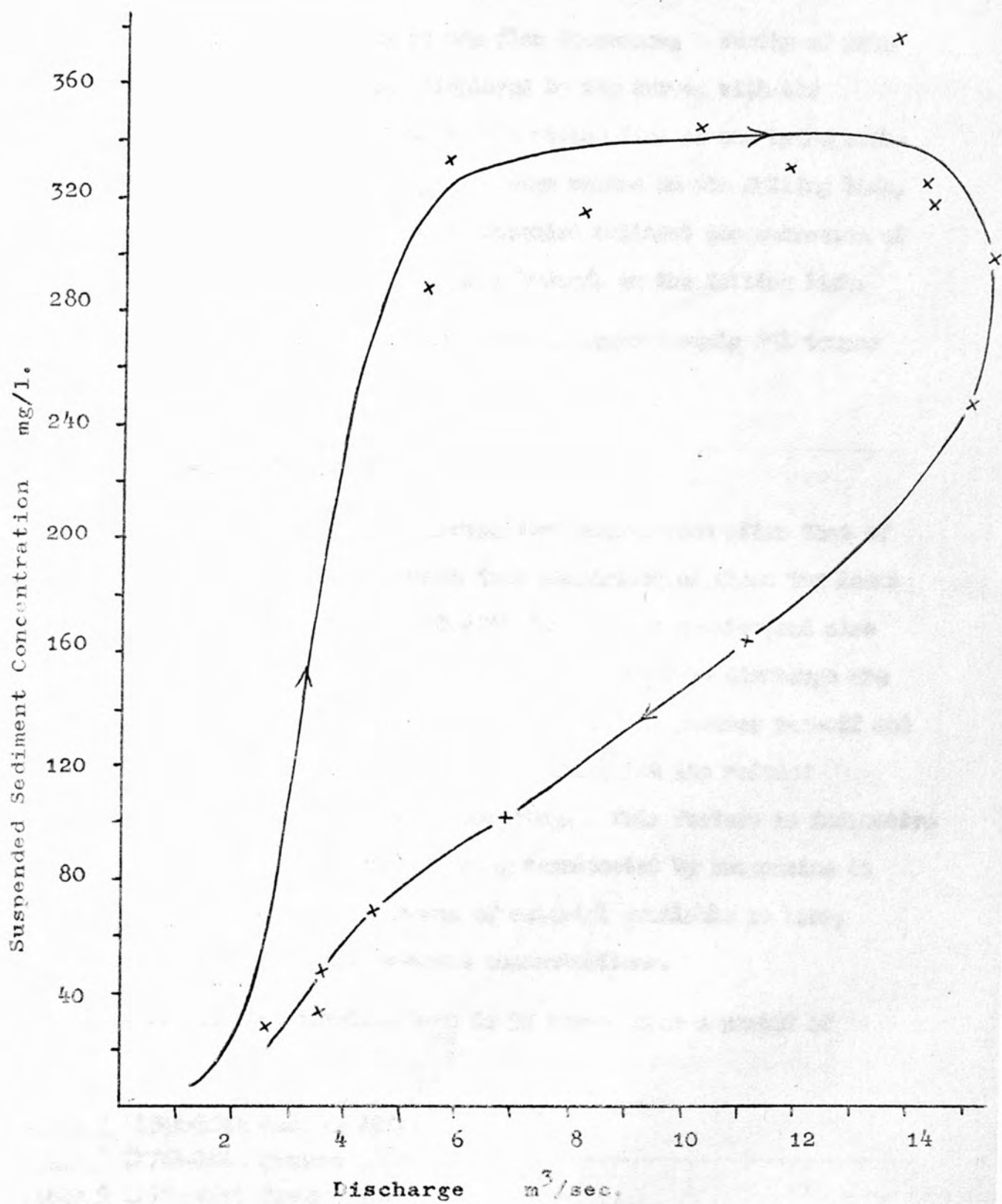


Fig. 5. Rating loop for storm hydrograph of 11-12 Jan. 1972.

continue to decrease gradually as the flow decreases. Worthy of note is the strong hysteresis effect displayed by the curve, with the suspended sediment concentrations on the rising limb of the hydrograph being greater than for equivalent discharge values on the falling limb, e.g. the discharge of $7\text{m}^3/\text{sec}$ has a suspended sediment concentration of 320mg/l on the rising limb, and of only 100mg/l on the falling limb.

The curve represents a sediment loss of approximately 251 tonnes in 48 hrs.

160

120

80

40

Figure 6 (13th-15th January 1972)

4

This represents a flood hydrograph that occurred soon after that of Fig. 5. The most noticeable features in a comparison of these two loops is that the peak discharge for 11th-12th January was greater, and also that the suspended sediment concentrations for any given discharge are higher. A greater discharge is easily explained by greater run-off and a difference in rainfall intensity, totals etc., but the reduced sediment concentrations are more interesting. This feature is indicative that material of a size capable of being transported by suspension is somewhat exhausted and so the amount of material available is less, resulting in lower suspended sediment concentrations.

The sediment loss involved here is 59 tonnes over a period of 54 hrs.

Figure 7 (15th-16th January 1972)

Figure 8 (17th-18th January 1972)

Figure 9 (19th-21st January 1972)

Discharge m^3/sec .

These three Figs. represent three flood events occurring in quick succession, and following on soon after those represented by Figs. 5 and 1972.

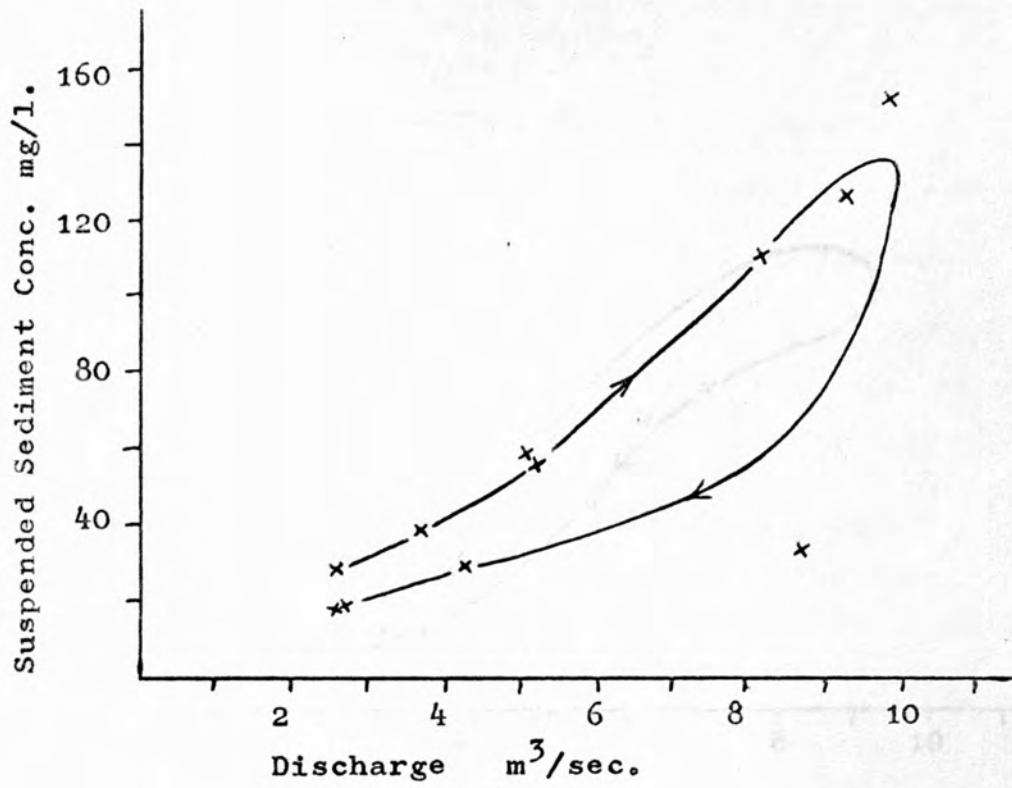


Fig. 6. Rating loop for storm hydrograph of 13-15 Jan. 1972.

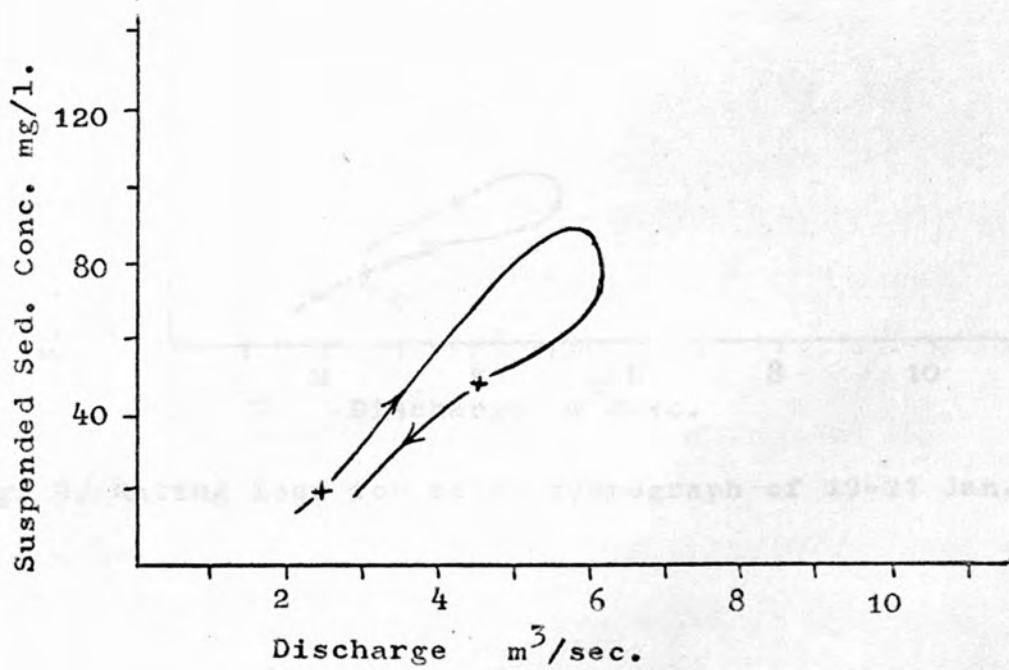


Fig. 7. Rating loop for storm hydrograph of 15-16 Jan. 1972.

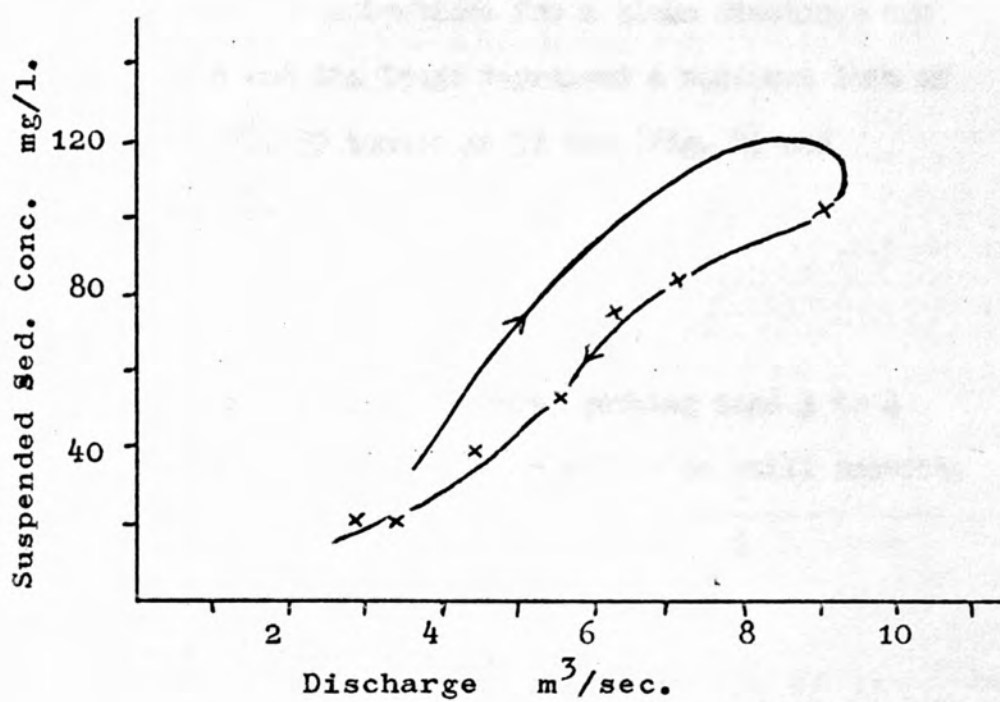


Fig. 8. Rating loop for storm hydrograph of 17-18 Jan. 1972.

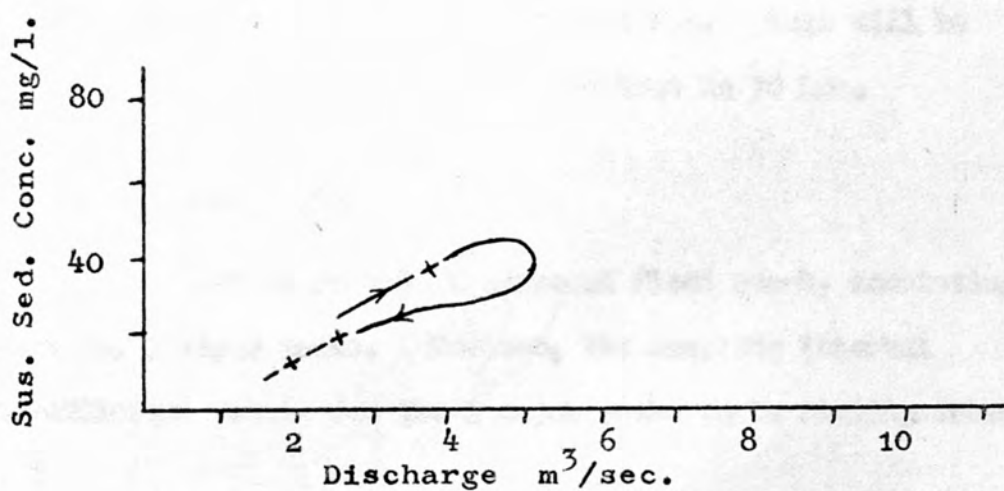


Fig. 9. Rating loop for storm hydrograph of 19-21 Jan. 1972.

and 6. Suspended sediment concentrations for a given discharge are similar to those of Fig. 6 and the loops represent a sediment loss of 25 tonnes in 36 hrs (Fig. 7), 59 tonnes in 57 hrs (Fig. 8) and 16 tonnes in 66 hrs (Fig. 9).

Figure 10 (24th-25th January 1972)

A simple flood event is represented here, peaking some 3 to 4 days after the previous one. The hysteresis effect is still present, and 29 tonnes were removed in 44 hrs.

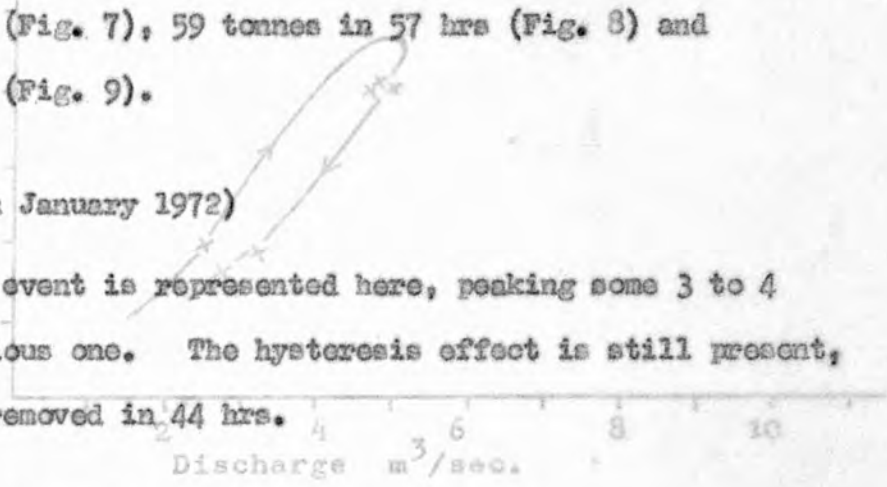


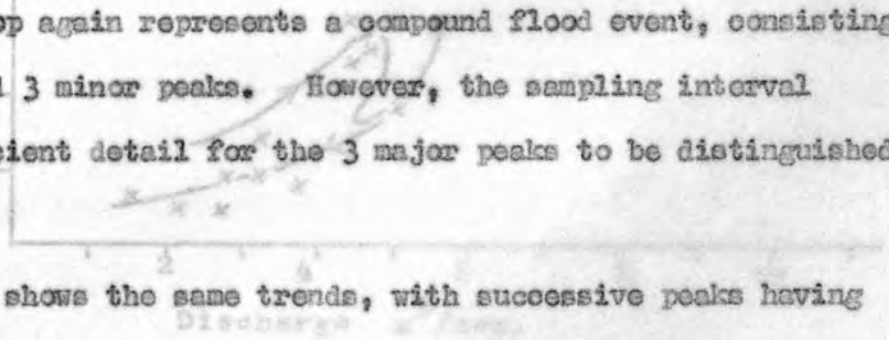
Figure 11 (26th-28th January 1972)

Fig. 10. Rating loop for storm hydrograph of 24-25 Jan. 1972

This rating loop represents a compound flood event consisting of two peaks; the first with a discharge of $5\text{m}^3/\text{sec}$, and a later one of $5.6\text{m}^3/\text{sec}$. The effect that the variation of the suspended sediment has on the shape of the loop is illustrated by the Fig. This will be considered in more detail later. 26 tonnes was lost in 70 hrs.

Figure 12 (1st-8th February 1972)

This rating loop again represents a compound flood event, consisting of 3 major peaks and 3 minor peaks. However, the sampling interval only provided sufficient detail for the 3 major peaks to be distinguished on the loop.



The loop again shows the same trends, with successive peaks having lower suspended sediment concentrations for a given discharge. During the 169 hrs represented here, 54 tonnes were lost from the catchment.

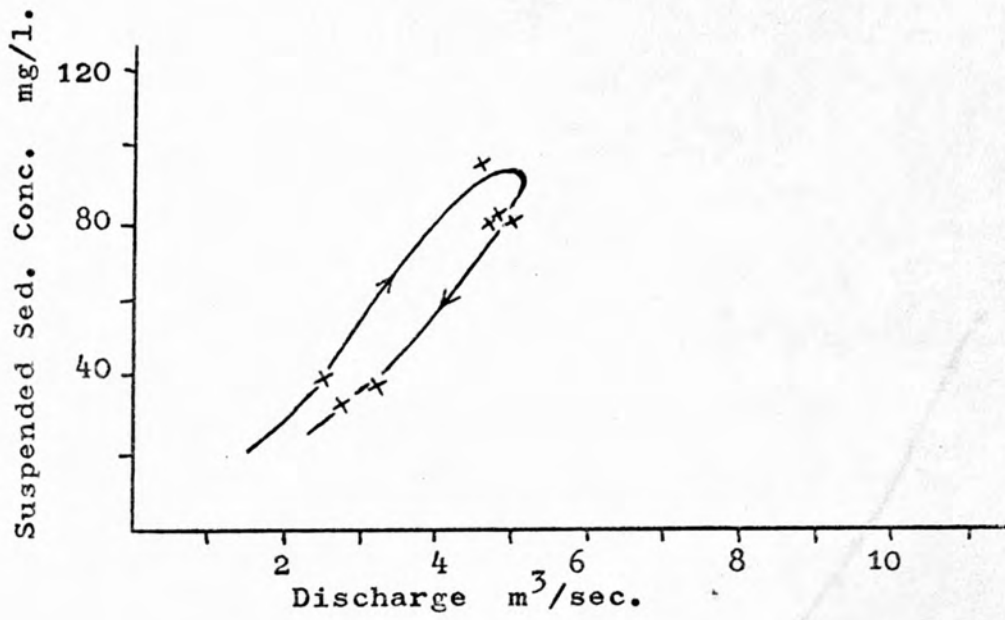


Fig. 10. Rating loop for storm hydrograph of 24-25 Jan. 1972

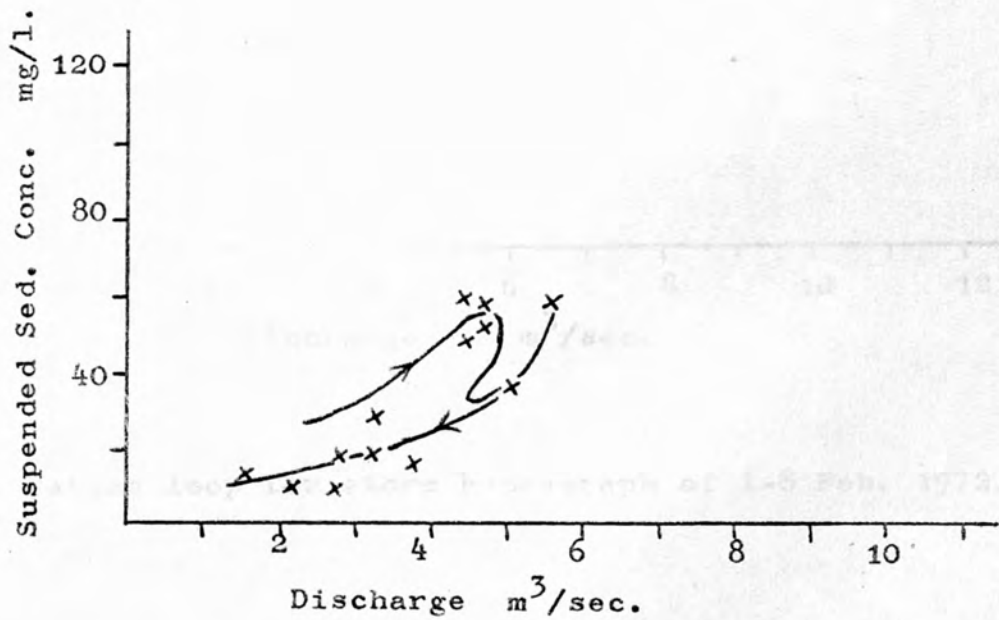


Fig. 11. Rating loop for storm hydrograph of 26-28 Jan. 1972.

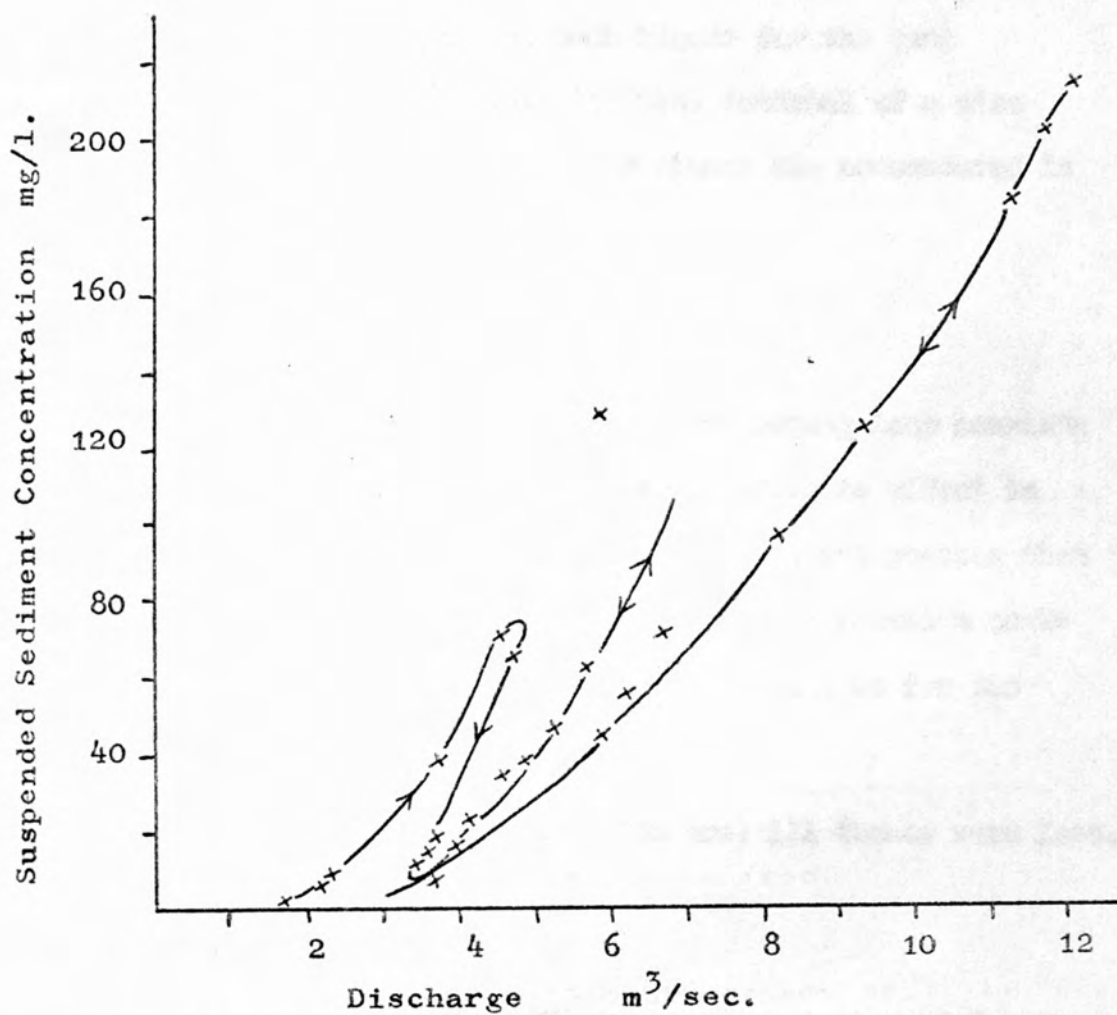


Fig.12. Rating loop for storm hydrograph of 1-8 Feb. 1972.

Figure 13 (11th-14th February 1972)

During the passage of the simple flood event represented here, 118 tonnes were lost in 114 hrs.

Values of suspended sediment are much higher for the same discharge than on Fig. 12, which indicates that material of a size capable of being transported as suspended sediment has accumulated in the short interval from 8th-11th February.

Figure 14 (15th-22nd February 1972)

The compound flood event represented by this rating loop consists of 3 peaks; the first two of which indicate a hysteresis effect in that rising limb concentrations of suspended sediment are greater than for the same discharge on the falling limb. Again, successive peaks are accompanied by lower suspended sediment concentrations for the same discharge.

For the period covered by this Fig. (180 hrs) 111 tonnes were lost.

Discharge $m^3/sec.$

Figure 15 (3rd-12th March 1972)

Fig. 15. Rating loop for storm hydrograph of 11-14 Feb. 1972. This loop represents a compound flood event consisting of 5 peaks following in quick succession. The sampling frequency during the passage of the first two peaks was somewhat inadequate but the author believes that the concentrations depicted by the Fig. are reasonable estimates of the true concentrations.

The rating loop displays well the hysteresis effect, and also the repeatedly lower concentrations for the same discharge produced by the increasing exhaustion of material of a size suitable to be carried in suspension.

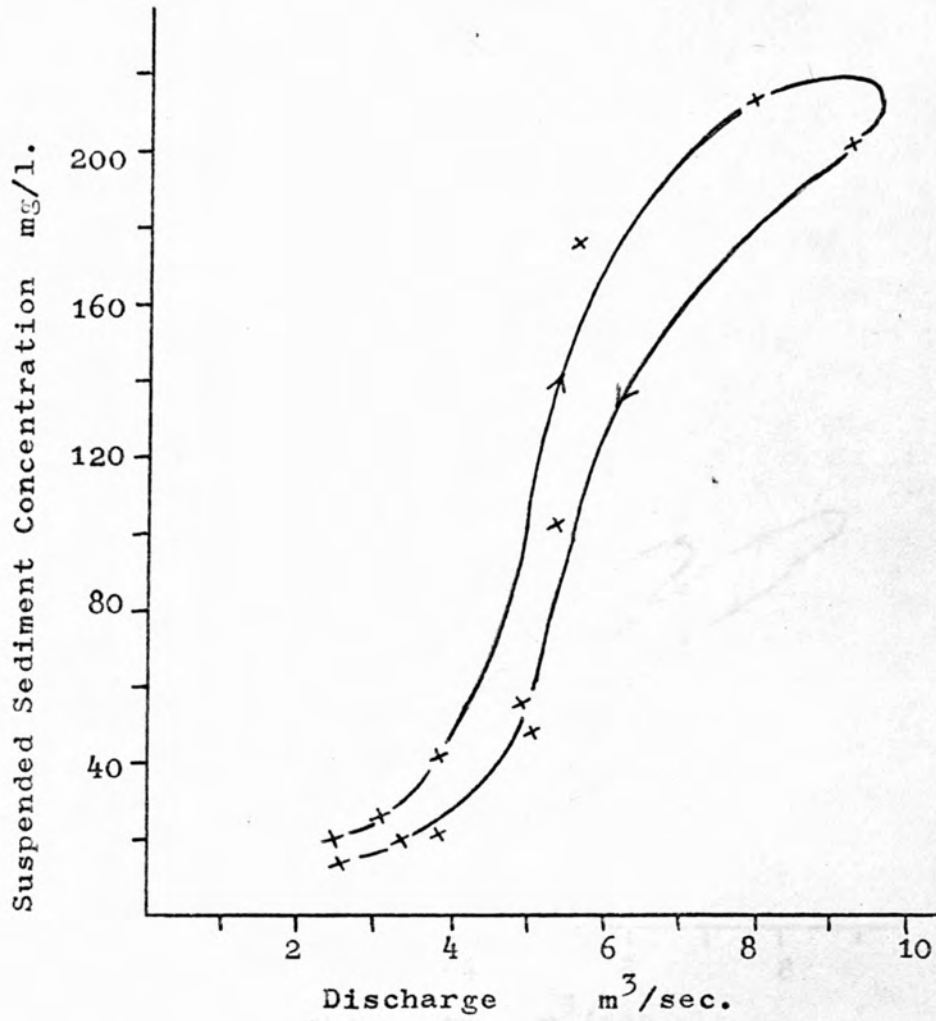


Fig. 13. Rating loop for storm hydrograph of 11-14 Feb. 1972.

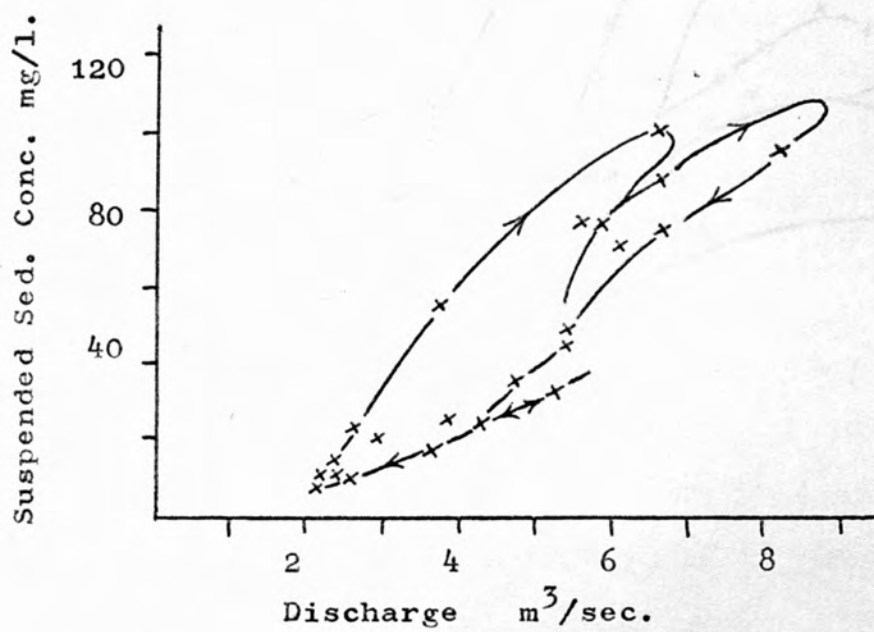


Fig. 14. Rating loop for storm hydrograph of 15-22 Feb. 1972.

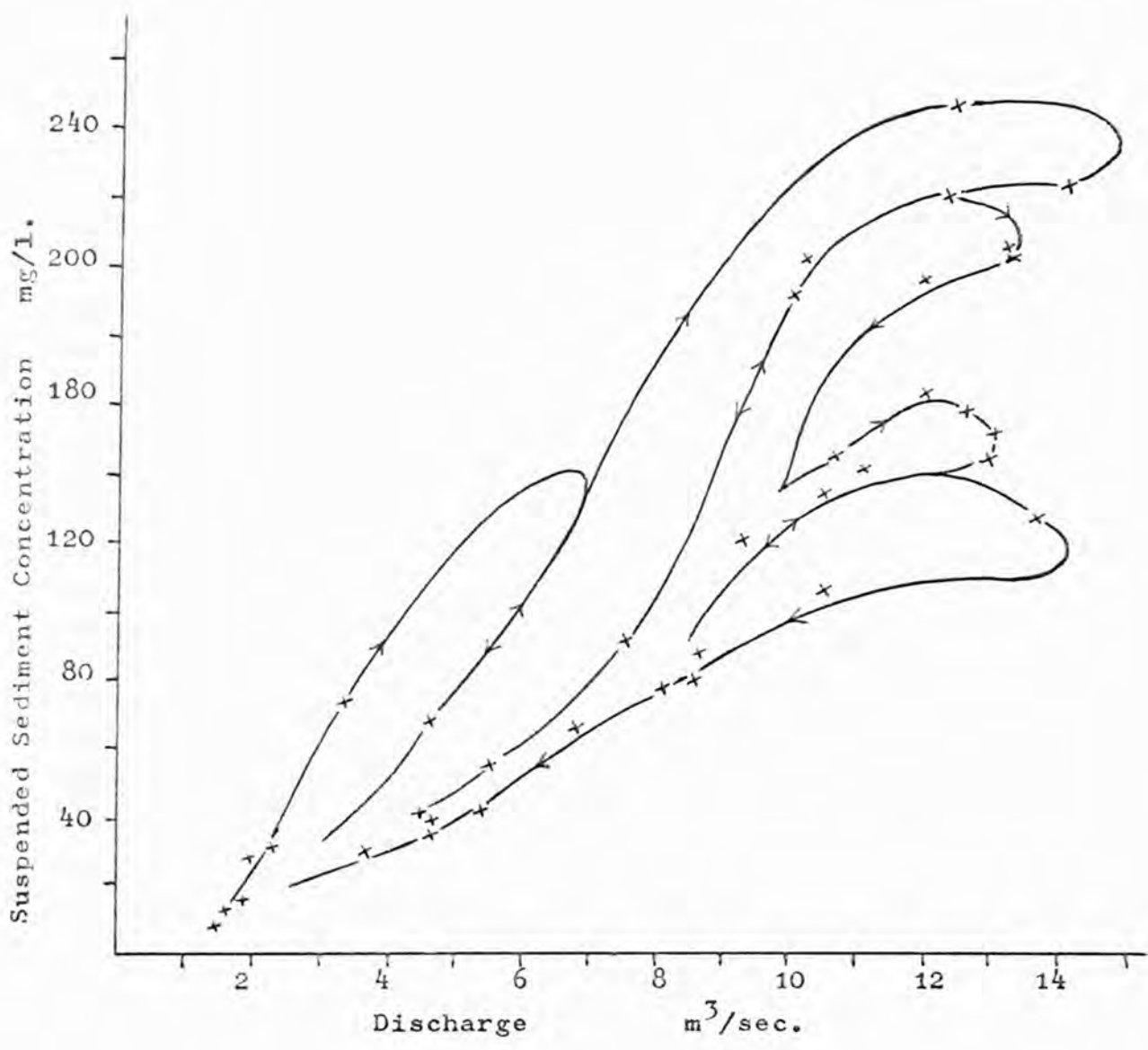


Fig. 15. Rating loop for storm hydrograph of 3-12 March 1972.

The whole Fig. represents the loss of 555 tonnes from the catchment in a period of 240 hrs.

Figure 16 (10th-11th May 1972)

This Fig. represents a simple flood event with a relatively small peak discharge during which 25 tonnes were lost in 41 hrs. Several such events occurred since the passage of the flood depicted by Fig. 15, and the sediment loss during these have been estimated from knowledge collected during this study:

14th April - 18 tonnes were lost in 24 hrs. $m^3/sec.$

29th-30th April - 30 tonnes were lost in 48 hrs.

Figure 16. Rating loop for storm hydrograph of 10-11 May 1972.

Figure 17 (13th-15th November 1972)

This represents the first flood of the 1972-1973 winter period to reach a discharge of over $3m^3/sec.$ The suspended sediment concentrations are high, and give no indication of different values for the same discharge when comparing the rising and the falling limb. This would be due to the large amount of material available for suspension that has accumulated over the summer, and because the storm hydrograph was not of sufficient duration for this to become exhausted.

This Fig. represents the loss of 19 tonnes in 83 hrs.

Figure 18 (19th-24th November 1972)

The flood represented here has a peak discharge similar to that of Fig. 17 but is of longer duration. Suspended sediment concentrations for any given discharge are similar to Fig. 17, but a slight hysteresis

Fig. 17. Rating loop for storm hydrograph of 13-15 Nov. 1972.

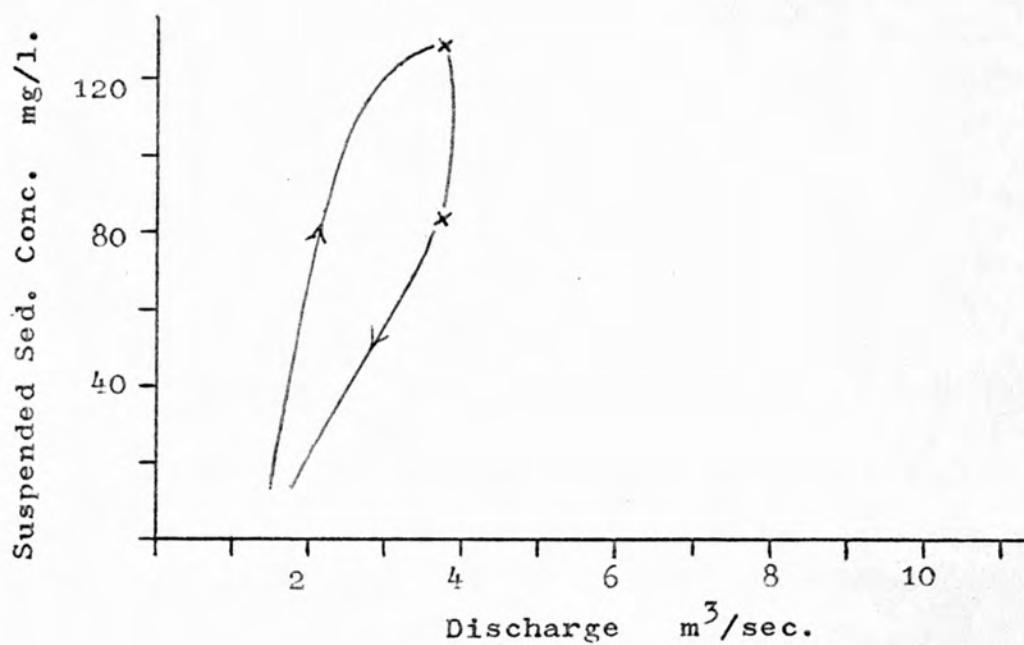


Fig. 16. Rating loop for storm hydrograph of 10-11 May 1972.

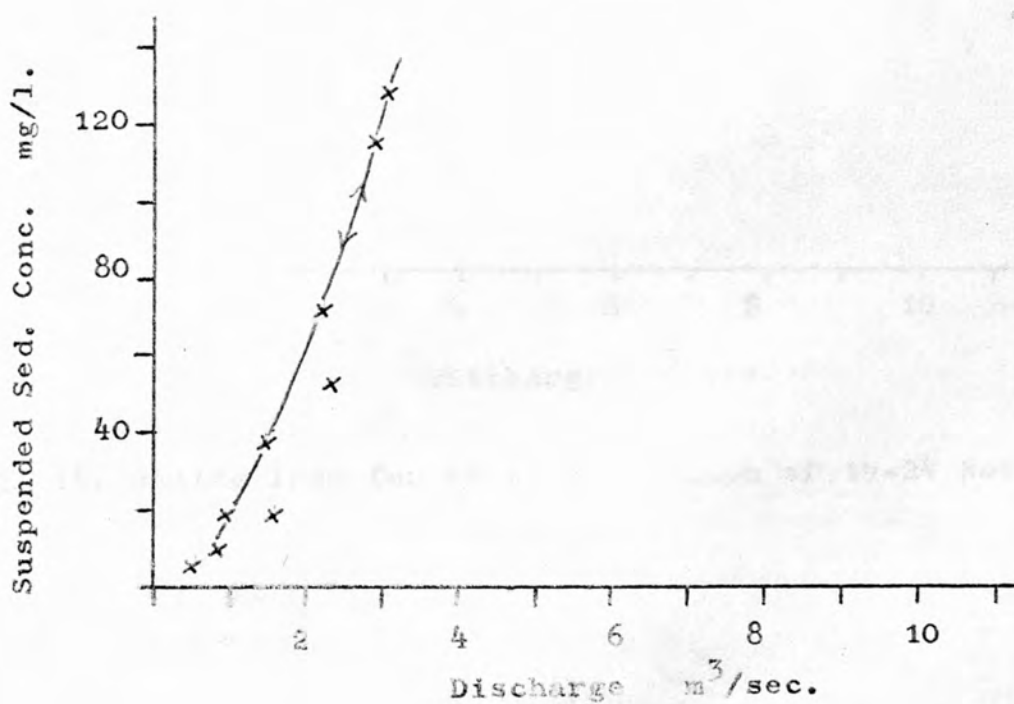


Fig. 17. Rating loop for storm hydrograph of 13-15 Nov. 1972.

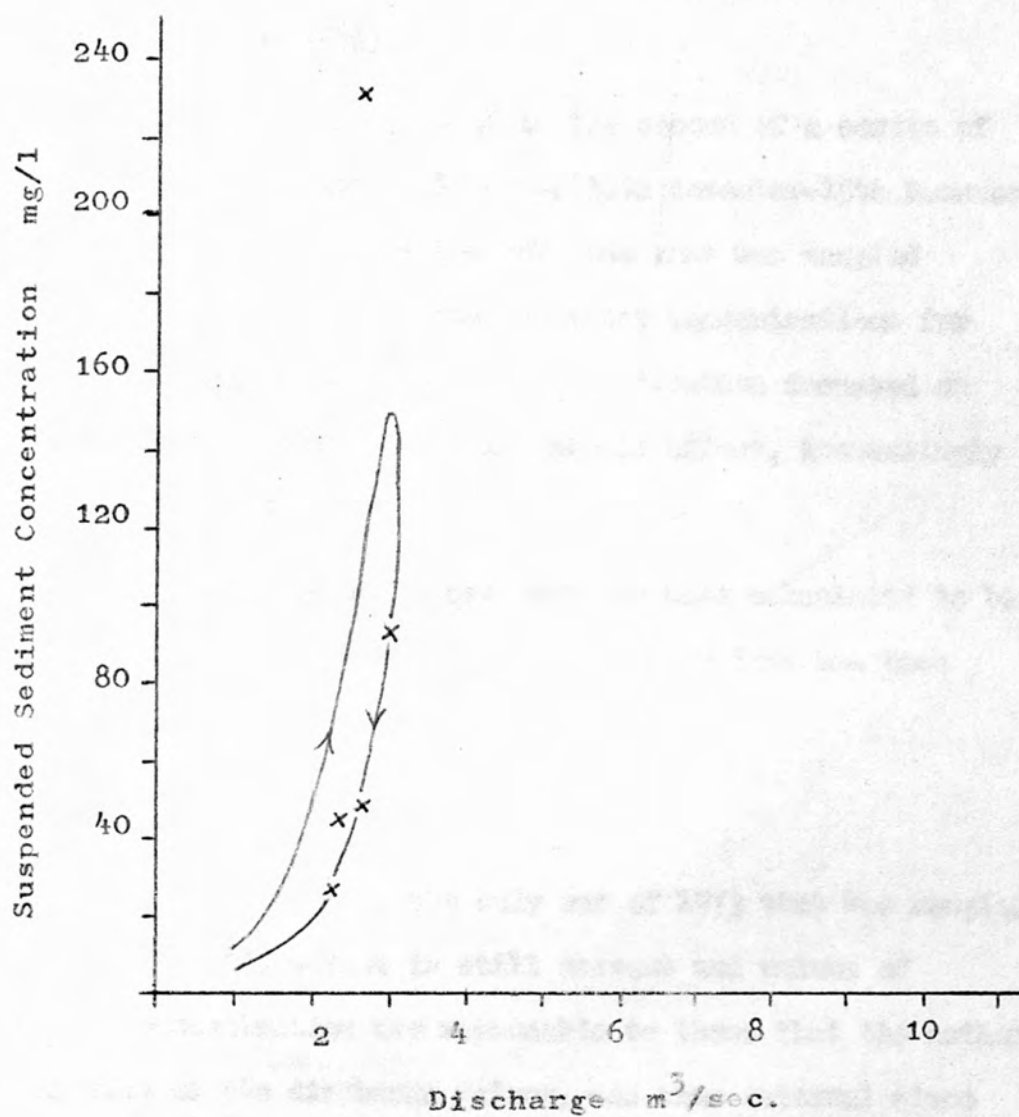


Fig. 18. Rating loop for storm hydrograph of 19-24 Nov. 1972.

effect is probably present.

23 tonnes were lost in 140 hrs.

Figure 19 (1st-3rd December 1972)

This graph represents a flood which is the second of a series of 10 that occurred within a period of 16 days. (30th November-15th December). The peak indicated by the figure is the only one that was sampled (albeit very infrequently) and suspended sediment concentrations for the other nine peaks have been estimated (with attention focussed on information collected from this study: hysteresis effect, increasingly lower concentrations, etc.).

The Fig. represents a sediment loss that has been calculated to be 294 tonnes in 70 hrs, but the total removed in the 16 days has been estimated to be in the region of 595 tonnes.

Figure 20 (15th-19th January 1973)

The flood represented here is the only one of 1973 that was sampled in detail. The hysteretic effect is still present and values of suspended sediment concentration are reasonable to those that the author would expect in view of the discharge values, and time interval since the previous hydrograph (13th-15th December 1972).

The possibility of any trends being present in the suspended sediment concentration/discharge relationship with different hydrographs through time is expanded in the discussion. The calculations and estimations based on the rating loops (Figs. 5-19) indicate that approximately 2,013 tonnes of material ^{was} removed during the passage of floods during 1972. The total duration of these was 1,803 hrs. (just

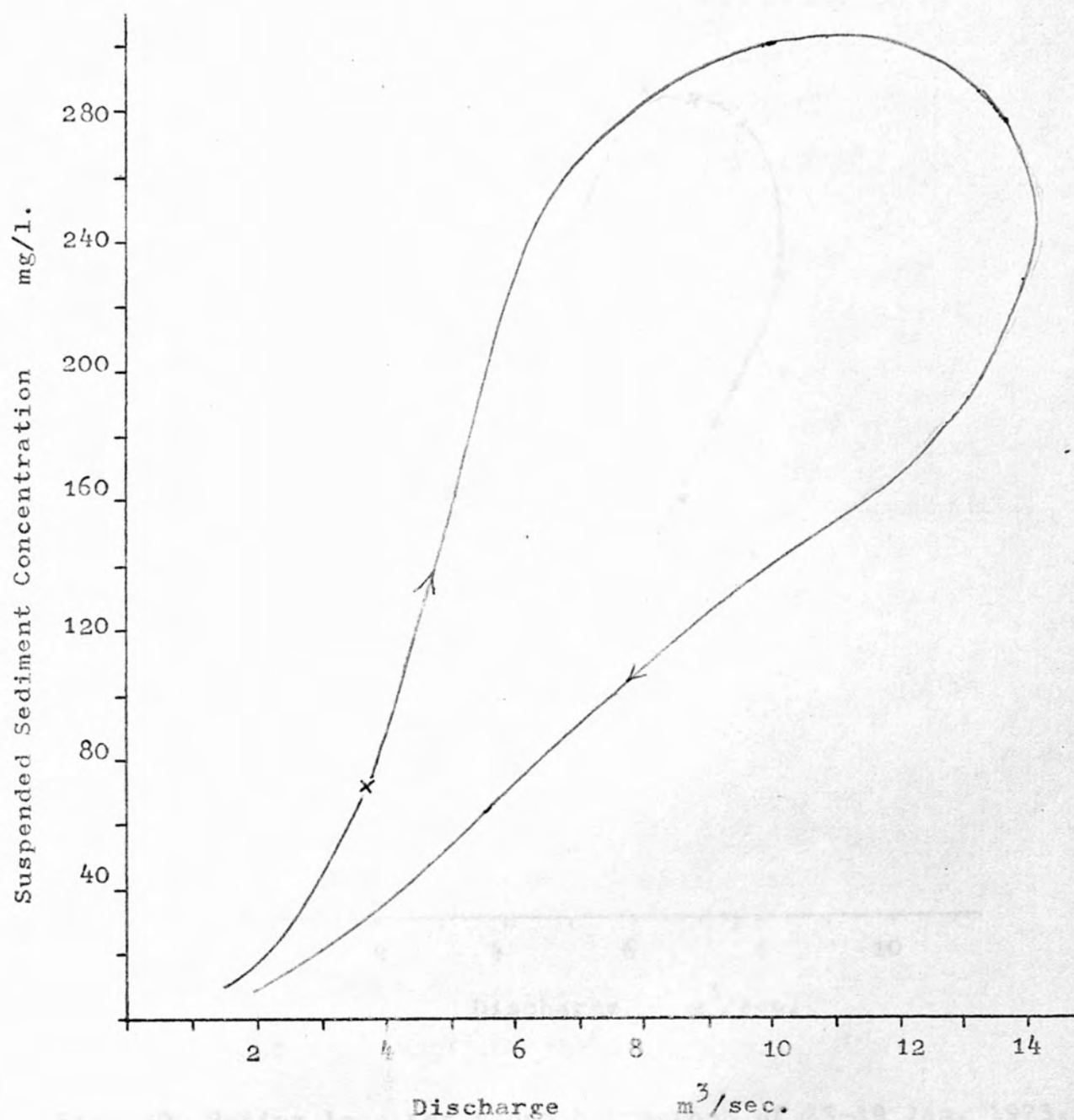


Fig. 19. Rating loop for storm hydrograph of 1-3 Dec. 1972.

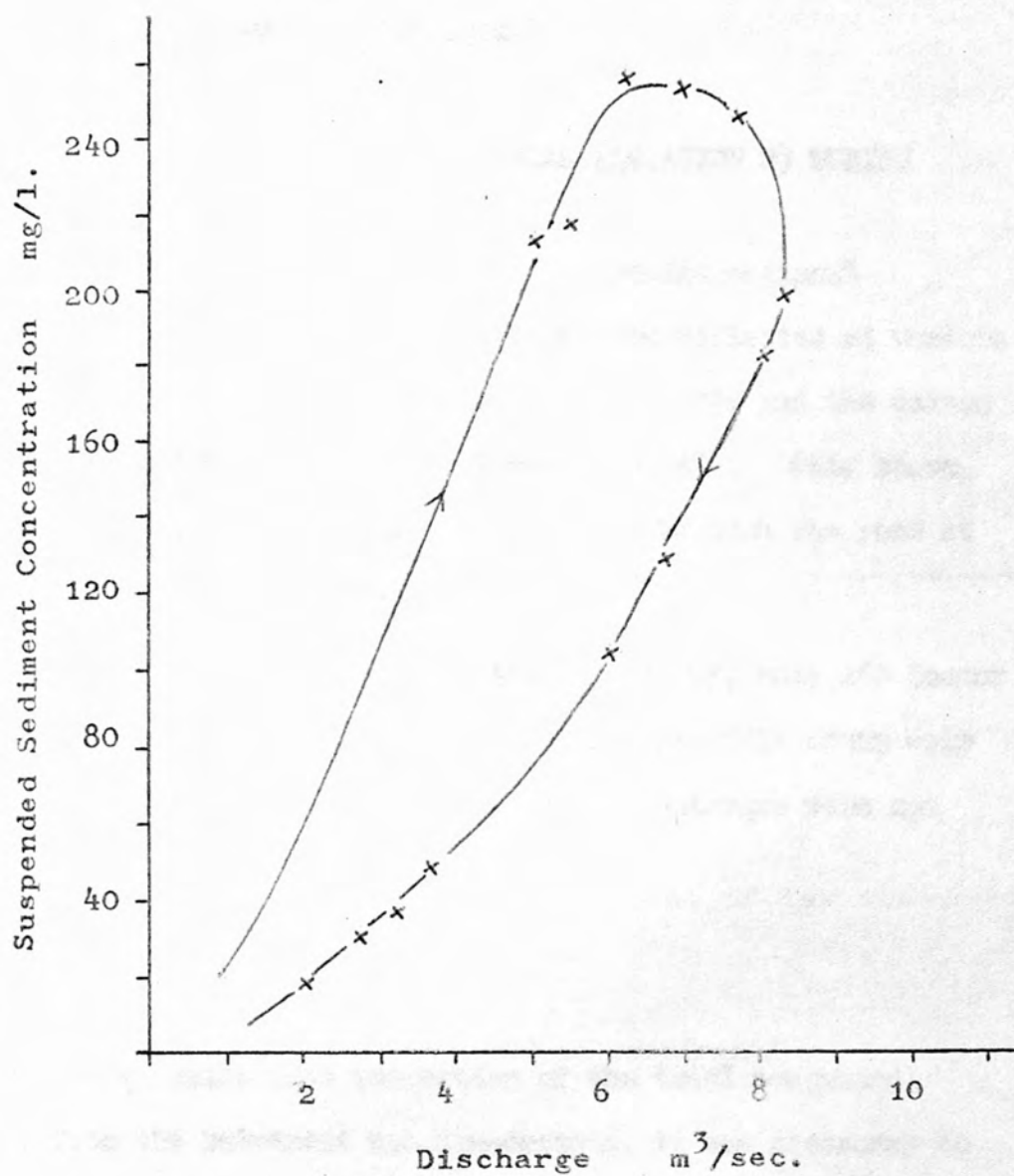


Fig. 20. Rating loop for storm hydrograph of 15-19 Jan. 1973.

over 75 days). Of this 2,013 tonnes of suspended sediment, 555 tonnes were removed in 10 days (Fig. 15) and 595 tonnes in 16 days (Fig. 19 and associated compound hydrograph).

SEDIMENT LOST FROM CATCHMENT ABOVE IPING MILL (LOCATION F) DURING BASE FLOW

Water samples for the determination of suspended sediment concentrations during conditions of base flow were collected at various times throughout the year from Iping Mill (location F), and the values obtained have been plotted against discharge (Fig. 21). This curve has been used as a rating curve for sediment lost through the year at different conditions of base flow.

It has been calculated that during the year (1972) only 169 tonnes of sediment were transported in suspension over Iping Mill crump weir during conditions of base flow (i.e. when flood discharges were not occurring).

Fig. 21. Rating curve for conditions of low flow.

ORGANIC CONTENT

In order to determine what proportion of the total suspended sediment lost from the catchment was non-organic, it was necessary to determine the amount of organic material present. Consequently, the percentage of organic material to total suspended sediment was determined for samples collected at low flow, and during the passage of two storms. The accuracy of the method used was greater at conditions of high flow when suspended sediment concentrations were higher, while at low flow the accuracy was estimated to be within the region of $\pm 25\%$.

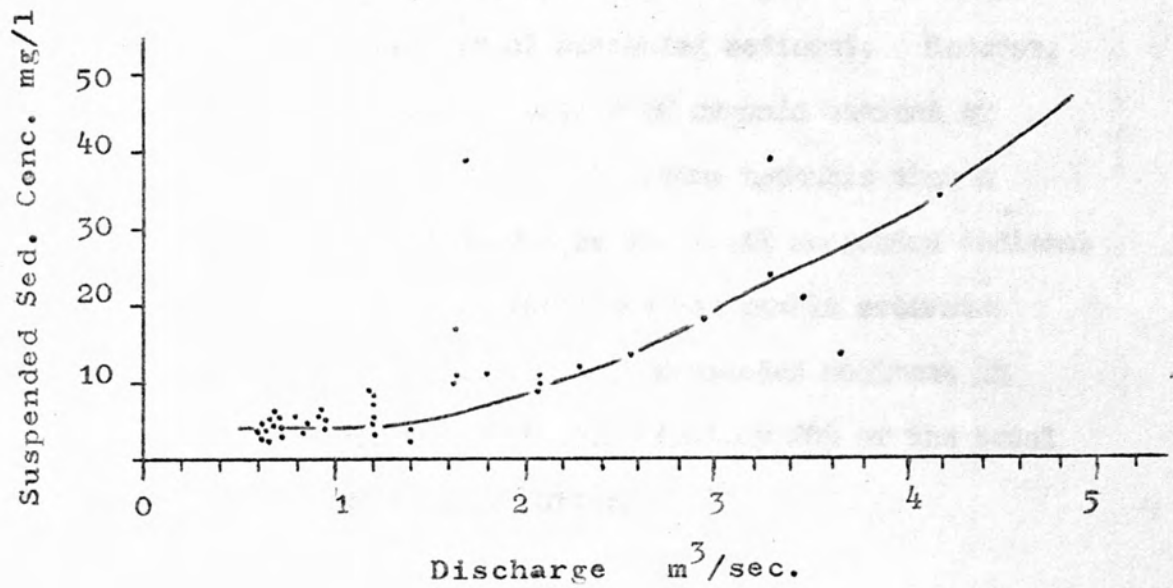


Fig. 21. Rating curve for conditions of low flow.

Organic Content during Non-Base Flow

Figs. 22 and 23 show the variation in the percentage of organic content to total suspended sediment through time during the passage of storms. In both Figs. the organic content by weight can clearly be seen to increase with increased total suspended sediment. However, although the determined values for percentage of organic content of the total suspended sediment are variable, it seems probable that a slight reduction in the percentage occurs as the total suspended sediment concentration increases. If the two Figs. are reasonable estimates for the percentage of organic content to total suspended sediment at conditions of high flow, it appears that approximately 20% of the total suspended sediment consists of organic matter.

Organic Content during Base Flow

The organic content of suspended sediment samples collected during conditions of base flow occurring throughout the year was also determined. Values obtained were varied and ranged from 25% to 46% of the total suspended sediment, but in general values were between 30% and 40%. The sampling programme during base flow conditions was not intensive enough for any trends or annual variations to be determined.

13th.

14th.

January 1972

TOTAL SUSPENDED SEDIMENT LOST FROM THE CATCHMENT

It has been shown above that, in 1972, during conditions of non-base flow, 2,013 tonnes, and during conditions of base flow, 169 tonnes of suspended sediment were lost from the catchment above Iping Mill crump weir (location F).

 River Stage
 --- % organic to total suspended sediment

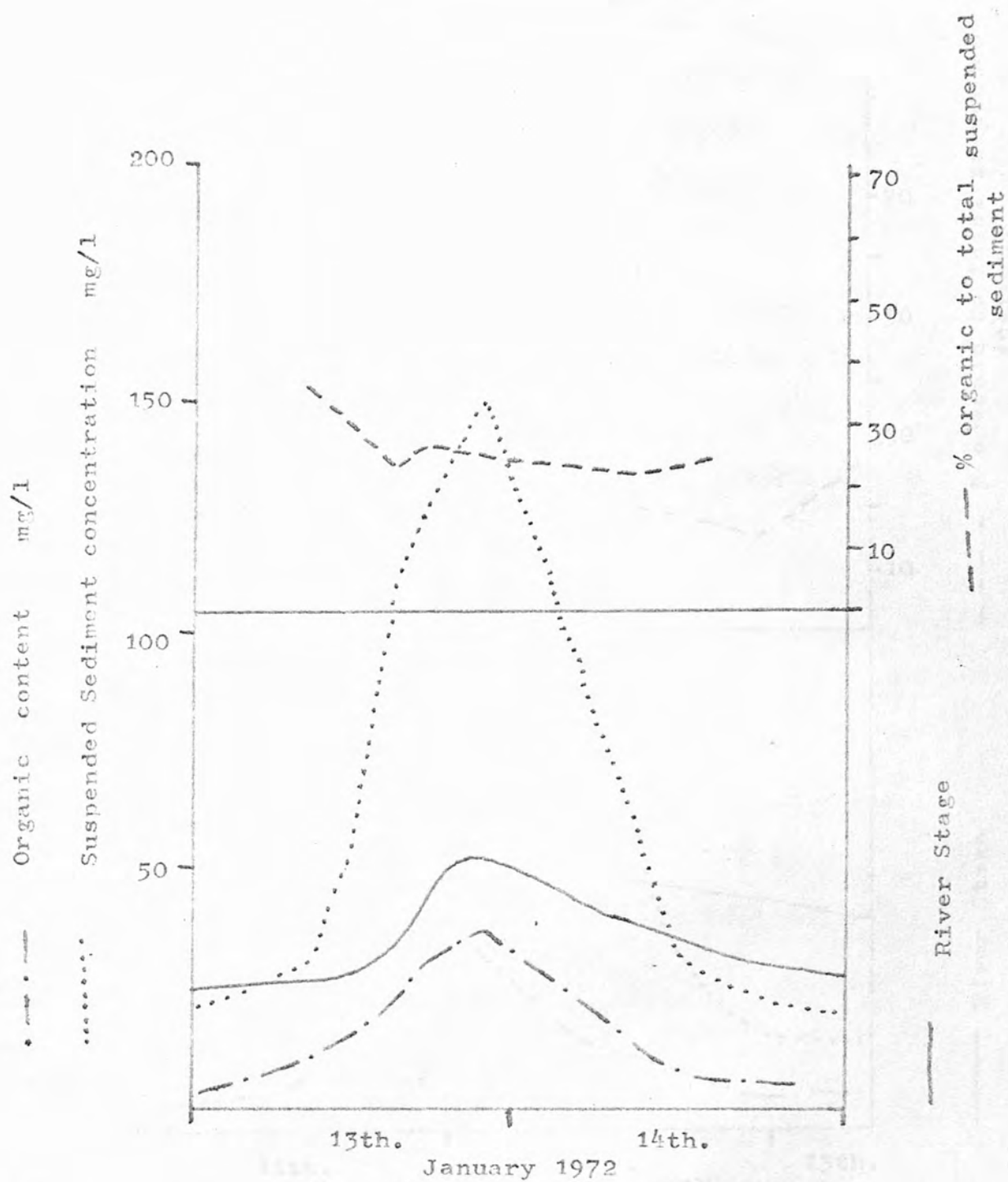


Fig. 22. Relationship between river stage, suspended sediment concentration, and organic content, Iping Mill, for 13-14 January, 1972.

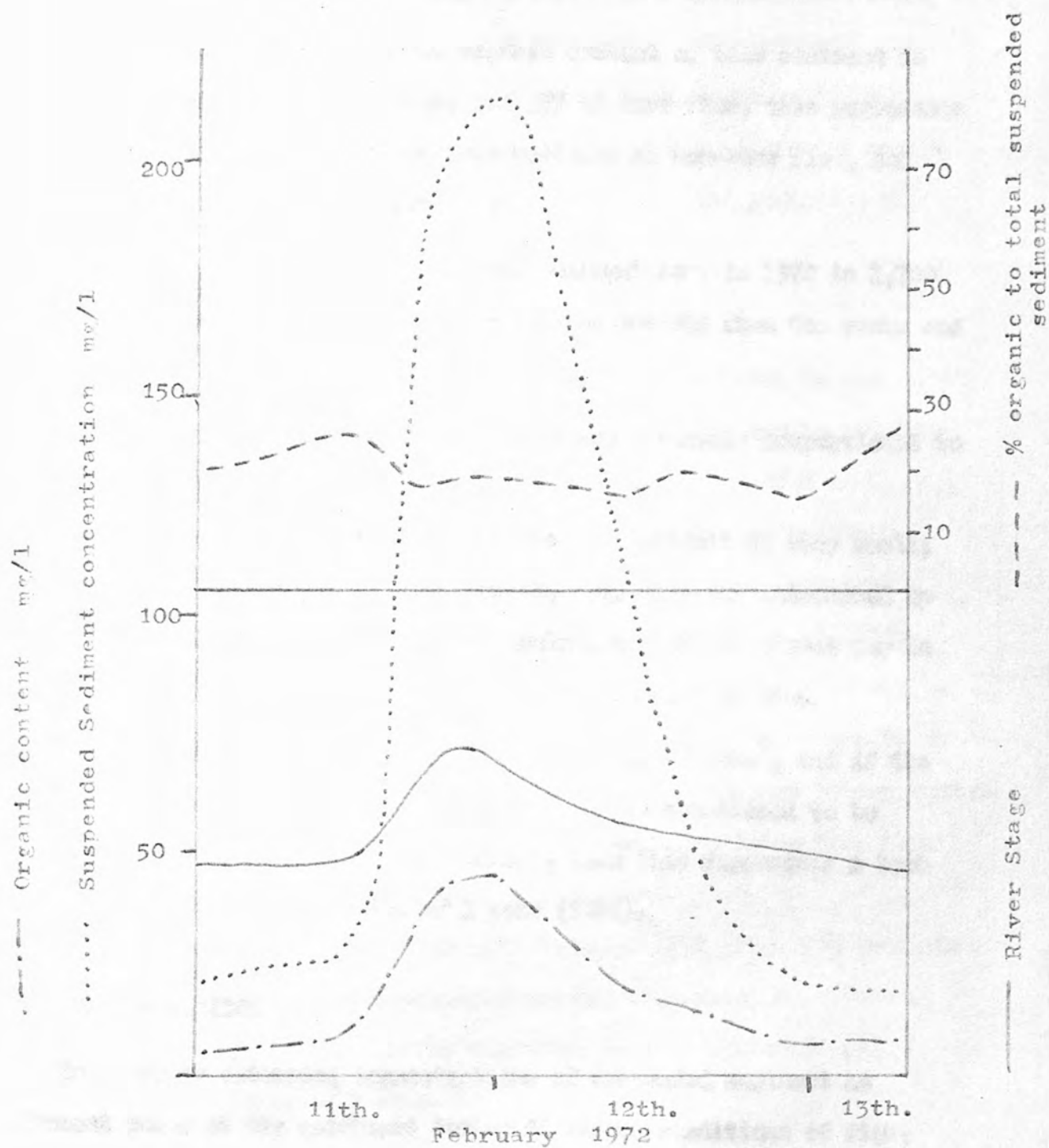


Fig. 23. Relationship between river stage, suspended sediment concentration, and organic content, Iping Mill, for 11-13 February, 1972.

With the assumption that the organic content of this sediment is 20% of the total at non-base flow, and 35% at base flow, this represents a loss of 1,610 tonnes of non-organic sediment at non-base flow, and 110 tonnes of non-organic at base flow.

The total of non-organic suspended sediment lost in 1972 is 1,720 tonnes. This amount may be considered to be derived from the rocks and soils of the catchment as:

1. material blown into the catchment is approximately proportional to that blown out;
2. material washed out of the atmosphere by rainfall is very small;
3. material derived from other sources, e.g. material introduced by man, is likely to be small, and again material introduced may be balanced by material removed from the catchment by man.

As the area of catchment above Iping Mill is 153.9 km^2 , and if the material of the non-organic suspended sediment is considered to be derived equally from the entire catchment, then this represents a loss of 11 tonnes/ km^2 for the period of 1 year (1972).

DOWNSTREAM VARIATION

In order to determine concentrations of suspended sediment at different parts of the catchment during different conditions of flow, samples were collected from all of the 9 sampling locations (Table 37 and Fig. 3) during the passage of 4 floods. Three of these followed on from each other and may be considered as a single compound hydrograph (6th-9th March 1972) and the other was a simple hydrograph (12th-14th November 1972).

The results of the analysis of these samples are presented along with the river stage data (Fig. 24 and Fig. 25). The sampling interval was too great for any particular conclusions to be drawn, as some details are lost: for example, the stage peak as indicated on the Figs. are not necessarily of the correct magnitude and position, but are the result of the sampling interval.

Some overall conclusions can be drawn however:

1. Relatively low suspended sediment values are found in the Hammer Stream (location H). This is possibly due to settling out of sediment in a pond, just upstream of location H.
2. The suspended sediment concentrations of all nine sampling locations during the 3 peaked compound hydrograph had peak values that were decreasing, whereas the discharge at Iping Mill was greatest during the passage of the 3rd peak (Fig. 24). The lower sediment concentrations can again be explained by an exhaustion of suitably sized sediment for transport by suspension.
3. The peak discharge arrives at an increasingly later time with an increasing distance from river source.
4. Samples collected on 12th-14th November 1972 (Fig. 25) indicate that peak sediment concentrations are decreasing downstream. This trend is only partly supported by data collected for 6th-9th March 1972 (Fig. 24).

DISCUSSION

When concerning suspended sediment concentration values plotted against discharge, it is evident from Fig. 4 that the scatter of points

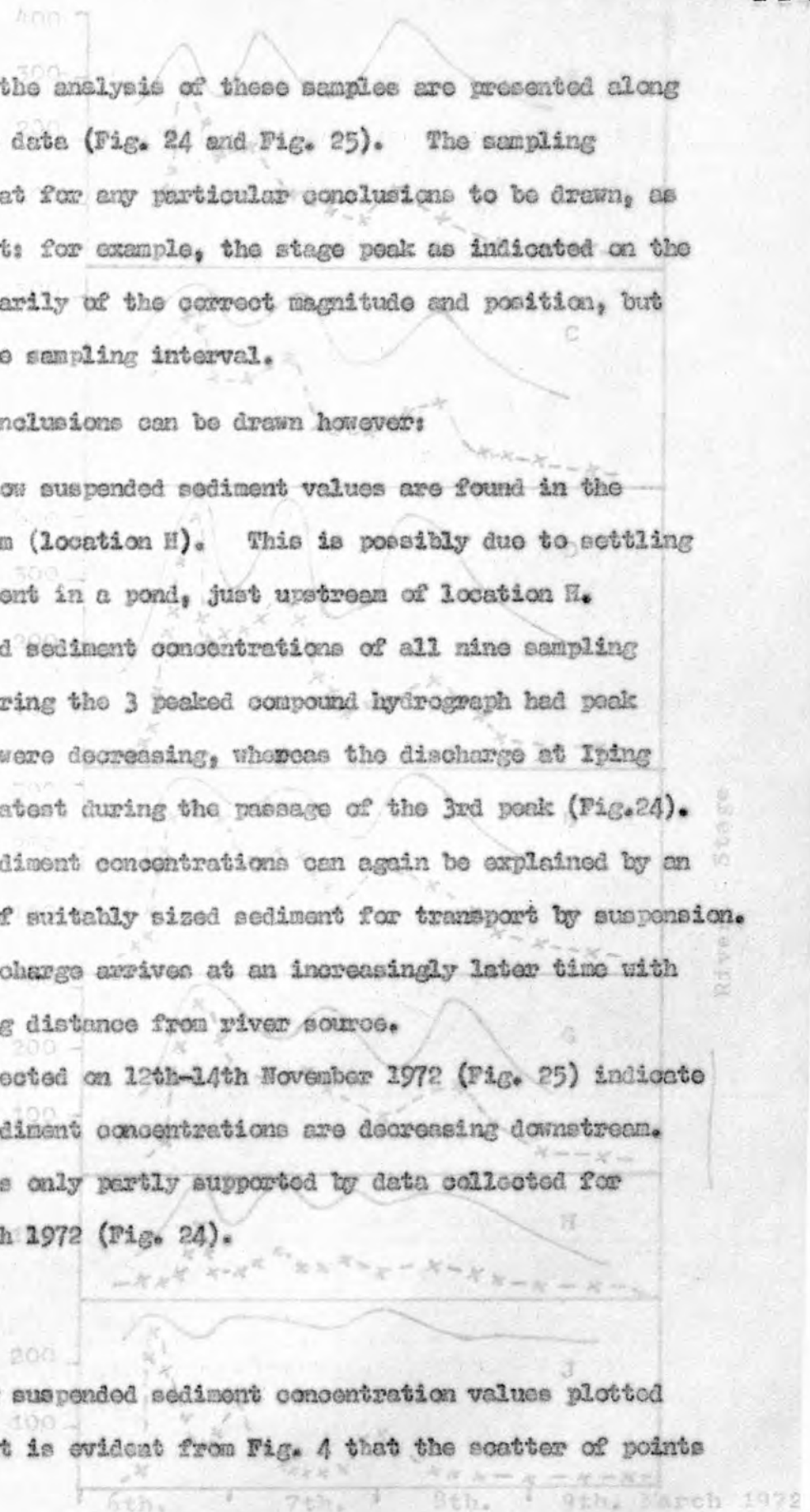


Fig. 24. Relationship between suspended sediment concentration and river stage at various sampling localities, March 1972.

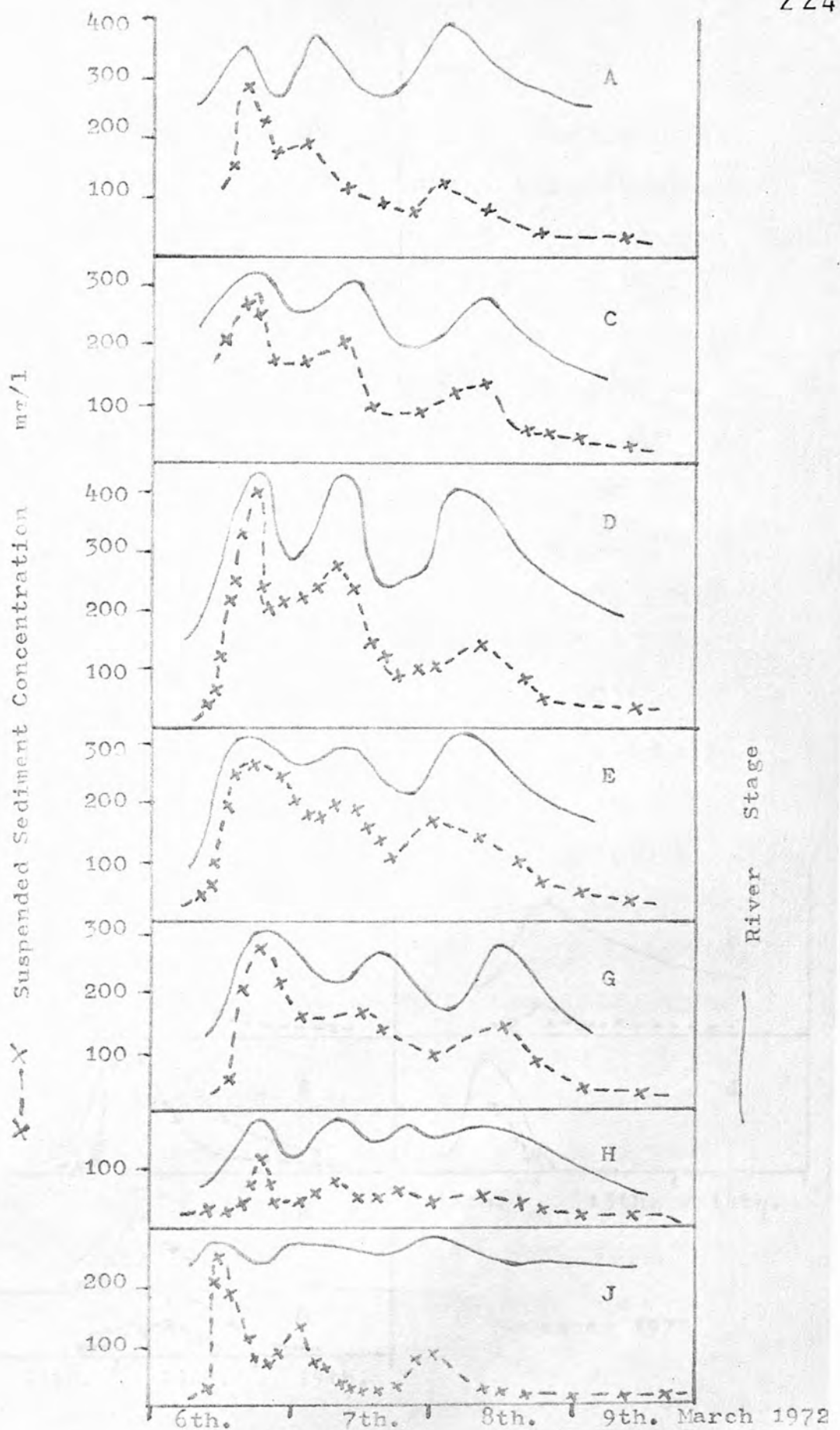


Fig. 24. Relationship between suspended sediment concentration and river stage at various sampling localities, March 1972.

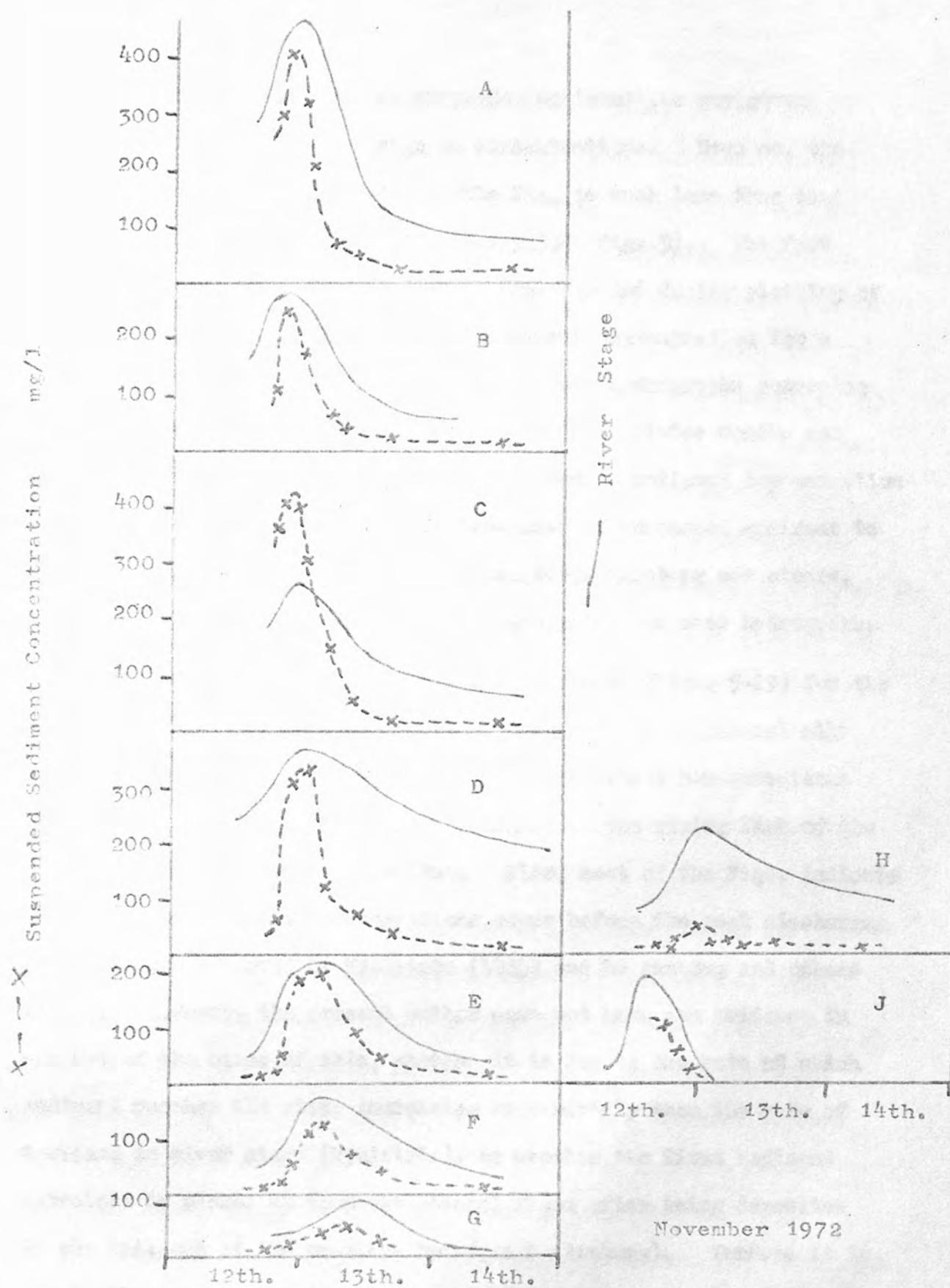


Fig. 25. Relationship between suspended sediment concentration and river stage at various sampling localities. November 1972.

is quite considerable and that suspended sediment for any given discharge may cover a wide range of concentrations. Even so, the scatter and variation indicated by the Fig. is much less than that obtained by Walling and Teed (op.cit., p.334, Fig. 5). The fact remains, however, that the scatter is present, and during plotting of Fig. 4 it was evident that values of sediment concentration for a given discharge are generally higher for storm hydrographs occurring during the early winter months than in the later winter months and spring. This suggests that some factor governs sediment concentration through time, and in order for the true loss of suspended sediment to be determined it is necessary for rating loops (Arnborg and others, 1967; Walling and Teed, 1971) to be constructed for each hydrograph.

Such rating loops were therefore constructed (Figs. 5-19) for the majority of the flood events of 1972. These loops in general all exhibit a hysteresis effect, with suspended sediment concentrations for the same discharge being usually higher on the rising limb of the hydrograph than on the falling limb. Also, most of the Figs. indicate that the peak sediment concentrations occur before the peak discharge. This has been observed by Hjølström (1935) and by Arnborg and others (1967). However, the present author does not have any evidence in support of the cause of this, whether it is due to the rate at which sediment reaches the river increasing more rapidly than the rate of increase in river stage (Hjølström), or whether the first sediment entrained is picked up from the channel floor after being deposited by the tail end of the previous hydrograph (Arnborg). Perhaps it is merely the result of sediment of a size suitable for suspension becoming exhausted before the peak run-off rate occurs.

If the rating loops are considered through time, perhaps the relationship between suspended sediment concentration, discharge and time will become more apparent. It is debatable whether or not the series of loops from January-March 1972 (Figs. 5-15) give an overall picture of a decrease in suspended sediment concentration with a given discharge. However, it is obvious that this does occur when one hydrograph peak follows on quickly from the previous one to form a compound hydrograph, e.g. Figs. 11, 12, 14 and 15. This tendency is also shown by Figs. 5 and 6, and 10 and 11, which are pairs of consecutive hydrographs. Indeed, the hydrographs represented by Figs. 5 to 9 are consecutive, but the reduction in sediment concentration, if present, is obscured by the sampling frequency of Figs. 7, 8 and 9 being insufficient. (However, the actual samples that were collected do suggest that there is a reduction in suspended sediment for a given discharge). This reduction in sediment concentration suggests that the supply of sediment of a size suitable for transporting in suspension has become somewhat exhausted.

A comparison of Figs. 9 and 10, however, contrasts with the others so far discussed as the later hydrograph (Fig. 10) has higher concentrations for the same discharge than the previous hydrograph (Fig. 9). Now, an inspection of the water level records for Iping Mill (location F) indicates that a period of 5 days occurred between the peak discharge of Fig. 9 and of Fig. 10. The question arises: is this 5-day period sufficient for the somewhat exhausted supply of sediment capable of suspension to start being re-accumulated? Processes that are most likely to be involved here are biological activity,

freeze/thaw and other weathering processes. Minimum temperatures for these 5 days indicate an air temperature below freezing for three consecutive nights, and ground frost for only two of these nights.

Likewise, between the peaks of the flood events, represented by Figs. 11 and 12, there is a period of almost 7 days. This is again accompanied by an increase in suspended sediment for the same discharge in the later hydrograph (Fig. 12), when compared to the earlier (Fig. 11). This increase, however, is somewhat smaller than that between Figs. 9 and 10 despite the time interval being for a longer period. Minimum temperatures again show that 3 nights have air temperatures below freezing, and that ground frost occurred on these 3 nights. However, the meteorological data for these 3 days also suggest that the ground remained frozen during the day, and consequently reduced the efficiency of freeze/thaw and biological activity.

The period between the last peak of Fig. 12 and the peak of Fig. 13 is 5 days, but the increase in sediment concentration for a given discharge in Fig. 13 over Fig. 12 is large. Temperatures again indicate that freeze/thaw could have occurred on 3 nights out of these 5, and it is likely that thawing did occur during each day.

The flood represented by Fig. 14 follows soon after that of Fig. 13 and does exhibit the reduction in suspended sediment concentration.

The first peak of the compound hydrograph of Fig. 15 shows a large increase in suspended sediment concentration over the last peak of Fig. 14 (and indeed even over the first peak of Fig. 14). Here the time period for re-accumulation of exhausted sediment is in the order of 15 days.

Figure 16, occurring much later, again has high suspended sediment values for a given discharge. This tendency should ultimately culminate in the first large storm of the next winter where high suspended sediment concentrations would be obtained as a result of accumulation of suitably sized material over the summer months.

So, if hydrographs follow on in quick succession, the suspended sediment concentration for a given discharge will decrease due to exhaustion of material. However, the period of recovery and re-accumulation of this supply in the catchment is quite short, and is probably, but not conclusively, controlled by weathering processes and biological activity. The period of recovery and re-accumulation of a given amount of material is likely to vary with the time of year, and type of process prominent at that time, e.g. ploughing in spring and autumn may also be a major process during these times.

As the re-accumulation period between successive hydrographs is generally longer during the summer months, and if these processes occur in other catchments, this may explain the high suspended sediment concentrations for the summer months recorded by Hall (1967) working on the River Tyne.

If the rating loops presented here are compared with the four curves presented by Arnborg and others (1967) some similarities can be seen. Although actual numerical values are different, some of the loop shapes are similar. For example, Arnborg in his Fig. for 1st June to 8th June compares favourably with Figs. 5, 16, 19 and 20. This is an event where the peak suspended sediment concentrations occur before the peak discharge. This has meant, in the present study at least, that

the unit of time during which the maximum loss of suspended sediment past a point occurs is somewhere between the times of these two peaks.

Similarly, their Fig. for 22nd June to 8th September indicates suspended sediment concentrations on the rising limb to be similar to those on the falling limb, for the same discharge. Such a condition occurs in the present study for some of the individual peaks occurring in compound flood events (Figs. 11, 12 and 14). ^{and others} Arnborg explain that this condition indicates that the material originates from the river bed itself. If this is so, it implies an exhaustion of supplies from outside the river channel.

The data collected from various points of the catchment indicate a general downstream decrease in suspended sediment concentrations during the passage of flood hydrographs. However, this would be accompanied by an increased discharge and so the total suspended sediment lost may not necessarily decrease. It is probable, however, that increasing amounts of suspended sediment settle out or become part of the bed-load as the lower end of the catchment is approached.

As has been indicated, the total suspended sediment to pass over Iping Mill crump weir during 1972 has been calculated to be 2,182 tonnes (2,023 at non-base flow conditions, and 169 tonnes during base flow); of this, 1,720 tonnes is non-organic material, and 462 tonnes is organic. This would give an average erosion rate for the year of 11 tonnes/km² of non-organic material, and of 14 tonnes/km² of total organic and non-organic. These figures are probably a lower volume than for most years as 1972 was a year of comparatively low precipitation. Even with this consideration of low precipitation totals, the erosion rate is low when

compared to Hall's data (1967) for the Tyne Catchment ($2,957/\text{km}^2$). He estimates that 133,000 tonnes are lost per annum, and this would give an average erosion rate of approximately $45 \text{ tonnes}/\text{km}^2$.

The author believes that it is reasonable to believe that the 1,720 tonnes of non-organic material lost from the catchment represents an actual loss of material that has been primarily derived from the various source rocks. However, the actual proportion of sediment derived from each rock type was unable to be determined (Section I).

In recent years, much stress has been laid on the intensity and frequency of geomorphic processes (Tricart and others, 1961; Douglas, 1964; Wolman and Miller, 1960; Brown III and Ritter, 1971). This aspect is somewhat demonstrated here as it has been estimated that of the total suspended sediment lost in 1972 (2,182 tonnes), 555 tonnes was lost in 10 days, and 595 tonnes was lost in 16 days. This results in over 50% of the total being lost in 7% of the time, as a result of the increased intensity and also frequency of hydrographs. This compares with only 169 tonnes being lost during conditions of low flow which were maintained for almost 290 days.

Accuracy of Estimations and Predictions

A question arising from this study is the possibility of an accurate determination of suspended sediment concentrations for other hydrographs of the catchment without the need of field sampling. In other words, can the sediment loss for past and future years be determined from knowledge only of the hydrographs?

It seems likely that estimations can be made, but these would be

3. Suspended sediment concentrations for the same discharge become somewhat speculative in view of the very limited knowledge, and their accuracy would not be very great. However, if for example one flood in three was sampled and sediment concentrations determined accurately, then the other hydrographs could be related to this, and with the knowledge of recovery time for re-accumulation of sediment etc. presented here, the accuracy of the estimations for unsampled floods could be greatly increased. Eventually, over a period of a few years sufficient understanding of the processes involved may be obtained to allow almost complete irradiation of the need for field sampling. This is unlikely, however, on the very long term, as the land use, and building pattern are forever changing, and this will doubtless be accompanied by a change in the sediment concentration, both on the short and long term.

4. There is very little vertical concentration gradient in the suspended sediment due mainly to the tortuosity of the river.

CONCLUSIONS

The evaluation of suspended sediment concentrations of samples collected from the study area have led to the following conclusions:

1. The data support the necessity for rating loops (Walling and Teed, 1971) for accurate determination of suspended sediment losses. These rating loops in general exhibit a hysteresis effect as suspended sediment concentrations are higher for the same discharge on the rising limb of the hydrograph than on the falling limb.
2. The data suggests that the hysteresis effect is greatest for the first large storm of the water year during which exhaustion of material would occur, and that it becomes reduced through the winter.

3. Suspended sediment concentrations for the same discharge become reduced, if successive hydrograph peaks follow in rapid succession, due to exhaustion of material.

Only a short period (approximately five days) is necessary for the re-accumulation of suitable material for suspension so that the next hydrograph would have higher suspended sediment concentrations.

4. Generally, the maximum suspended sediment concentrations occur before the maximum discharge, but the highest rate of sediment loss per unit of time is generally between these two times.
5. Organic material comprises approximately 35% of the total suspended sediment at low flow, and approximately 20% at high flow.
6. There is very little vertical concentration gradient in the suspended sediment due mainly to the turbulence of the river.
7. There is a general decrease in suspended sediment concentrations downstream, but this does not necessarily imply a decrease in total suspended sediment lost.
8. The total suspended sediment lost over Iping Mill crump weir (location F) during 1972 was 2,182 tonnes of which 1,720 tonnes is non-organic. The majority of this is carried during floods.

The average erosion rate for the catchment above Iping Mill as a whole is 14 tonnes/km²/annum (organic and non-organic) of which 11 tonnes/km²/annum (non-organic) are primarily derived from the rocks of the catchment.

These figures are probably a little lower than for most years due to data being collected for one year only, and that the year concerned (1972) was a comparatively dry year.

CHAPTER 13

9. The accuracy of suspended sediment concentrations determined without field sampling, but from a knowledge of discharge only is considered low within the scope of present knowledge. However, such accuracy could probably be greatly increased with more work.

10. The major factors affecting suspended sediment concentrations are:

- a) river discharge
- b) duration of storm hydrograph
- c) frequency of storm hydrograph
- d) length of recovery time for re-accumulation
- e) affecting rate of sediment accumulation, time of year,

will vary with the cross-section of a channel, i.e. the more confined the channel the greater is the velocity. So with a river of varying cross-sectional area along its length, velocity and consequently sediment transport rate will vary. However, material in a reach of faster velocity can only be carried through it at the rate at which it enters the upstream end of that reach. This applies only if material is not eroded from the river bed or banks. If material is not eroded, however, and if the discharge remains constant for a sufficiently long period, the channel floor in that stretch will eventually become paved by a lag deposit of particles too large to be removed by the prevailing discharge. So, for any given river system, if a particular discharge prevails for a long enough period of time, and no sediment is being introduced into the channel by run-off processes (e.g. during conditions of base flow), a state of non-transport will be achieved because material in the slower velocity stretches will not reach the areas of greater velocity. This will apply more rapidly to bed load, but will ultimately apply to suspended load (with the possible exception

of very low concentrations), CHAPTER 3

During all periods of transport the rate will be controlled by

the slowest velocity stretch, which will also control transport totals

INTRODUCTION

The bed load of a stream is that part of the total sediment load that is comprised of elastic particles that move essentially in contact with or immediately above the river bed. The majority of the material of the bed load is assumed to be picked up from the river bed sediment.

Obviously, transport rates of bed load, and of suspended load depend on current velocity. Also, velocity of the current for any given discharge will vary with the cross-section of a channel, i.e. the more confined the channel the greater is the velocity. So with a river with varying cross-sectional areas along its length, velocity and consequently sediment transport rates will vary. However, material in a reach of faster velocity can only be carried through it at the rate at which it enters the upstream end of that reach. This applies only if material is not eroded from the river bed or banks. If material is not eroded, however, and if the discharge remains constant for a sufficiently long period, the channel floor in that stretch will eventually become paved by a lag deposit of particles too large to be removed by the prevailing discharge. So, for any given river system, if a particular discharge prevails for a long enough period of time, and no sediment is being introduced into the channel by run-off processes (e.g. during conditions of base flow), a state of non-transport will be achieved because material in the slower velocity stretches will not reach the areas of greater velocity. This will apply more rapidly to bed load, but will ultimately apply to suspended load (with the possible exception

of very low concentrations).

During all periods of transport, the rate will be controlled by the slowest velocity stretch, which will also control transport totals for the entire upstream catchment. The period of time for a state of non-transport to occur will approximate to the length of time it takes the particles that have just entered (towards the end of the falling limb of the flood hydrograph) the longest reach of greater velocity, to pass through it and become deposited in a downstream reach of slower velocity.

In the present study catchment, as in other rivers, these processes will apply, and also the size of material transported as bed load will vary with position in the stream, both along and across the channel. In zones of faster current velocities the size of material able to be moved as bed load will be larger than for zones of slower velocities.

One of the purposes of the present study involved the estimation of the bed load transport rates of the Rother. A literature survey (see Introduction to Section II) indicated that several methods of bed load estimation are available, but recent studies using tracer techniques indicate that "much more effort could be profitably devoted to the use of fluorescent tracers in studies of sediment movement in the fluvial environment." (Kennedy and Keuba, 1970).

FLUORESCENT TRACERS

Tracers used in the study of sediment movement have to have some property to allow their identification in a sediment. Consequently,

such tracers have generally been either radioactive or fluorescent.

Teloki (1966) defined fluorescent tracers as elastic particles coated with selected organic or inorganic substances, which upon excitation of 3650 Å or 2537 Å wavelengths ultra-violet light emit fluorescence of variable wavelengths and intensity in the visible region of the spectrum. Information on the available dyes and on the method of preparation of fluorescent tracers are available (Teloki, 1966, and Newman, 1964).

Fluorescent materials have been used extensively in the study of beach sediments (including Kidson and Carr, 1962, and Ingle, 1966, etc.), and more recently they have been used in studies of fluvial sand (Lean and Crickmore, 1963; Russell, Newman and Tomlinson, 1963; Crickmore and Lean, 1966; Crickmore, 1967; Kennedy, 1968; Kennedy and Kouba, 1970; Rathbun, Kennedy and Culbertson, 1971; and Rathbun and Nordin, 1971).

Much of the first work with tracers in river studies was carried out at the Hydraulics Research Station, Wallingford, England. Crickmore and Lean (1962) describe experiments in which the objective was to develop a method of measuring sand transport in rivers, and they conclude that the experiments show that the transport rate can be deduced by using tracer methods.

From there on, they produced several papers (1962, 1963 and 1966) concerned with the application of various tracer methods, along with a study by Russell, Newman and Tomlinson. These studies are summarised to an extent in a paper by Crickmore (1967), where the various tracer methods are applied to field conditions.

The main transport (or) concentration of sediment in a river channel is determined by the velocity of the water. In more recent years, tracer methods of river studies have been applied in the United States: Kennedy (1968), Kennedy and Kouba (1970), Rathbun and Nordin (1971), and Rathbun, Kennedy and Culbertson (1971). The theory and methodology used here is dominantly that outlined by Crickmore and Lean.

The velocity (or) of the material of the tracer cloud is

METHODS OF MEASUREMENT OF SAND TRANSPORT USING TRACERS

Three principal methods of determining sediment discharge using tracers have been determined, and these have been identified as:

1. the spatial Integration Method,
2. the Time Integration Method,
3. the Steady Dilution Method.

All three methods have been verified under steady flow conditions in laboratory flume studies (Crickmore and Lean, 1962, two papers; 1963),

but their applicability to loose boundary hydraulics met with in the field is a little less certain.

The steady dilution, and time integration methods are closely related and measure sediment discharge from a time approach. Both involve measurement of changes of tracer concentration at a section downstream of the position where the tracer was introduced. These methods, based on similar methods for determining river discharge, are only applicable to conditions of steady flow. The spatial integration method, however, is suitable for both steady and non-steady transport (Crickmore, 1967).

Spatial Integration Method

(Symbols used in this chapter are explained in Appendix 2).

The mean transport (qs) expressed as volume of compacted sand occurring over the entire channel width can be determined from the movement of tracer particles that behave with hydraulic similarity to the sediment particles of the stream bed (Crickmore, 1967). If the tracer is introduced as a line source across the entire width of the channel, the velocity (ut) of the centroid of the tracer cloud is equal to the mean velocity of the bed particles.

Consequently:

$$qs = ut \phi B \quad (16)$$

where ϕ is the mean depth of bed through which tracer particles are dispersed, and B is the channel width.

The position of the centroid of the tracer cloud at any time is given by

$$\frac{\int_0^{\infty} gt x dx}{\int_0^{\infty} gt dx} \quad (17)$$

where gt is the weight of tracer per unit length and X is the distance from the origin (point of tracer injection).

It follows that the centroid velocity (ut) can then be determined by the positional shifts of the centroid between successive times (t_1 and t_2):

$$ut = \left[\left(\frac{\int_0^{\infty} gt x dx}{\int_0^{\infty} gt dx} \right)_{t_2} - \left(\frac{\int_0^{\infty} gt x dx}{\int_0^{\infty} gt dx} \right)_{t_1} \right] \frac{1}{t_2 - t_1} \quad (18)$$

Rathbun and Nordin (1971) introduced the factors of specific weight of bed material, and of porosity of the bed, so that mean sediment transport can be determined as weight and not as volume.

The spatial integration method provides transport information at any time after t_0 , although in practice it was found that more reliable data are obtained after initial rapid rates of vertical dispersion give way to subsequent slower changes. Crickmore (1967) concludes that the spatial integration method is the most useful, but is impractical when transport rates are high because the time period for surveying the necessary channel length is too long to give a quasi-instantaneous picture of the tracer distribution.

The usefulness of sediment discharge data being determined as volume of sand per unit of time is limited in the light of the explanation (see Introduction to this chapter) of prolonged periods of non-transport at low flows, that are supported by experimental results (Experiment 1). Consequently the author chose to determine sediment discharge over a time period initially, which included, where possible, only one flood event. Thus, any sediment transport on the river bed could be attributed to a single flood hydrograph. This sediment discharge was determined as follows:

$$q = p t \phi B \quad (19)$$

where q is the transport, of a period since injection, expressed as volume of compacted sand, and $p t$ is the distance of the centroid of the tracer cloud from the injection point.

For each successive survey $p t$ can be determined:

$$p t = \frac{\int_0^{\infty} g t x dx}{\int_0^{\infty} g t dx} \quad (20)$$

In this manner, transport over the total period since injection

of the tracer can be obtained, and if the transport between successive surveys (qr) taken at times t_1 and t_2 is required it can be obtained:

$$qr = q t_2 - q t_1 \quad (21)$$

Time Integration Method

It is more widely known that fluvial discharge can be determined by introducing a known quantity of tracer into the flow, and by integrating the concentrations of tracer in samples collected at a station sufficiently downstream for mixing to have occurred, with respect to time:

$$Q = \frac{vf}{\int_0^{\infty} c dt} \quad (22)$$

where Q is the volume of discharge, vf is the volume of marker fluid introduced, and c is the concentration of tracer by volume at the sampling locality.

Two conditions must be fulfilled, however: the flow must be steady (Evans and Ely, 1963) and complete mixing of the tracer must have occurred.

This principle may be adopted for the measurement of sediment discharge:

$$qs = \frac{v}{\int_0^{\infty} c dt} \quad (23)$$

where v is the volume of tracer sand injected and c is the concentration of tracer at the sampling location.

Rathbun and Nordin (1971) again determine sediment discharge as weight by replacing (in equation 23) v and c with notations involving

As the sediment transport is a long process, the period of

weight and net volume, i.e. weight tracer introduced and concentration by weight.

There are many practical difficulties with the time integration method (Crickmore, 1967), the main one being to ensure that steady flow conditions prevail, as it may take a long period of time for the complete tracer cloud to pass the sampling section. This could be overcome to some extent by reducing the distance between the sampling location and the point of injection. However, this would then reduce the distance of transport, which should be sufficient for each particle to experience all the elements of the flow field so that they pass through the experimental stretch at a velocity representative of the bed material.

Steady Dilution Method

Steady dilution differs from time integration in that the former involves continuous injection of tracer, and only a single concentration measurement once equilibrium has been achieved, while the latter involves a single dose of tracer only, and a continuously monitored concentration at the measuring station.

With the steady dilution method, the mean transport (q_s) can be determined:

$$q_s = \frac{q'}{C_s} \quad (24)$$

where q' is the injection rate of tracer and C_s is the steady concentration.

As the sediment transport is a long process, the period of

containing is water bonded to the sand grains and "is sufficiently

continuous injection would necessarily have to be prolonged. Other disadvantages are those that apply to the time integration method, i.e. steady flow conditions must be maintained, and there is a minimum mixing length between injection and measuring points.

Again, the sediment discharge can be determined by weight, instead of volume, if the injection rate of tracer and the steady concentrations at the sampling section, are determined by weight and not volume.

Crickmore (1967) concludes that the spatial integration method is the most practical method (especially regarding sand transport) and it is applicable to both steady and non-steady flow conditions.

PREPARATION AND TESTS OF FLUORESCENT TRACERS

Whatever method is used for the determination of sediment discharge using fluorescent tracers, there are two factors that must be adhered to:

1. the tracer particles must be representative of, and behave as, the particles on the channel bed;
2. the tracer particles must be able to be identified after being retrieved in a sample.

Consequently, any fluorescent coating on a particle must survive the period of the particular survey.

Preparation of Fluorescent Tracers

The fluorescent tracers used in this study fall into two categories:

1. Commercially produced fluorescent sand obtained from British Industrial Sand Ltd. of Reigate, Surrey. The fluorescent dye coating is resin bonded to the sand grains and "is sufficiently

stable for use in fresh water for a reasonable period of time."

The coating is applied to a base sand of "Redhill T" which is quarried from the Lower Greensand of the Redhill area which is a similar facies to the Lower Greensand of the study catchment.

This fluorescent sand was dry sieved by the author into the desired size grades for the experiments.

2. Laboratory produced fluorescent tracer was also used to represent the coarser sized sediments (10-16 mesh and 5-8 mesh). The base material for the 10-16 mesh was sieved from the Folkestone Beds, while the base material for the 5-8 mesh was sieved from a beach gravel and sand mixture. The latter produced a fraction consisting principally of flint fragments with some rock fragments, which is also characteristic of this size fraction in the channel bed sediment.

The base materials were washed in water to remove any adhering clay particles and then placed in a glass bath and covered slowly with HCl (36.46), care being taken to avoid frothing over. This process removed any shell debris (with different hydraulic properties) that was present in the original deposit, and it also generally cleaned the base materials to allow the fluorescent coating to adhere better. The material was then thoroughly washed and dried, and then laid out on a surface and sprayed with a "Humbrol" fluorescent paint. Agitation of the particles was necessary to encourage an all-over coating. After the paint had dried, the material was re-sieved to break up any aggregates.

For some of the yellow tracer (10-16 mesh) which was produced in
Tests for Fluorescent Tracers it was found that if the yellow grains were

Samples of all the fluorescent tracers used in this study were subjected to various tests including solution tests, abrasion tests,

non-wetting tests, and clustering tests, and the median fall diameter was compared with that of river bed sediment of the same size.

1. Solution Test. Two containers, one with tracer and river bed sand, and one with tracer only, were filled with water and left, with occasional agitation and changing of the water, for over a year. The results of the test showed that no deterioration in fluorescent properties of the tracers occurred.
2. Abrasion Test. Three containers, one with sand and tracer mixture only, one with fluorescent sand and water, and one with river bed sand, tracer and water, were agitated for a period of time. The results showed no significant loss in the fluorescent property of the tracers.

Another test included some tracer that was subjected to conditions simulating river bed transport for a length of over 5,000 metres. The result was, again, no reduction in the fluorescent property.

3. Non-wetting and Clustering Test. Some fluorescent coatings have a non-wetting property, and so when placed in water the particles may have a tendency to cluster together in groups. Rathbun, Kennedy and Culbertson (1971) overcame this problem by adding detergent to the fluorescent material before injection.

All of the fluorescent tracers used in this study were subjected to tests to see whether or not any clustering occurred. These tests showed no tendency for clustering in any of the tracers used, except for some of the yellow tracer (10-16 mesh) which was produced in the laboratory. However, it was found that if the yellow grains were mixed with tracer of a smaller size range before being injected,

Table 39. Summary of median fall diameters of fluorescent tracers and of river bed material.

the tendency to cluster was overcome as the yellow grains were initially separated from each other before being introduced into the channel.

4. To test median fall diameters of different sieve classes. Median fall diameters were determined for each of the sieve classes of tracers used, by dropping particles into a column of quiescent distilled water at 20°C, and thus obtaining its fall velocity. This fall velocity was then converted to median fall diameter by using Rubey's General Formula for Settling Velocities. The median fall diameters are summarised in Table 39, along with the median fall diameters for river bed material of the same size.
5. To test deterioration during drying. As samples collected from the channel bed would have to be oven dried it was necessary to design a test to determine if any deterioration of the fluorescent coating would occur during this drying. It was found that there was no loss of brilliance of the fluorescent coating if drying temperatures did not exceed 100°C.

SELECTION OF EXPERIMENTAL STRETCH

The importance of the relationship between current velocity, discharge and area of channel cross-section on bed load transport has been explained (Introduction to this chapter). Factors considered during the selection of the experimental stretch therefore included:

1. a slow velocity stretch with a sandy bed where bed transport of sand sized material would occur only during the passage of a storm;
2. the hydrological pattern of its catchment has to be similar to that

Table 39. Summary of median fall diameters of fluorescent tracers and of river bed material.

of the catchment of Iyng Hill crump weir, so that the discharge data and hydrograph from the latter could be of use in accessibility, but sufficiently isolated so as to remain free from human influences and interferences.

Median Fall Diameters, mm

T r a c e r s

Size	River Bed Material	Green Grains	Yellow Grains	Red aggregates	Blue grains	Red grains
65-8	3.35-2.00	6.05	4.95	---	---	---
10-16	1.68-1.00	1.93- 2.70	---	2.10	0.93	---
25-30	0.60-0.50	0.61	---	---	0.57	0.58
52-60	0.30-0.25	0.28	---	---	0.26	0.27
100-120	0.15-0.12	0.13	---	---	0.14	0.13

area (Fig. 26), and is a slightly curved stretch, part of a meander, 100 m in length. The average depth of water at the thalweg (the deepest part) is about 1.70 m (see Fig. 27). The channel bed also varies, from coarse and very coarse sand to the finest, to fine and very fine sand towards the inside of the bend. Fig. 28 shows the sediment size distribution of the channel.

A comparison of stage levels obtained from the experimental stretch, with the hydrograph obtained from Iyng Hill crump weir,

Table 40. Centroid positions during experiment one.

Days after injection	Centroid position m. from origin
0	0
39	0
46	3.2
49	14.9
52, 57 & 60	38.1
70	46.0
72 & 85	beyond 46.0

measured 7-8 hours later at the experimental stretch. Current velocities were obtained at various stage levels (see Fig. 29). This data, and these are presented in Fig. 29.

EXPERIMENTAL DETAILS, FIELD SAMPLING AND LABORATORY PROCEDURES

After sieving into the required size grades the fluorescent tracers were introduced directly into the river bed (as a line source across the entire width) through an 8 cm diameter plastic pipe from a rubber dingy to a rope stretched across the entire channel. When different size grades of tracers were introduced together an attempt was made to concentrate the coarser grades in that part of the channel cross-section where a higher proportion of coarser material was

of the catchment of Iping Mill crump weir, so that the discharge data and hydrograph from the latter would be of use;

3. accessibility, but sufficiently isolated so as to remain free from major human influences and interference.

The stretch finally selected is upstream of North Mill, Easebourne, Sussex (Fig. 26), and is a slightly curved stretch, part of a meander, and of 200 m in length. The average depth of water at the thalweg (during base flow) is approximately 190 cm (see Fig. 27). The channel bed sediment also varies, from coarse and very coarse sand in the thalweg, to fine and very fine sand towards the inside of the bend. Fig. 28 shows the sediment size distribution of the channel.

A comparison of stage levels obtained from the experimental stretch, with the hydrograph obtained from Iping Mill crump weir, indicated that the hydrographs were similar, but that the peak discharge occurred 2-3 hours later at the experimental stretch. Current velocities were obtained at various stage conditions using a Braystoke Flow Meter, and these are presented in Fig. 29.

EXPERIMENTAL DETAILS, FIELD SAMPLING AND LABORATORY PROCEDURE

After sieving into the required size grades the fluorescent tracers were introduced directly onto the river bed (as a line source across the entire width) through an 8 cm diameter plastic pipe from a rubber dinghy/^{Fixed} to a rope stretched across the entire channel. When different size grades of tracers were introduced together an attempt was made to concentrate the coarser grades in that part of the channel cross-section where a higher proportion of coarser material was

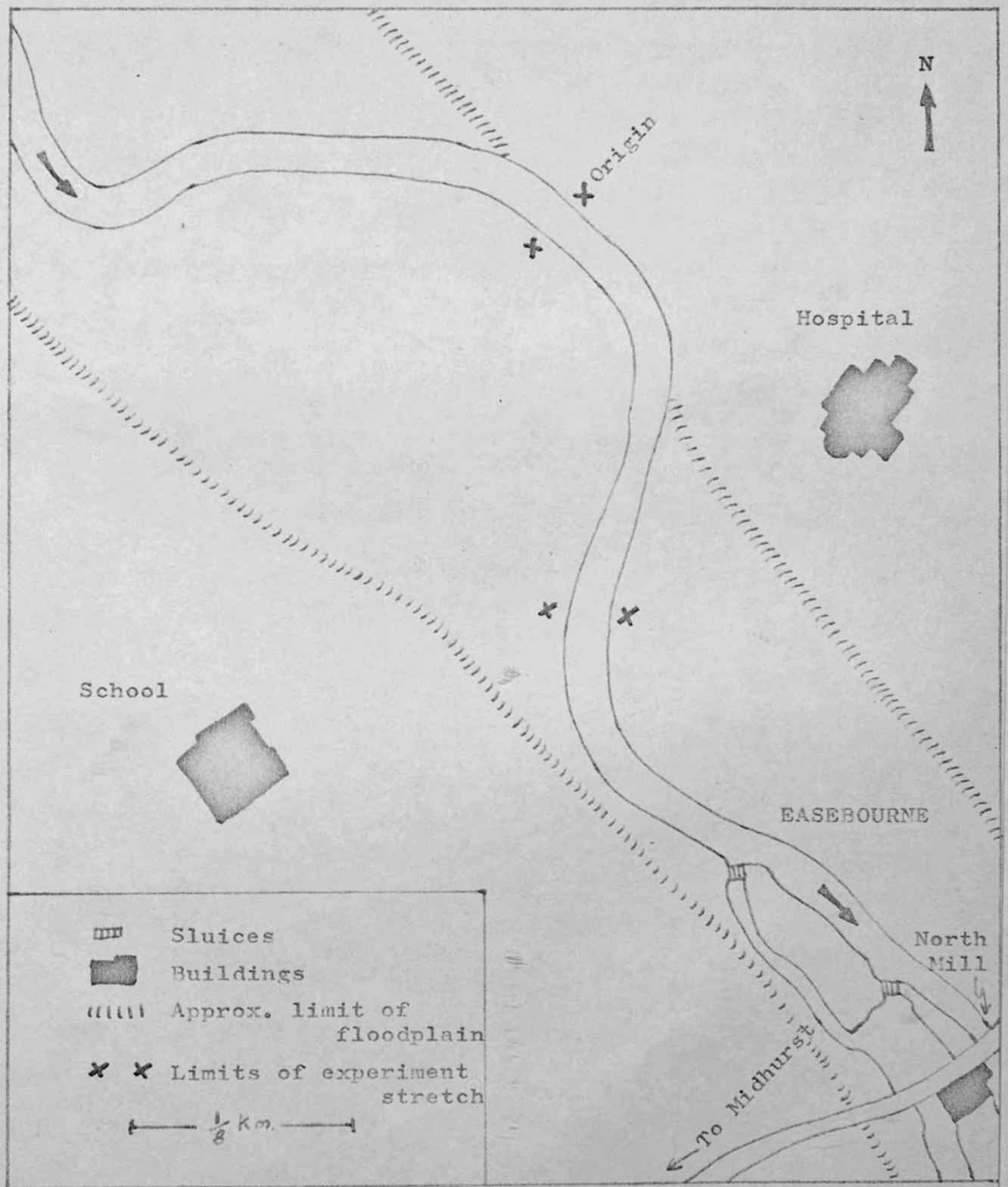


Fig. 26. The experimental stretch, upstream of North Mill, Easebourne, Midhurst.

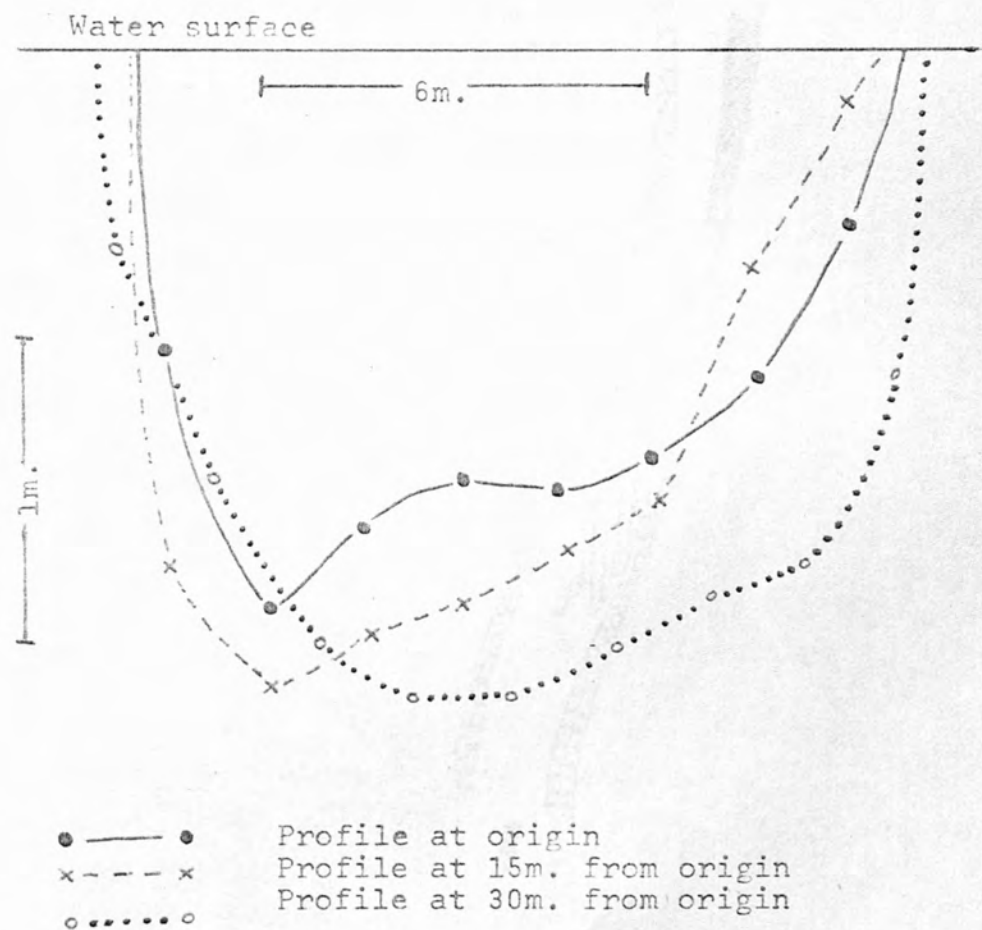


Fig.27. Cross-sectional profiles of the experimental stretch, Easebourne.

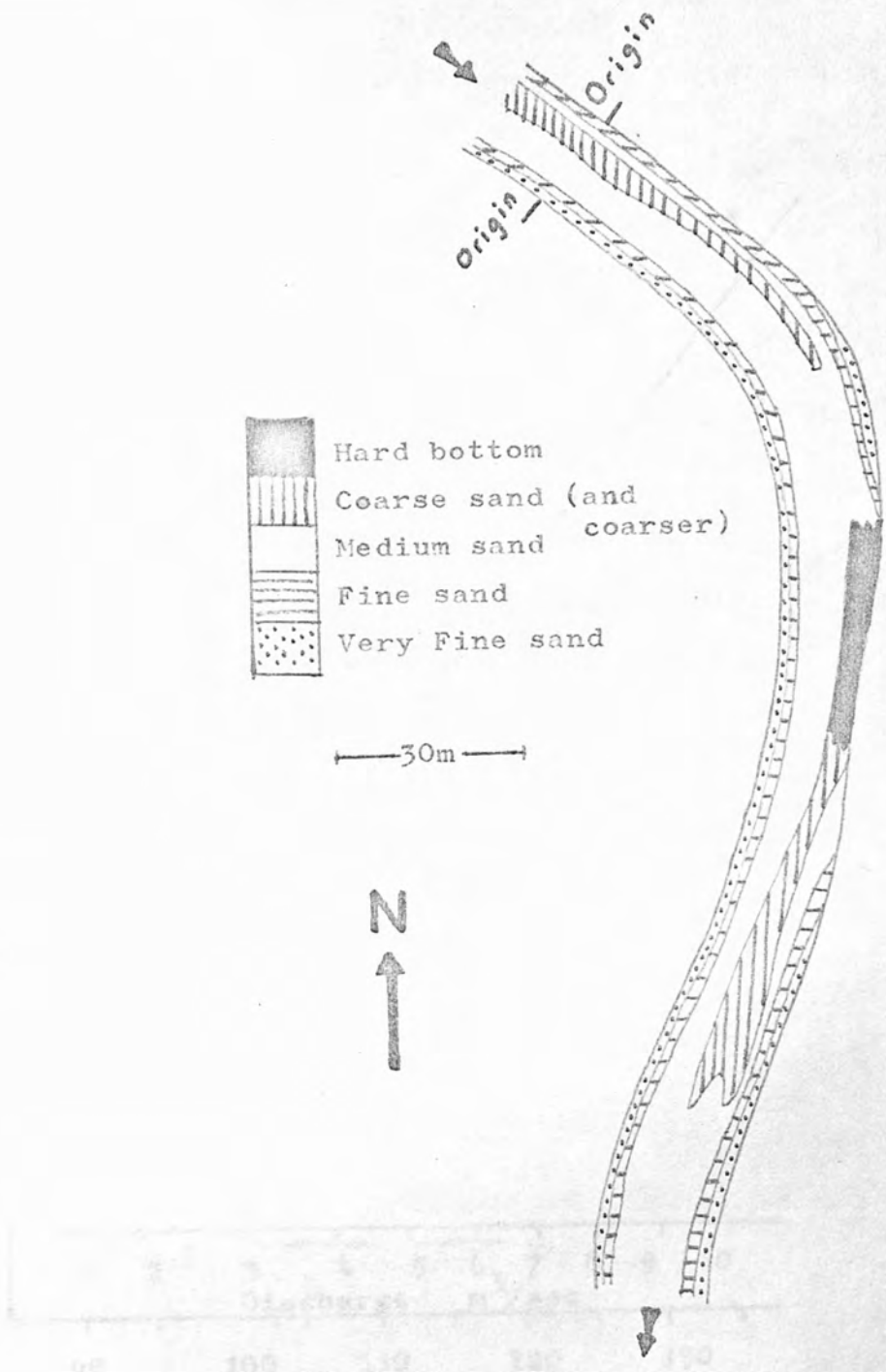


Fig. 28. Sediment distribution on the river bed of the experimental stretch, Easebourne, 20 Sept. 1972.

Fig. 29 Relationship between velocity, stage and discharge, Easebourne.

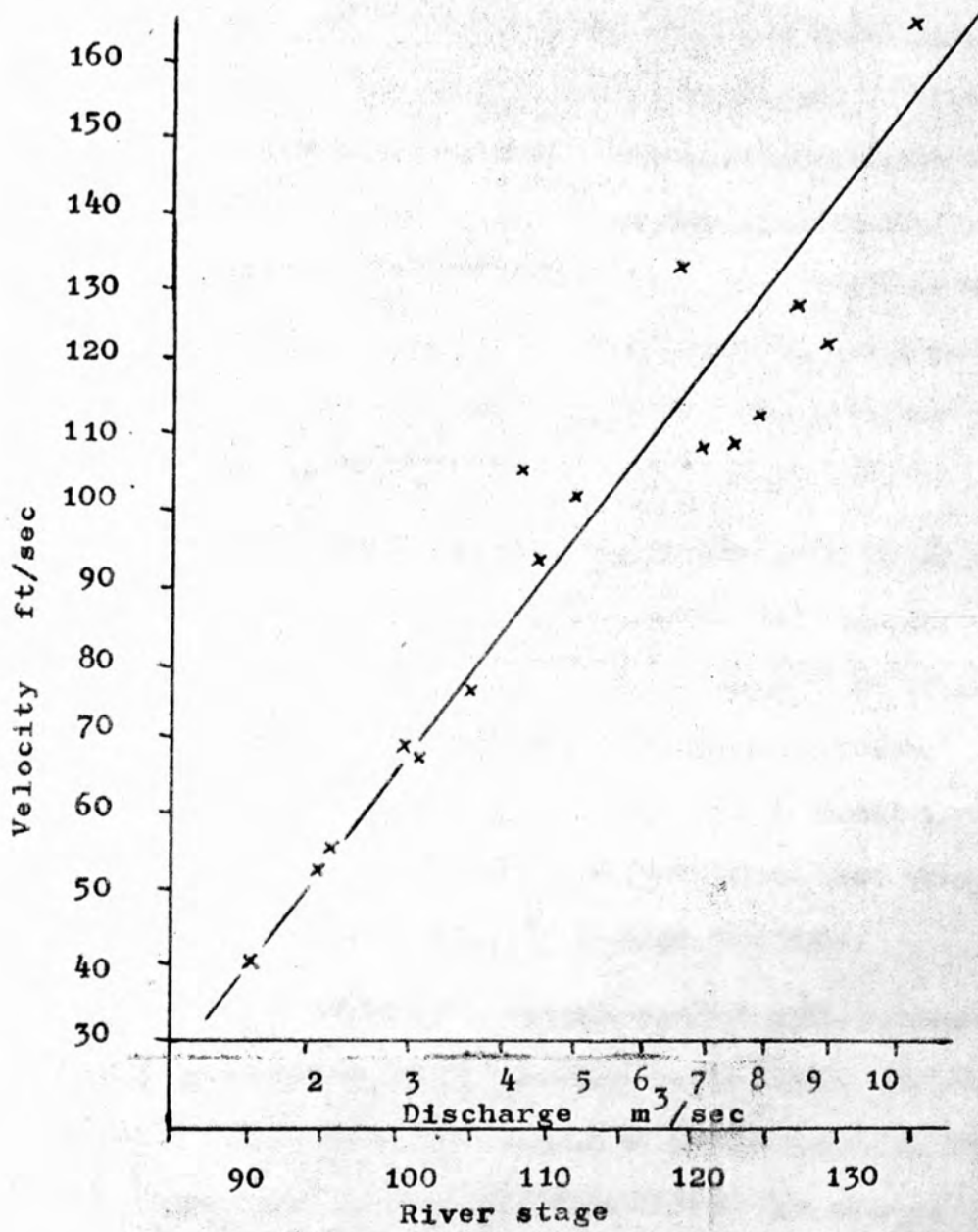


Fig. 29 Relationship between velocity, stage and discharge, Easebourne.

present in the bed sediment, for further tracer experiments.

Subsequent samples were collected downstream, again from a dinghy attached to a rope, using a simple scoop type sampler, with detachable sample holder. This allowed rapid sampling and labelling of samples, and each sample was up to 50g in weight. Approximately 6 samples were collected (1.5 m apart) at each sampling cross-section, and each sampling cross-section was 15 m apart. Such sampling was usually carried out for up to 180 m from the injection point for the spatial integration method, and only at 30 m from the injection point for the time integration method.

The samples were then dried in an oven at a temperature below 105°C, and after drying were inspected for the presence of fluorescent grains; the samples were spread onto a large sheet of white paper under ultra-violet light in a photographic dark room. The fluorescent grains were counted and removed using a small pencil type painting brush. The fluorescent tracer concentrations were then determined as number of fluorescent grains in 5 grams of sample.

The method of counting the fluorescent grain concentrations was tested for accuracy and it was found to be high. Indeed, it was found harder to introduce a known amount of tracer particles into a sample, than it was to count them when they were in the sample.

FLUORESCENT TRACER EXPERIMENT 1 - SPATIAL INTEGRATION

The first fluorescent tracer experiment was one designed to familiarise the author with the processes and methodology involved, and the injection. Concentrations are low, and tend to form a semi-linear

45 days after injection

to provide some data as a basis for further tracer experiments.

On 11th October 1971, 4,355g of red fluorescent tracer was injected as a line source onto the channel bed at the origin (Fig.26). The size distribution of this tracer was approximately the same as that of a compound sample collected from the channel floor of the experimental stretch. Subsequent downstream sampling was carried out after a period of 4 days, 11 days, 25 days and 39 days. Up until this period of time base flow conditions had prevailed with some small floods and no fluorescent grains were recovered at the sampling localities, indicating that no bed load transport had occurred of sediment of tracer size. However, after a period of 39 days, several storms occurred during the following 62 days, i.e. a period ending 101 days after the date of injection. The distribution of tracer concentrations in the river bed samples for the various surveys during this period of time are presented in Fig. 30, A - H.

Time of Injection to 39 days after (19.11.71)

Samples collected during this interval gave no indication of transport of bed material. The hydrographs for this period indicate that the discharge never exceeded $2.5 \text{ m}^3/\text{sec}$, and discharges of 2.4 and $2.2 \text{ m}^3/\text{sec}$ did occur. This indicates that, in the experimental stretch at least, bed load transport of material of tracer size does not occur at discharges of and below $2.5 \text{ m}^3/\text{sec}$.

46 days after Injection (26.11.71). Fig. 30, A

The distribution of tracer concentrations on this day indicates that some transport of bed material has occurred since 39 days after the injection. Concentrations are low, and tend to form a semi-linear arrow indicating flow direction.

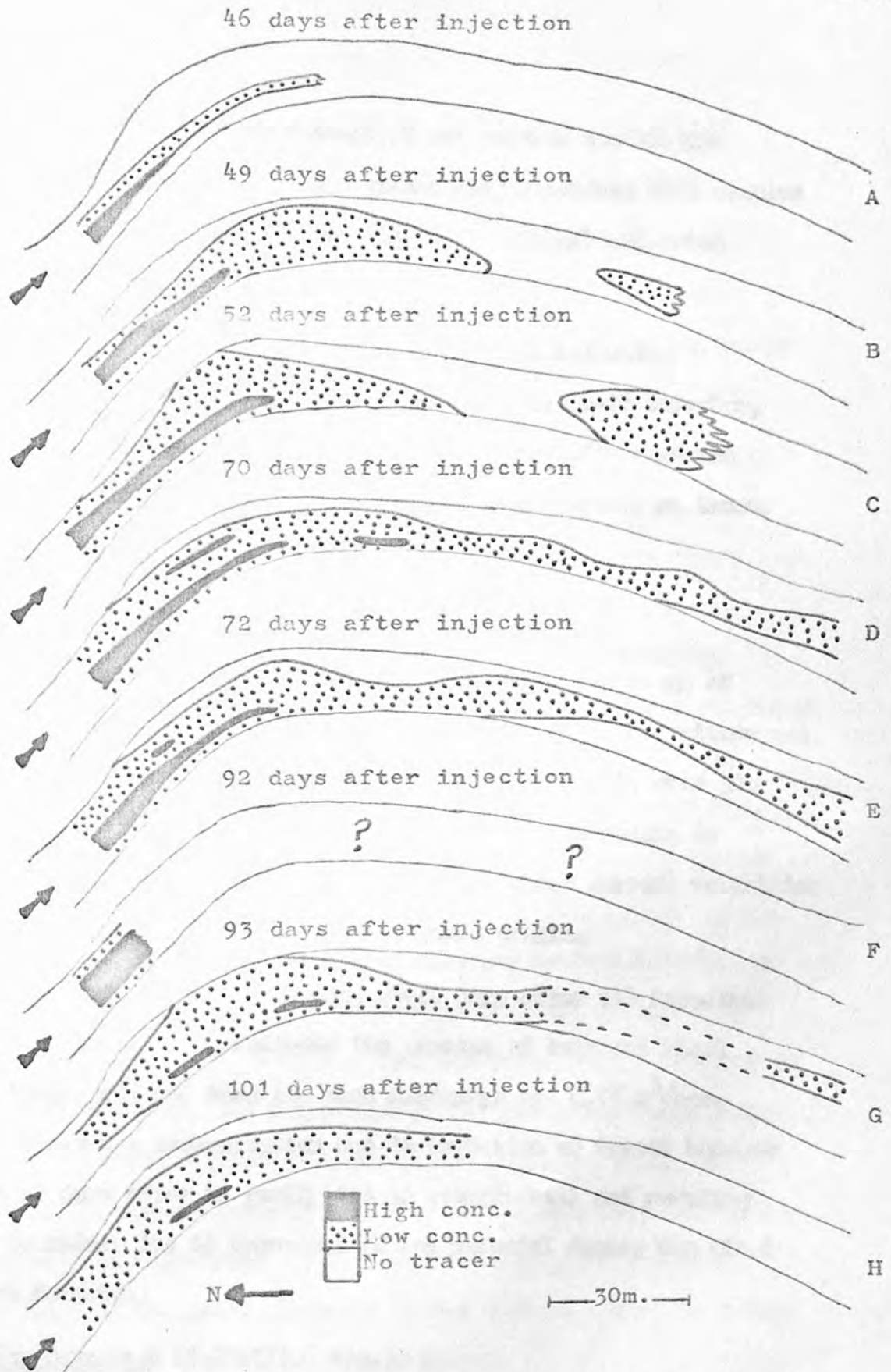


Fig. 30. Distribution of tracer concentration on river bed during first experiment. Tracer origin is the position of the arrow indicating flow direction.

pattern with a bias for higher concentrations towards the western bank. No, or very few, fluorescent grains were recovered from samples of coarser sediment (coarse sand and very fine pebbles) collected from the thalweg.

The hydrograph for the period 39-46 days after injection indicates only the passage of one flood occurring on 21-22 November, where the peak discharge was $7.7 \text{ m}^3/\text{sec}$. This indicates that the discharge threshold value for the transport of bed material of tracer size is between 2.5 and $7.7 \text{ m}^3/\text{sec}$.

49 days after Injection (29.11.71). Fig. 30 B.

The distribution pattern on this day shows a greater range of concentrations, and a more widespread distribution. Concentrations are again generally low with higher concentrations extending to over 30m from the origin. There is again a lack of fluorescent grains in samples collected from the thalweg and elsewhere where current velocities are greater, e.g. in the vicinity of 105m from origin.

The hydrographs during the period 46-49 days after the injection of fluorescent tracer again indicate the passage of only one flood (28th-29th November), and here the peak discharge was $8.75 \text{ m}^3/\text{sec}$. The difference in the concentration and distribution of tracer between 46 days and 49 days after is partly due to experimental and sampling error, but is mainly due to transport of bed material during the flood of 28th-29th November.

52 days after Injection (2.12.71). Fig. 30 C

The distribution pattern and concentration of fluorescent particles

on this day is very similar to that of 49 days after, except that the higher concentrations are somewhat more widespread. These differences are due to two possible causes:

- a) due to sampling and counting errors;
- b) a real difference due to movement of fluorescent grains during transport of bed material.

An inspection of the hydrograph from 49-52 days after injection indicates that no flood hydrographs occurred during this time. However, the experimental stretch was still experiencing the "tail-end" of the flood hydrograph of 28th-29th November, and for a period of time after the previous survey a discharge of up to approximately $2.4 \text{ m}^3/\text{sec}$ prevailed, albeit for a short time. Now, whether a discharge of this amount is sufficient to remove material towards the end of November, when it was not sufficient in early October, is debatable. However, the author would like to mention two points that may favour this:

1. The discharge level in November was following on from a period of bed load transport, whereas in October no bed load transport had occurred for some months over the summer period. This latter fact may have resulted in some compaction of bed material, which would then need a greater threshold value before transport would be initiated. However, contrary to this, is the fact that the tracer had not been in the stream for the summer period, but for only 3 days prior to the first discharge of $2.4 \text{ m}^3/\text{sec}$. Now, is 3 days sufficient for any such compaction to occur?
2. In November, it is possible that any vegetation on the river bed

that may tend to inhibit bed load movement, may have been removed by earlier and higher discharge conditions, whereas in October such vegetation was in evidence. The removal of such vegetation would again result in lower threshold values for the initiation of bed load transport.

57 days after Injection (7.12.71)

The distribution pattern for 57 days after injection is similar to that for 52 days after, and this coupled with hydrographs showing an almost constant discharge of approximately $1.08\text{m}^3/\text{sec}$ between this and the previous survey suggests a period of non-transport on the river bed, during which flow conditions fall off from $2.1\text{ m}^3/\text{sec}$.

60 days after Injection (10.12.71)

The distribution determined on this survey is again similar to that for 52 days after, and the hydrographs again show an almost constant discharge of approximately $1.00\text{m}^3/\text{sec}$. This is again a period of non-transport of bed material, where channel width is slightly reduced

70 days after Injection (20.12.71). Fig. 30 D

This survey showed concentration distributions that are again similar to that for 52 days after, but there is a slight difference. The lower concentrations are more persistent to over 165m from the origin, and higher concentrations are traceable to over 75m from the origin.

The hydrograph for this period since the previous survey indicates that a flood discharge occurred on the 69-70 days and that the stretch

was experiencing the falling limb discharge conditions during the sampling period itself. This flood hydrograph peaked at $5.8 \text{ m}^3/\text{sec}$ and would be responsible for some movement of bed material.

72 days after Injection (22.12.71). Fig. 30 E

The distribution pattern determined by this survey is similar to that of 70 days after, except that the higher concentrations were not determined beyond 45m from the origin, and there has been some lateral shift in the main lower concentration band. During the 2 days since the previous survey the experimental stretch was experiencing the falling limb discharge conditions of the flood of 69-70 days after injection; during which flow conditions fell off from $2.1 \text{ m}^3/\text{sec}$. Whether this discharge is capable of causing transport of bed material in the experimental stretch seems unlikely, but as has been seen (52 days after) there is a possibility that a discharge of $2.4 \text{ m}^3/\text{sec}$ may cause transport. However, if the $2.1 \text{ m}^3/\text{sec}$ discharge is capable of causing bed movement, it may be responsible for the reduction of high concentrations beyond 45m, where channel width is slightly reduced which would result in slightly increased velocities for the same discharge conditions.

85 days after Injection (4.1.72)

The concentration distribution determined by this survey gave the same pattern as that for 72 days after injection. Discharge conditions after the previous survey did not exceed $1.3 \text{ m}^3/\text{sec}$ and no transport of bed material would have occurred in this time.

121 days after Injection (20.1.72). Fig. 30 F

Here again the distribution and concentration pattern is similar

92 days after Injection (11.1.72). Fig. 30 F

A survey was attempted on the 92nd day after injection. However, due to the practical difficulty involved in the sampling procedure during the high flow conditions that occurred at this time ($> 7,00 \text{ m}^3/\text{sec}$), the stretch was sampled only at one cross-section, 15m from origin. From these few samples, the pattern at 15m from origin is essentially similar to 72 days after, with the possible exception that higher concentrations predominate.

The stretch was experiencing the rising limb of a flood event at the time of the survey, which eventually peaked approximately 8 hours later at a discharge of over $15 \text{ m}^3/\text{sec}$.

93 days after Injection (12.1.72). Fig. 30 G

The survey conducted on this day provided a concentration pattern somewhat different from that of all previous surveys as concentrations were predominantly low.

This survey was conducted during the falling limb of the flood mentioned under 92 days after injection, and so the change in the pattern of distribution and concentration since Fig. 30 B is the result of transport during this flood where discharge conditions were the greatest experienced since the time of injection. Transported amounts of bed material during this time were considerably higher than all previously mentioned floods, and were responsible for the removal from the experimental stretch of a lot of the tracer.

101 days after Injection (20.1.72). Fig. 30 H

Here again the distribution and concentration pattern is similar to the survey, the proportion of tracer that has passed out of the experimental

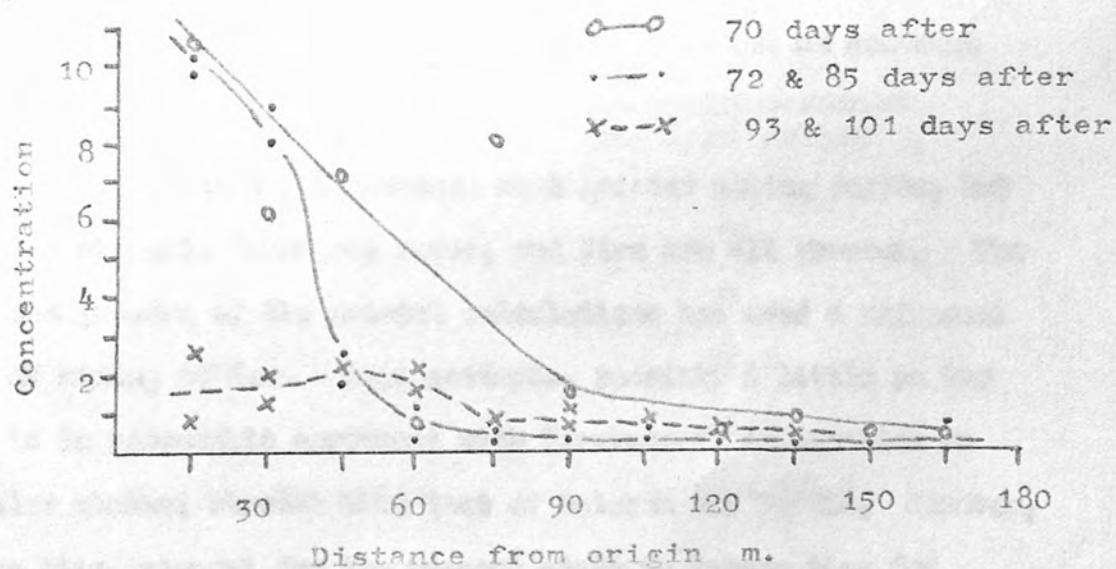
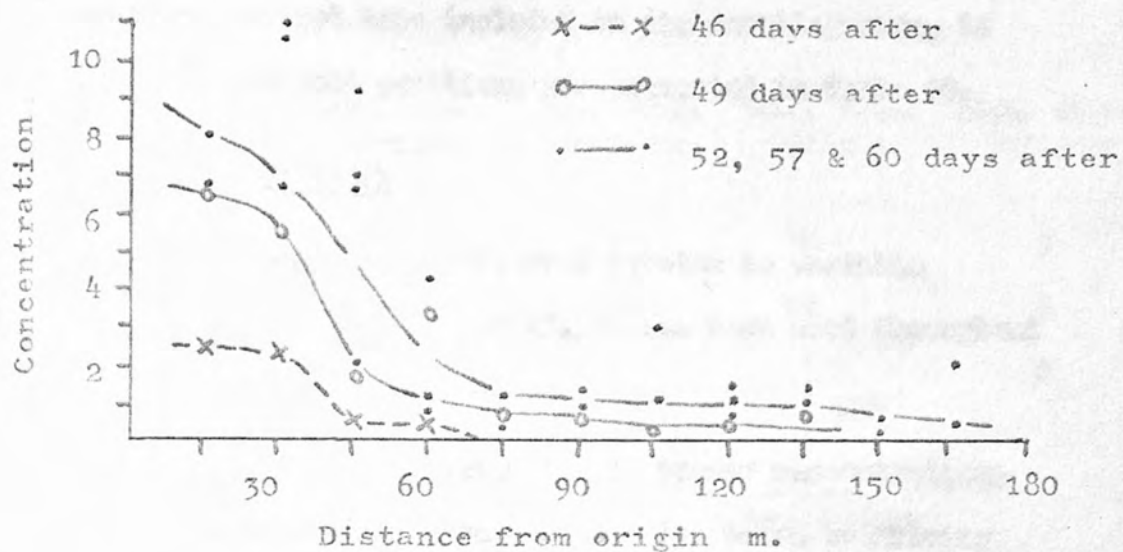


Fig. 31. Longitudinal distribution of tracer concentration, first experiment.

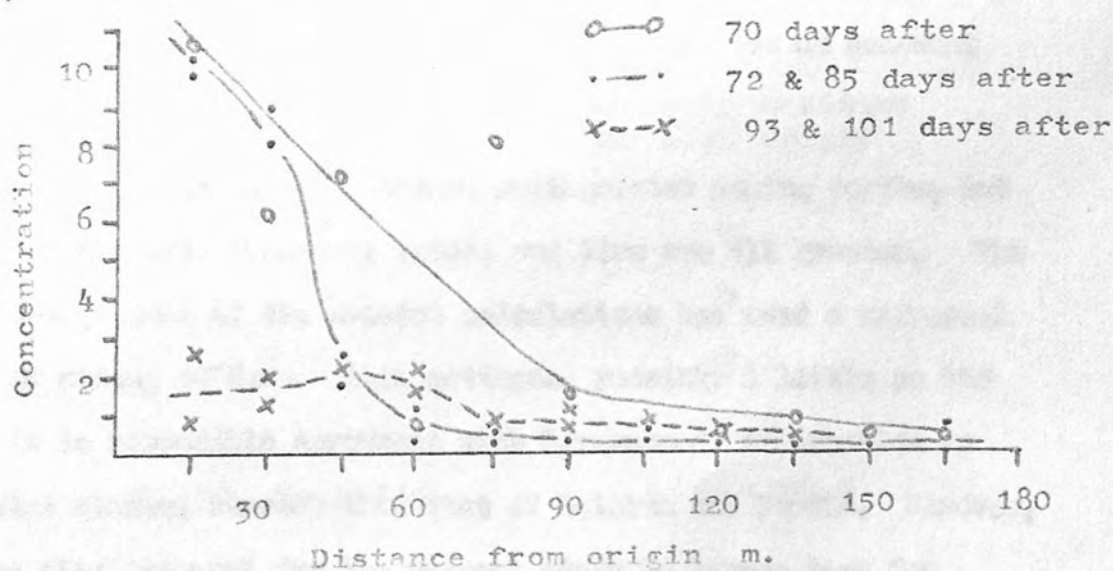
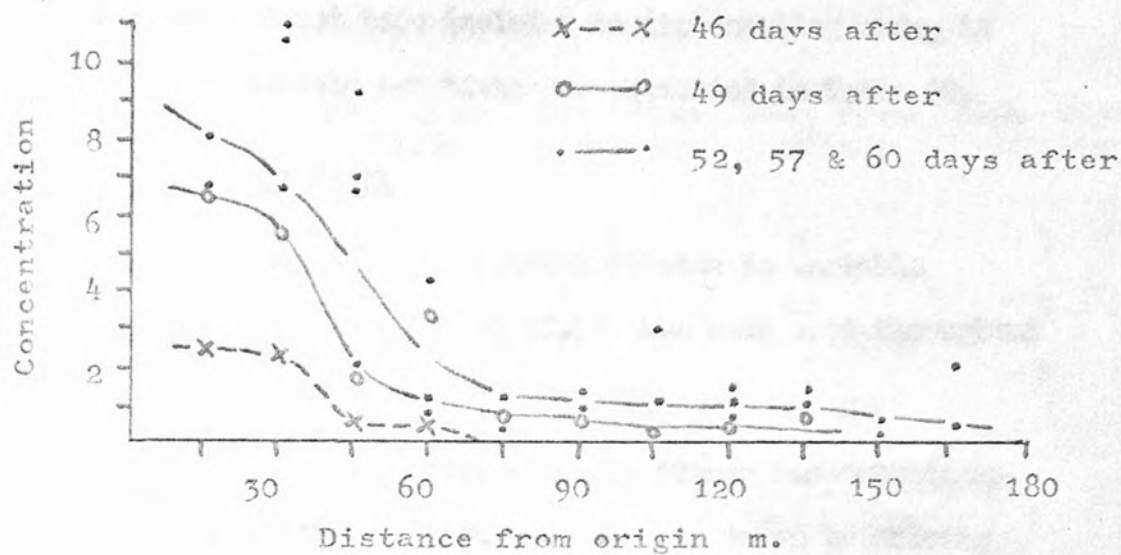


Fig. 31. Longitudinal distribution of tracer concentration, first experiment.

Table 41. Depths of mixing during experiments 1 and 2.

stretch, and therefore has not been included in the sampling area, is high. The calculated centroid positions are presented in Table 40.

Depth	15m. from	30m. from	45m. from	60m. from	75m. from
m	origin	origin	origin	origin	origin

Depth of Mixing and Channel Width

The channel width along the experimental stretch is variable (between 9 and 15m) and a mean value of 13.5m has been used throughout the calculations of bed load transportation.

Information on the vertical distribution of tracer concentrations during the experiment was obtained from core samples taken by driving an open steel cylinder, 4cm diameter, into the bed. The top of the cylinder was then closed off and the cylinder retracted holding the core in place. In practice this procedure was somewhat problematical.

Crickmore (1967) goes into some detail on the determination of the mean depth of mixing of the tracer, and the data collected on the present study (Table 41) compare favourably with his, but are somewhat unreliable.

Days after injection

Centroid position
m. from origin

Rathbun and Nordin (1971) obtained much greater mixing depths, but here the river channel, transport rates, and time are all greater. The author for the purpose of the present calculations has used a universal mean depth of mixing of 6cm. This estimate, possibly a little on the high side, is in reasonable agreement with Crickmore's information on a more similar channel stretch than that of Rathbun and Nordin. However, although the time interval for the present study is larger than for that of Crickmore, the actual number of days of transport is low. Of course, depth of mixing is not only dependent on duration of sediment transport, but also on flow regime and bed form; but it is probable that

Table 41. Depths of mixing during experiments 1 and 2.

During the two experiments, the tracer concentration in grains / 5g. of sample was the major source of vertical mixing. The average tracer concentration in the period cm

Depth cm	15m. from origin	30m. from origin	15m. from origin	30m. from origin	60m. from origin
0-2	10	58	12	12	3
2-4	1	6	26	11	3
4-6	0	1	?	5	2

66 days after 1st. injection 34 days after second injection

(Fig. 32 A-F) so that the relationship of sediment discharge to river stage is clearly seen.

These data (Fig. 32, A-F) on the first impression seem to provide some useful information, but closer inspection indicates the presence of some features in need of explanation.

Table 42. Centroid positions during experiment two.

Table 42. Centroid positions during experiment two.

Days after injection	Centroid position m. from origin
0	0
7	0
20	38.7
29	48.8
56, 81, 85 & 102	beyond 48.8

where 6.6m³ of sediment transport was determined. This can be explained by either the requirement of a period of time during which the tracer concentrations vary rapidly both vertically and horizontally, or due to the requirement of a higher threshold value for transportation to commence, due to either a) the long lag time period which suspension would require, or b) a greater amount of water during the hydrograph of 2 than that of 1. However, as the material itself was only introduced 41 days before, is this period long enough for this suspension? A third alternative c) is that the discrepancy is a reflection on the accuracy of the methods involved.

Fig. 32. Sediment discharge during experimental period.

5
 during the transport period in the present study channel, ripples were the major cause of vertical mixing, as they were for the first period of Grickmore's experiment.

5
Estimation of Sediment Loss during the 1st Experiment

As bed transport of sediment occurs only during conditions of flood, and as sediment discharge for any particular flood hydrograph can be determined (equation 21), the author feels the sediment loss for this period should be presented along with the hydrographs (Figs. 32 A-F) so that the relationship of sediment discharge to river stage is easily seen.

These data (Fig. 32, A-F) on the first impression seem to provide some useful information, but closer inspection indicates the presence of some features in need of explanation.

1
Fig. 32 G. Here a low bed load discharge (2.7 m^3) has been recorded despite the peak river discharge being greater than that for Fig. 32 F where 6.6 m^3 of sediment transport was determined. This can be explained by either the requirement of a period of time during which the tracer concentrations vary rapidly both vertically and horizontally, or due to the requirement of a higher threshold value for transportation to commence, due to either a) the long summer period over which compaction would occur, or b) a greater amount of weed during the hydrograph of G than that of F. However, as the material itself was only introduced 41 days before, is this period long enough for this compaction? A third alternative c) is that the discrepancy is a reflection on the accuracy of the methods involved.

Time hrs.
 Fig. 32. Bed load transport through experimental stretch during first experiment. All sand sizes.

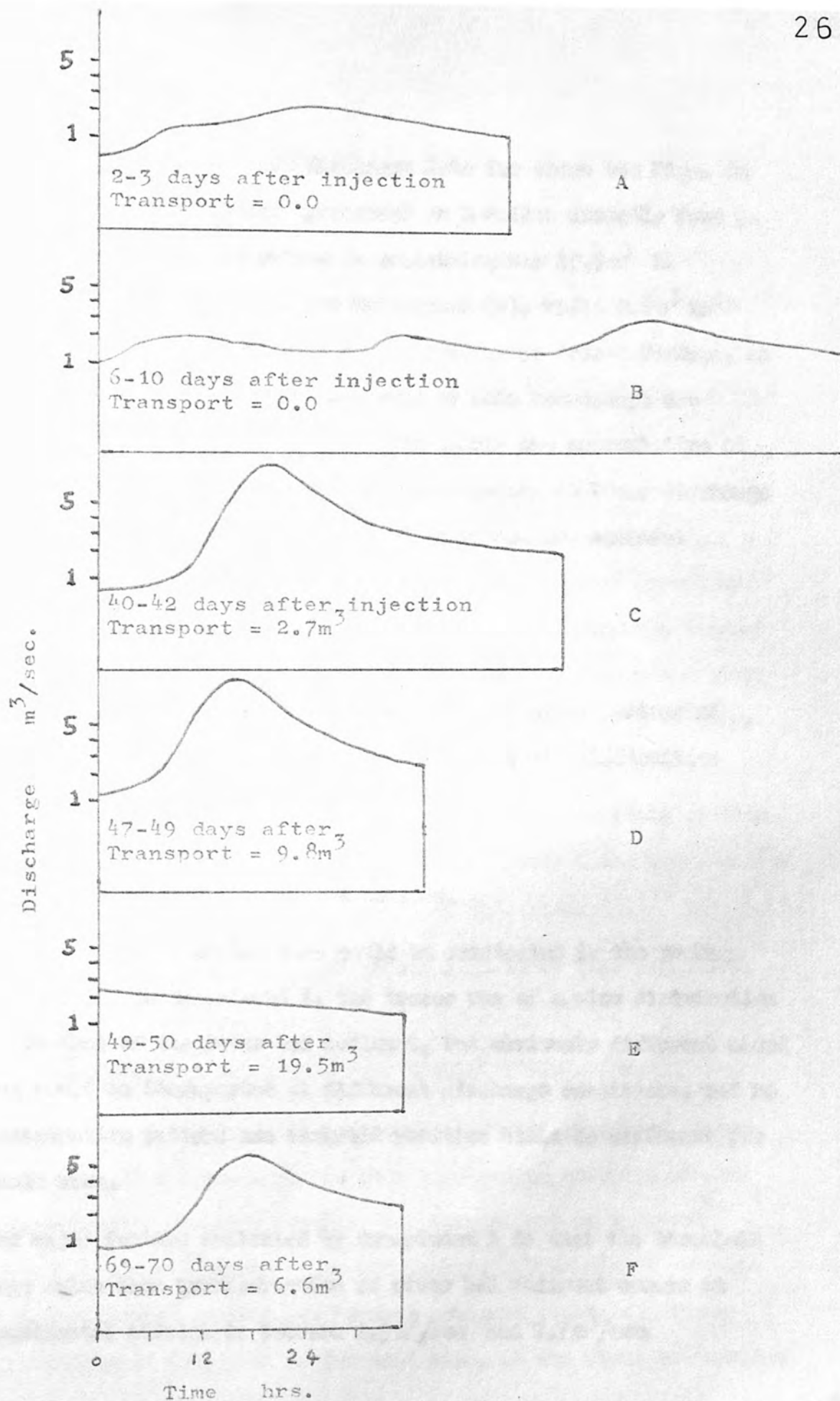


Fig. 32. Bed load transport through experimental stretch during first experiment. All sand sizes.

Fig. 32 D and E. The bed load discharge data for these two Figs. in fact refer to only one storm hydrograph as E follow directly from D. Here again some difficulty arises in explaining why 19.5m^3 is transported in the tail end of the hydrograph (E), while 9.8m^3 is transported during the major part of the hydrograph (D). Perhaps, as was explained earlier, the peak discharge of this hydrograph was a flow sufficient to remove a lot of the surface debris and accumulation of old wood so that transport could occur more readily at lower discharge conditions. This would also explain an increased bed sediment discharge during F than during G.

Conclusions on Experiment 1

This experiment familiarised the author with the experimental procedures, and provided an indication of some of the difficulties involved. Principally that:

a) effects of compaction are not understood;

b) any effects of weed etc. are unknown.

One complicating factor that could be eradicated is the problem of grain size. In Experiment 1, the tracer was of a size distribution similar to that of the river bed sediment, but obviously different sized sediment would be transported at different discharge conditions, and so the concentration pattern and centroid position would be different for each grain size.

The major feature indicated by Experiment 1 is that the threshold discharge value when transportation of river bed sediment occurs in the experimental stretch is between $2.5\text{m}^3/\text{sec}$ and $7.7\text{m}^3/\text{sec}$.

TRACER OF VERY FINE PEBBLE SIZE

Towards the end of Experiment 1, the author was aware of the problem of differential rates of movement of tracers of different sizes, and in order to obtain a better understanding of the movement of larger grain sizes some green fluorescent tracer of very fine pebble size was prepared. 911g was introduced at the origin as a line source on 11th January, 1972 (92 days after injection of the first fluorescent tracer). This injection time was chosen as it was during the rising limb of a hydrograph that had every indication of having a high discharge where sediment of very fine pebble size may indeed be transported. This hydrograph did, in fact, prove to have the largest peak discharge of the winter. Unfortunately, however, only one grain of green tracer was recovered downstream and that was at 45m from the origin on 16th March, 1972. This lack of recovery consequently furnishes very little information concerning sediment movement of this size, and is due to a) too small a quantity of tracer being used, and/or b) the result of non-movement of sediment of this size.

Some more will be said of this tracer size later (2nd injection, 56 days after).

FLUORESCENT TRACER EXPERIMENT 2. SPATIAL INTEGRATION

On 20th January 1972, 4,690 g of red fluorescent tracer of medium sand size (mesh 30-60) was injected as a line source onto the channel bed. Subsequent downstream sampling was carried out at intervals, where possible after a single storm had passed. This proved somewhat difficult in practice however, as several compound events occurred. The distribution of tracer of medium sand size, in the river bed samples

collected during the subsequent surveys are presented in Fig. 33 A-C.

7 days after 2nd Injection (27.1.72) after injection

A survey of the tracer concentration distribution was carried out on the 7th day after the introduction of the tracer. This followed a 3 peaked compound flood event that occurred on the 4-7 days after, and reached discharges of $5\text{m}^3/\text{sec}$, $5\text{m}^3/\text{sec}$ and $5.6\text{m}^3/\text{sec}$.

During the survey, no fluorescent grains of medium sand size were recovered downstream of the injection point, except for a few insignificant and isolated grains. This indicates that the threshold discharge value for the commencement of transport of bed material of medium sand size is greater than $5.6\text{m}^3/\text{sec}$.

20 days after 2nd Injection (9.2.72). Fig. 33 A

The distribution shows the presence of medium sized tracer particles at a distance greater than 150m from the origin. Also, high concentrations occur up to 45m from the origin, and as in Experiment 1, the general pattern again has a tendency to have higher concentrations on the inner side of the curved channel.

The hydrograph for the period 7-20 days after shows the presence of 5 flood peaks: $5\text{m}^3/\text{sec}$, $6.6\text{m}^3/\text{sec}$, $5.8\text{m}^3/\text{sec}$, $3.9\text{m}^3/\text{sec}$, and $12.1\text{m}^3/\text{sec}$. Thus, any movement of tracer from the origin indicated in the concentration pattern (Fig. 33 A) can almost entirely be thought of as the result of the single flood that peaked at a $12.1\text{m}^3/\text{sec}$ discharge. Consequently, movement of medium sized sand on the river channel commences at a discharge of between 5.6 and $12.1\text{m}^3/\text{sec}$.

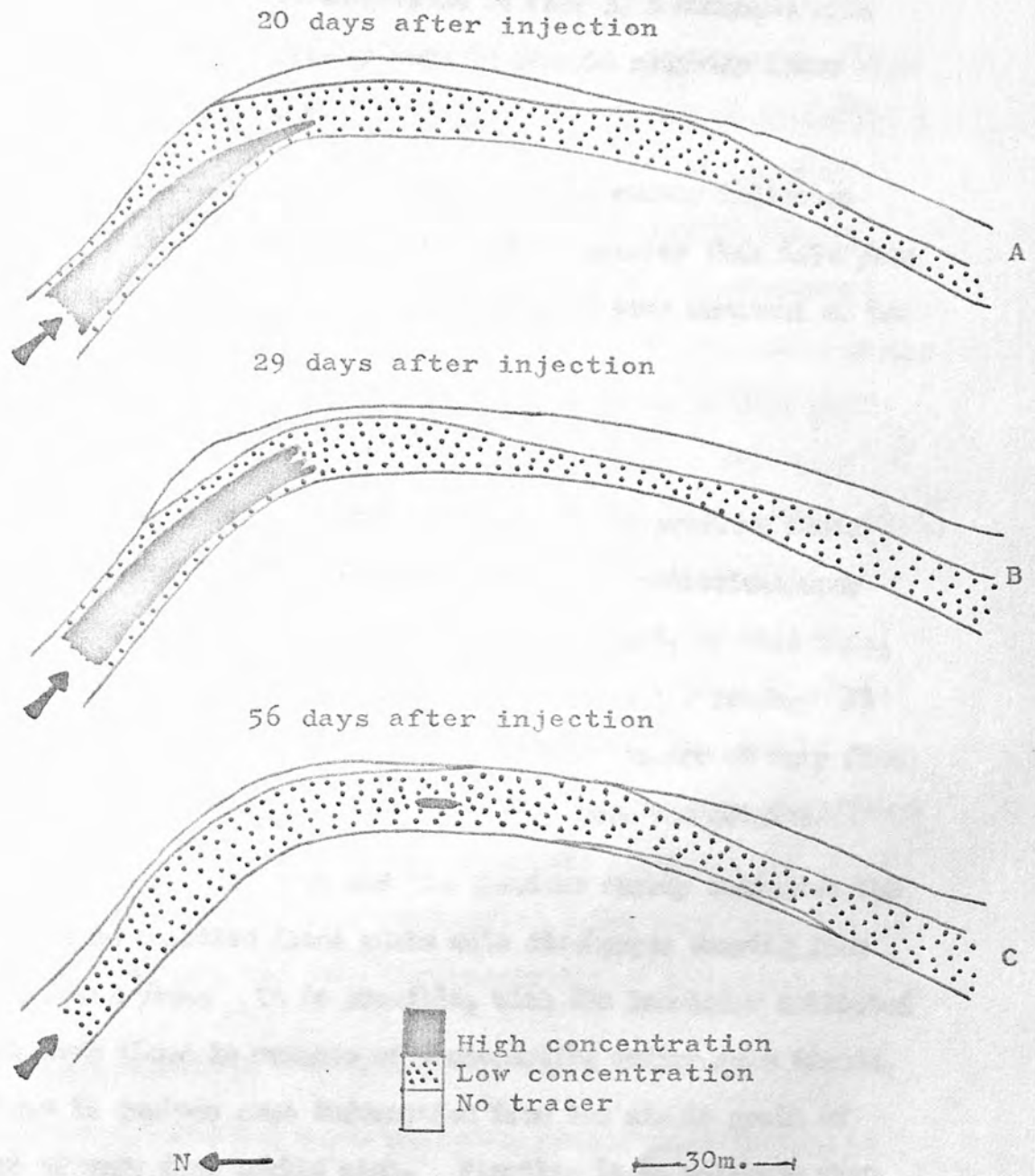


Fig. 33. Distribution of tracer concentration on river bed during second experiment. Tracer origin is the position of the arrow indicating flow direction.

29 days after 2nd Injection (18.2.72) Fig. 33 B remained at the origin.

The distributions of concentrations in Fig. 33 B compares with Fig. 33 A, although concentrations were in general slightly lower in the high concentration zone.

The hydrograph between this and the previous survey indicates the presence of 3 flood peaks, each of which is greater than $6.5 \text{ m}^3/\text{sec}$, and so, with the present knowledge, is capable of some movement of bed material.

56 days after 2nd Injection (16.3.72). Fig. 33 C

Fig. 33 C shows quite a radical change over the previous survey, in that there is complete elimination of higher concentrations near the origin. Also, a lot of the tracer material would, by this time, have passed right through and beyond the experimental stretch. It was during this survey that the one grain of green tracer of very fine pebble size was recovered at a distance of 45m from the origin.

The hydrograph between this and the previous survey indicates the occurrence of 5 consecutive flood peaks with discharges varying from $6.9 \text{ m}^3/\text{sec}$ to $14.4 \text{ m}^3/\text{sec}$. It is possible, with the knowledge collected so far, that each flood is capable of transporting medium size tracer. However, there is perhaps some information from the single grain of green tracer of very fine pebble size. Firstly, it is unlikely that the particular grain reacted differently from the rest, and was the only grain to move. This is evident from the unlikelihood of it being recovered. On the other hand, the fact that only one grain was recovered is acceptable due to the small numerical amount of grains

introduced, and the possibility that some still remained at the origin. Now, the flood occurring immediately after these tracer grains were introduced peaked at a discharge of over $15 \text{ m}^3/\text{sec}$, whereas the floods just prior to this survey were 6.9, 12.9, 13.2, and two at $14.4 \text{ m}^3/\text{sec}$. As the movement of particles of very fine pebble size on the channel floor is likely to be very irregular specially, and individual grain movement may be induced momentarily due to favourable local current conditions such as increased turbulence, eddies, vortices, etc., it can be expected that transport of this sized material will be very slow and irregular, unless a very great discharge, associated with high current velocities, is available. This approach could possibly explain why it was not until after the passage of the flood prior to this survey that the grain was recovered, i.e. movement would have been limited for that first hydrograph, but the sustained higher flow just prior to this survey would cause greater distances of movement. This, however, is somewhat speculative, and still discharge rates of sediment of this size would be very low, and the threshold discharge for commencement of movement even more speculative being very dependent on local conditions of flow, and even characteristics of individual grains.

81 days after 2nd Injection (10.4.72)

Here the survey produced a concentration distribution pattern that was similar to that of 56 days after. The hydrographs during the period between these two surveys indicate only 2 small storms reaching a peak discharge of only 3.2 and $3.0 \text{ m}^3/\text{sec}$ which is not capable of transporting material of medium sand size.

By this time, an unknown amount of tracer would have

85 days after 2nd Injection (14.4.72)

Again the concentration distribution is similar to that of 56 days after, and again the only flood that occurred since the previous survey did not have a peak discharge of greater than $5\text{m}^3/\text{sec}$.

102 days after 2nd Injection (1.5.72)

Again a similar concentration distribution pattern to that of 56 days after, and again, as in 85 days after, the only flood did not have a peak discharge of greater than $5\text{m}^3/\text{sec}$.

Longitudinal Distribution of Tracer Concentrations and Centroid Position

The longitudinal distribution of tracer concentrations on the days of the surveys during Experiment 2 are plotted in Fig. 34. The sequence of concentration pattern change through time is similar to that of the first experiment. The centroid positions of the tracer cloud calculated from these curves are presented in Table 42.

Estimation of Sediment Loss during 2nd Experiment

Tracer of medium sand size was used to provide more definite threshold values for transport, but it can still provide some information on transport rates in general as medium sand forms the bulk of the river bed sediment.

Using equation 21, the bed load discharge of sediment was calculated and is presented along with the hydrographs which caused the movement in Fig. 35 A-D.

Fig. 35 D indicates a low amount of transport, but this is easily explained as, by this time, an unknown amount of tracer would have

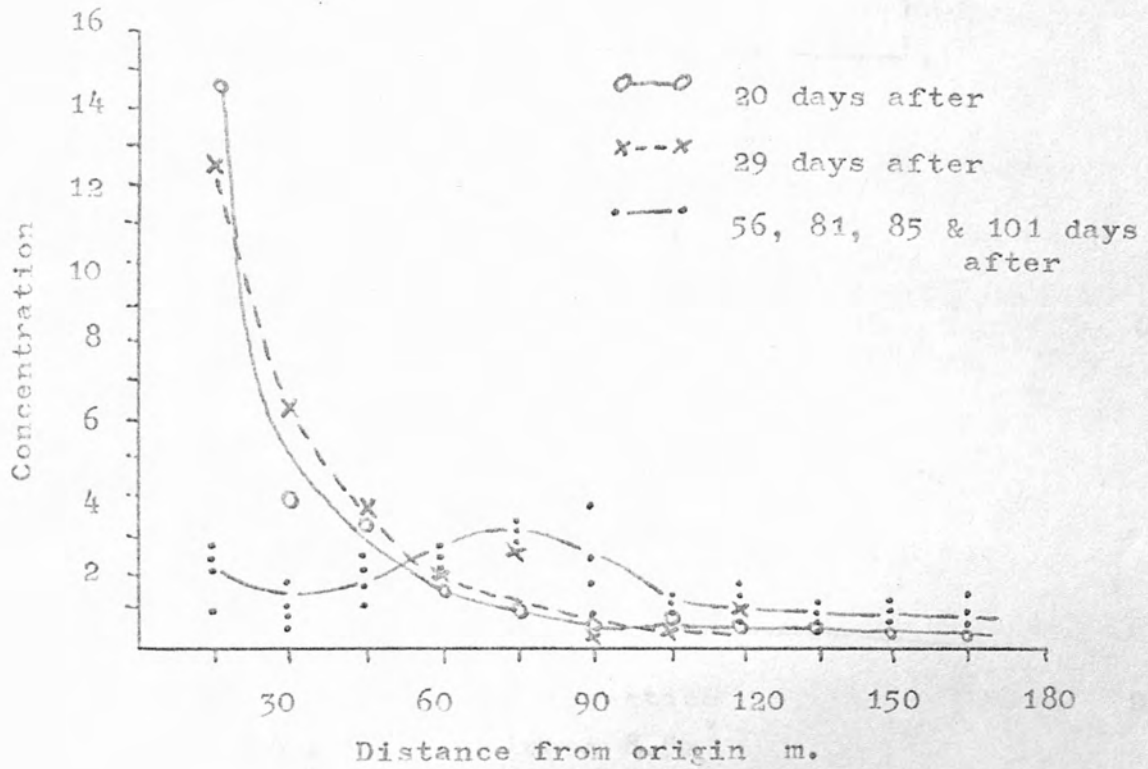


Fig. 34. Longitudinal distribution of tracer concentration, second experiment.

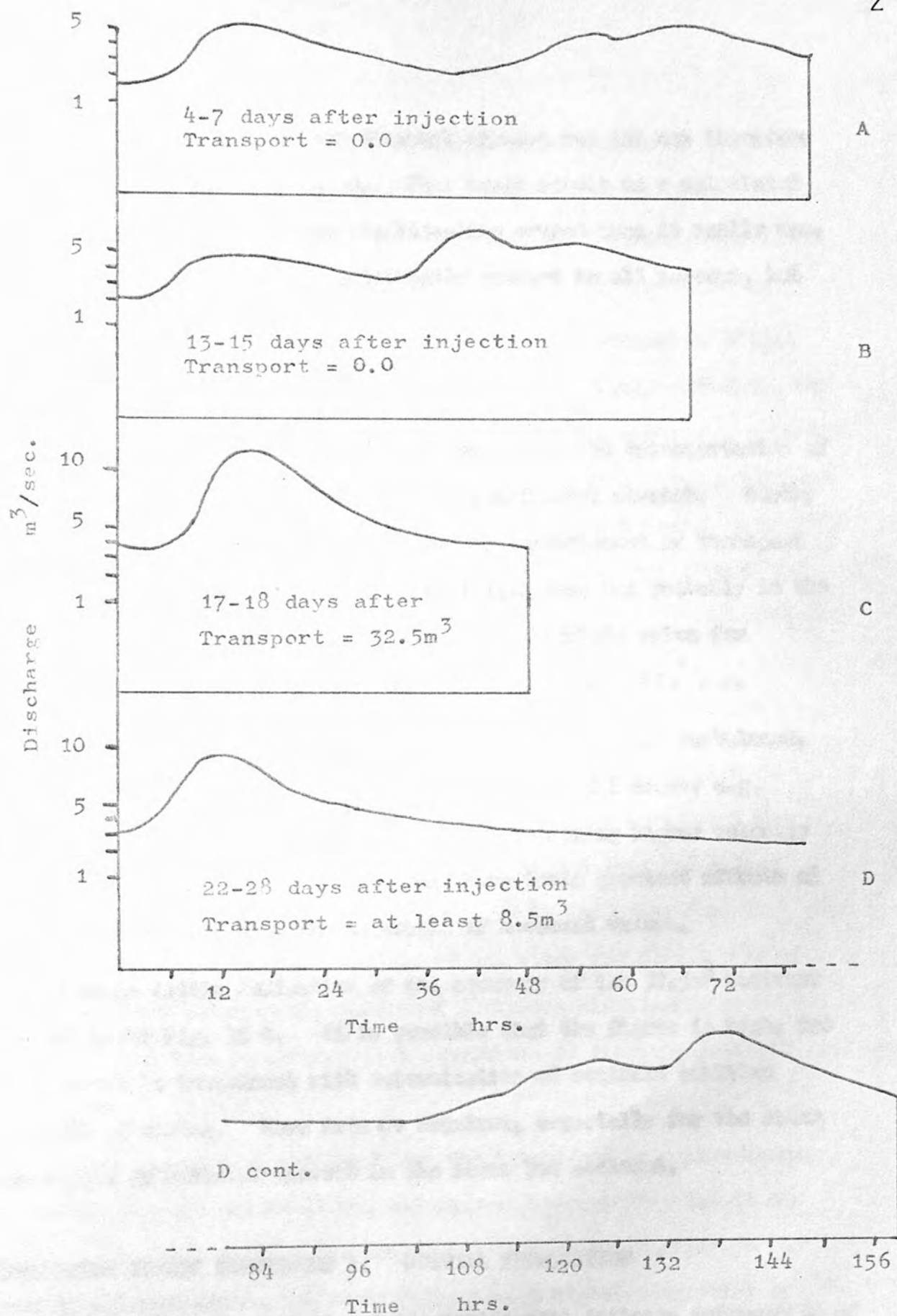


Fig. 35. Bed load transport through experimental stretch during second experiment. Medium sand only.

passed entirely through the experimental stretch and has not therefore been included in the calculation. This would result in a calculated centroid position being nearer the injection source than it really was. Indeed, this factor is almost undoubtedly present in all surveys, but the error is probably small.

Conclusions on Experiment Number 2

This experiment provided some information on the transportation of medium sand on the channel floor of the experimental stretch. Worthy of note is that the threshold value for the commencement of transport of medium sized sand is between 5.6 and $12.1 \text{ m}^3/\text{sec}$, and probably in the region of $8.0 \text{ m}^3/\text{sec} \pm 2.0 \text{ m}^3/\text{sec}$. Also, the threshold value for commencement of movement of very fine pebbles is below $15 \text{ m}^3/\text{sec}$.

Transport is also dependent on local factors such as turbulence, and eddies increasing the current velocities in small areas, e.g. vortices which were seen to proceed downstream during higher velocity and discharge conditions. These would have their greatest effects at discharge conditions near the threshold of movement values.

There is little indication of the accuracy of the 32.5 m^3 sediment loss value for Fig. 35 C. It is possible that the figure is high, and errors could be introduced with determination of centroid position and depth of mixing. More data are required, especially for the other size ranges of material present in the river bed sediment.

FLUORESCENT TRACER EXPERIMENT 3. SPATIAL INTEGRATION

This experiment was designed to provide more definite information of

the threshold discharge value for commencement of movement, and total sediment loss of medium sand; this size range was again chosen as it forms a high percentage of the river bed sediment and thus would give an indication of total sediment loss.

5,695 grams of medium sand size tracer was introduced as a line source across the river, at the origin, on 17th May 1972. However, by the end of October a flood discharge of sufficient amplitude to move medium sized sand had not occurred. So it was decided in the interest of speeding up the rate of collection of information to abort this particular experiment and to include the already introduced, but unmoved, tracer in the more extensive fourth experiment.

FLUORESCENT TRACER EXPERIMENT 4. TIME INTEGRATION

The experiment was designed to provide more information on transport rates for different sized fractions during a storm. The time integration approach was used, despite this method being less suitable for conditions of variable flow, as it was hoped that by frequent sampling at a fixed section of the river the actual time of commencement of movement of tracers of different sizes could be determined and then correlated with conditions of discharge, velocity and stage.

Tracer material of various sizes was introduced as a line source at the origin, but before it was injected an attempt was made to mix the various sizes so that the proportion of each was similar to that of the sediment on the river bed; i.e. a higher proportion of coarser material was introduced into the thalweg, while a higher

concentration of fines was injected towards the inner side of the bend.

Table 43 shows the amount of tracer of each size that was introduced. It can be seen that tracer of very coarse sand size consisted of individual grains, and also of aggregates of smaller grains. An inspection of river sediment of this size indicated a high proportion of aggregates occurring and as the hydraulic properties and fall rates of these would differ from individual grains the author decided to use tracer material consisting of individual grains and of aggregates for this size range. Also, it will be noted that tracer material of very fine sand size was not used; this is because this sized material forms only a low percentage of the river sediment, and also there are practical difficulties associated in working with tracer of this size.

The tracer, except that of medium sand size which was already on the river bed, was injected at the origin on 19th November at 19.35 hours, during the rising limb of a storm that peaked at $3.1 \text{ m}^3/\text{sec}$. Consequently, from the knowledge collected up to this point, it would be expected that any material transported would be of a size smaller than medium sand.

Results of Experiment 4

The tracer concentrations of samples collected during the time integration study are presented in Fig. 36 along with the hydrograph occurring during the time. The peak position of tracer concentrations only are plotted, and each has a different vertical scale.

Table 43. Weight of fluorescent tracers introduced onto the channel bed during experiment four.

Grade	S I Z E Mesh	Colour	Weight introduced
Very coarse sand - grains	10-16	Yellow	688g.
Very coarse sand - aggregates	10-16	Red	241g.
Coarse sand - grains	25-30	Blue	1,377g.
Medium sand - grains	52-60	Red	5,695g.
Fine sand - grains	100-120	Blue	2,531g.
Total			10,532 g.



Fig. 56. Fourth experiment - Time in days after at 50m from origin. Peaks only plot

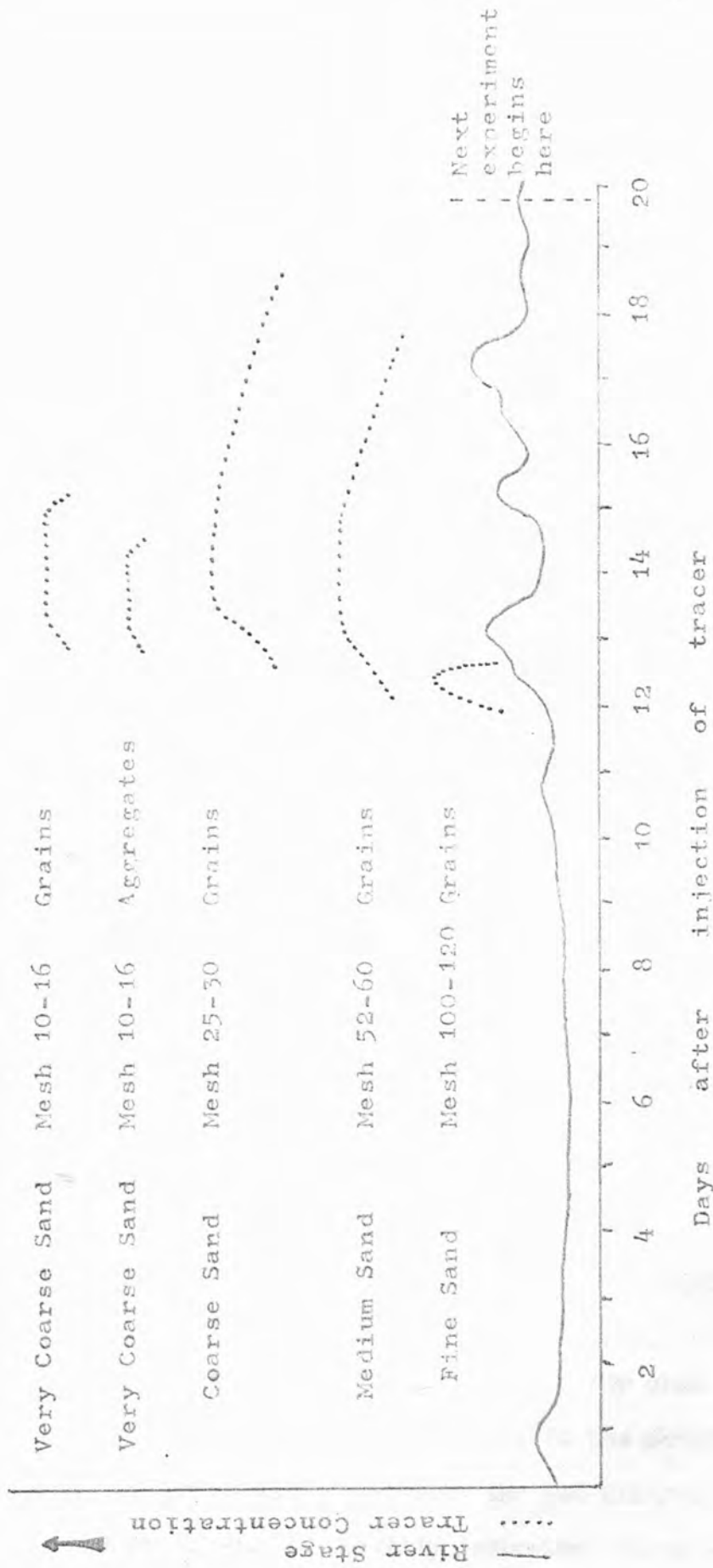


Fig. 36. Fourth experiment- Time intergration, variable flow. Tracer concentrations at 30m from origin. Peaks only plotted.

Despite flows on the first day ($3.1\text{ m}^3/\text{sec}$) and eleventh day ($3.3\text{ m}^3/\text{sec}$) after injection being higher than base flow it is evident that transport of the bulk of tracer, even of the fine sand size, did not occur. There was however a variable background concentration of fine sand during the first 11 days, but these concentrations were much lower than those forming the peak. The initial variation was probably the result of transport of fine sand that was in an unstable environment on the channel floor, i.e. under conditions of flow where this size would not normally be present unless artificially introduced.

Examination of the data presented in Fig. 36 indicate that:

1. Non-transport of material larger than and including fine sand occurs at a discharge of and below $3.3\text{ m}^3/\text{sec}$.
2. The threshold discharge value for transport of sediment between fine sand and very coarse sand is between $3.3\text{ m}^3/\text{sec}$ and $11.7\text{ m}^3/\text{sec}$.
3. As expected, transport of successively larger sizes commences at successively greater discharges.
4. The approximate discharge for the commencement of transport of different sizes can, with some reasonable estimation, be drawn at:

Fine sand	$6.7\text{ m}^3/\text{sec}$
Medium sand	$9.0\text{ m}^3/\text{sec}$
Coarse sand	$10.0\text{ m}^3/\text{sec}$
Very coarse-aggregates	$10.5\text{ m}^3/\text{sec}$
Very coarse - grains	$11.0\text{ m}^3/\text{sec}$

5. A plateau of concentration of tracer occurs for each size range, except for fine sand. This is because, as the storm discharge subsides, the total amount of tracer has not cleared the sampling section and so becomes temporarily desposited there maintaining

the high concentration for each sample collected. However, during the passage of the next flood, flows are of sufficient discharge for movement to occur, and of sufficient duration for the tracer to become clear of the sampling section.

The peaks of tracer concentration plotted in Fig. 36 represent sediment transport rates of:

0.003 m ³ of very coarse grains	(mesh 10-16) in 52 hrs
0.005 m ³ of very coarse aggregates	(mesh 10-16) in 28 hrs
0.020 m ³ of coarse sand	(mesh 25-30) in 147 hrs
0.226 m ³ of medium sand	(mesh 52-60) in 130 hrs
0.031 m ³ of fine sand	(mesh 100-120) in 12 hrs

These data, however, are not comparable as different time units are involved. In an attempt to enable easier comparison, for a particular hydrograph, the following assumptions, although somewhat erroneous, have been made:

- a) Although the tracer size range is only a small percentage of the size range of each particular size grading (e.g. mesh 100-120 forms only 0.5% of the river sediment, while other mesh sizes within the fine sand size form 1.2% [72-100 mesh] and 3.5% [60-70 mesh]) the transport rates of the remaining sediment within the size range is similar.
- b) Once the threshold discharge value for transport for each grain size has been reached, transport commences at a "mean" rate that is maintained despite any further increases in discharge, until the discharge subsides below the threshold value.

These two assumptions (a and b) will tend to cancel each other out to some extent, but the overall effect will probably remain an underestimate.

With reference to Fig. 36, the duration of the approximate threshold values of discharge or larger for each grain size during the 20 days after injection, are presented in Table 44 along with calculated mean volume of sediment lost per hour.

The data in column 9 (Table 44) gives an indication of transported amounts of various grain sizes during the duration of the hydrograph depicted in Fig. 36. As may be expected, the total amount transported increases with a decrease in grain size; this can be explained by two main reasons: a) smaller grains are more readily moved, and b) the duration of the flow with a discharge value of, or greater than the threshold value, decreases with an increase in grain size (column 3, Table 44).

Also, worthy of note is the fact that transported fine sand is greater than transported medium sand. This has occurred despite fine sand forming a much smaller percentage of the total bed sediment (only 6%) than medium sand (56%).

The amount of medium sand transported over these 2 days is considerably less than the amount determined by the spatial integration method (Experiment 2, Fig. 35 C), where the duration of a discharge of threshold value or greater was less than 12 hours. The data presented in Table 44 are more agreeable with the low transported values obtained by Crickmore (1967), but obviously different channel characteristics are present and so the data are not truly comparable.

Despite the time integration method of determining bed load transport being less useful than the spatial integration method during

Table 44. Determination of volume of sediment lost during experiment 4. See text for explanation.

Discharge of, or greater than, m^3/sec	6.7	9.0	10.0	10.5	11.0	1
Size grade transported	Fine Sand	Medium Sand	Coarse Sand	Very Coarse Sand Aggregates	Very Coarse Sand Grains	2
Duration during 20 days of experiment, hrs.	90	59	41	34	28	3
Duration during passage of peak, hrs.	12	59	41	18	14	4
Vol. of sediment of tracer size transported during passage of peak, m^3	0.031	0.226	0.020	0.005	0.003	5
Mean vol. of sediment of tracer size transported, m^3/hr	.0026	.0038	.0005	.0003	.0002	6
Vol. of sediment of tracer size transported in 20 days, m^3 ; $6x3$.232	.226	.020	.009	.006	7
% of tracer of actual size grade	9	26	32	64	64	8
Vol. of sediment moved of total size range in 20 days, m^3 ; $\frac{7x100}{8}$	2.580	0.870	0.060	0.014	0.009	9
Mean vol. of sediment lost of total size range during duration of flow, m^3/hr ; $\frac{9}{3}$	0.029	0.015	0.0015	0.0004	0.0003	10

conditions of variable flow (Crickmore, 1967), the author believes that the data presented in column 9 (Table 44) are a more reasonable estimate than data collected in Experiments 1 and 2. The low transport values are expected as the experimental stretch was chosen in the belief of being a controlling stretch of sediment transport (see Selection of Experimental Stretch). However, further experimentation would throw more light on the subject.

Conclusions on Experiment 4

Obvious major factors controlling sediment transport of any given size range include the availability of sediment of a suitable size, and also the duration of the flow of a discharge of threshold or greater values. The data provided by Experiment 4 conflict to some extent with that from Experiment 2. However, the following conclusions are tentatively proposed:

1. The threshold discharge values for commencement of bed transport of various sized grains has been determined:

Fine sand	Mesh 60-120	-	6.7 m ³ /sec ± 2m ³ /sec
Medium sand	Mesh 30-60	-	9.0 m ³ /sec ± 2m ³ /sec
Coarse sand	Mesh 16-30	-	10.0 m ³ /sec ± 2m ³ /sec
Very coarse sand aggregate	Mesh 5-16	-	10.5 m ³ /sec ± 2m ³ /sec
Very coarse sand grains	Mesh 5-16	-	11.0 m ³ /sec ± 2m ³ /sec

Obviously these values are not cut and dried as transport may also be induced by localised effects such as eddies, turbulence, etc. that may momentarily cause a local increased velocity sufficient to cause transport.

2. Once the threshold discharge has been reached the mean volume/hour

of transport of sand of various size grades is:

Table 45. Weight of fluorescent tracers introduced	
Fine sand	.029 m ³ /hr
Medium sand	.015 m ³ /hr
Coarse sand	.0015 m ³ /hr
Very coarse sand aggregates	.0004 m ³ /hr
Very coarse sand grains	.0003 m ³ /hr

These conclusions, although somewhat inaccurate and tentative, should be used as a basis upon which to construct a model using data collected from further experiments.

FLUORESCENT TRACER EXPERIMENT 5. TIME INTEGRATION

This experiment was undertaken to collect more information of various sizes of sediment. It follows directly on from the previous experiment's period of sampling. The study was again one of time integration and the procedure was as for Experiment 4.

Table 45 shows the amounts, and size ranges, of tracer sand used. These various grades were mixed together and introduced as a line source on the river bed at 10.30 on 9th December 1972.

Results of Experiment 5

Fig. 37 shows the hydrograph that prevailed during the experiment, and also the position of the peak of tracer concentration of different sizes. The peak for coarse sand is *queriable* as the sampling frequency towards the end of the period was insufficient for its position to be determined with any accuracy.

Tracer injection occurred during the falling limb of the hydrograph, and the flow was sufficient for transport of medium and fine

Table 45. Weight of fluorescent tracers introduced onto the channel bed during experiment five.

S Grade	I Size	Z Mesh	E Colour	Weight introduced
Coarse sand - grains		25-30	Red	712 g
Medium sand - grains		52-60	Blue	1,600 g
Fine sand - grains		60-120	Red	<u>667</u> 712 g
Total				3,024 g



Fig. 14. Fifth experiment - Fine Intergration - The river origin, Peaks only plotted.

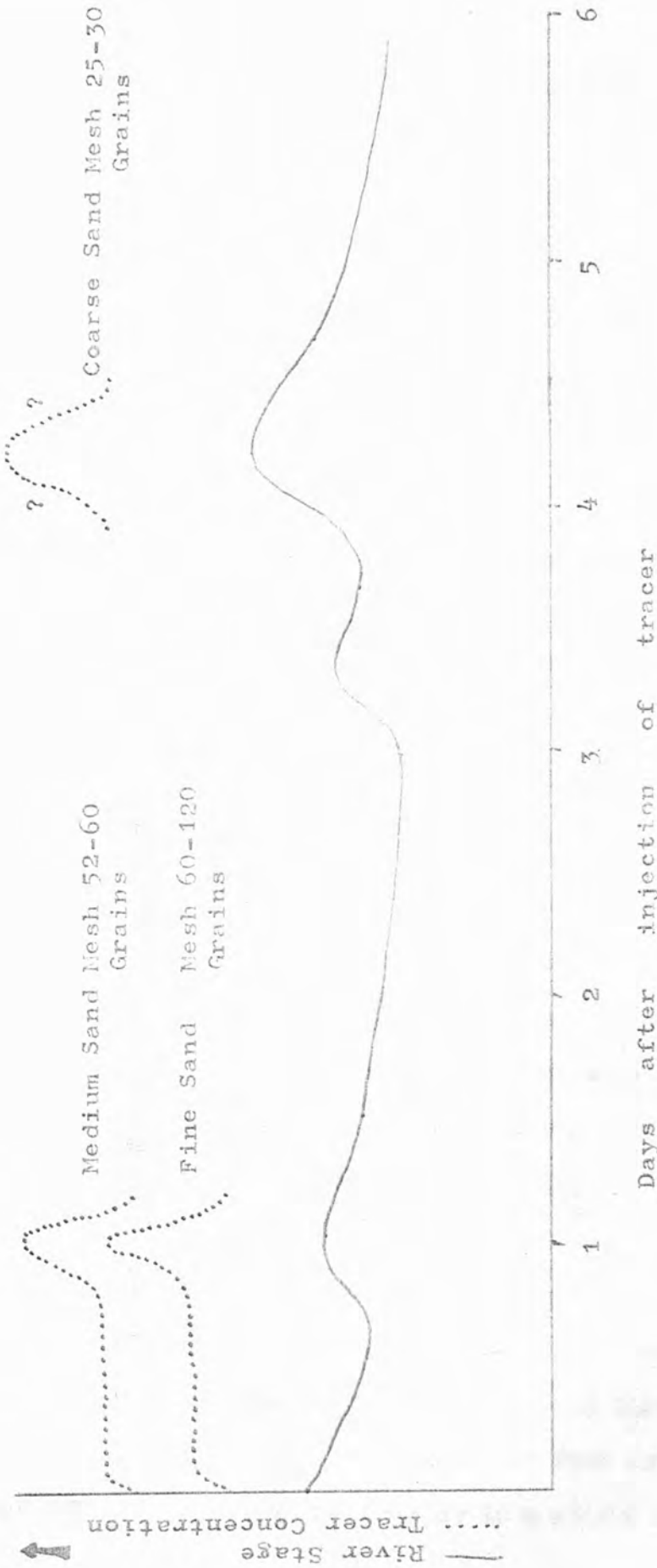


Fig. 37. Fifth experiment - Time Intergration, variable flow. Tracer concentrations at 30m from origin. Peaks only plotted.

tracer to commence, but was not of sufficient duration for it to clear completely the sampling section. However, this did occur by the time a peak occurring some 24 hrs after the injection had subsided. Now, this indicates that tracer of both fine and medium sand size has moved during the passage of this peak (24 hrs after injection), and the peak discharge was $7.8 \text{ m}^3/\text{sec}$. This casts some doubt on the validity of the tentative conclusions of Experiment 4 where the threshold value for transport of medium sand was determined at $9 \text{ m}^3/\text{sec}$. It would in fact appear to be somewhat lower, possibly around $7.5 \text{ m}^3/\text{sec}$.

The peaks plotted in Fig. 37 represent transport rates of:

0.024 m^3 of medium sand (Mesh 52-60) in 47 hrs

0.017 m^3 of fine sand (Mesh 60-120) in 42 hrs

However, as before, this does not take into account a period of non-transport between the two peak flows. This has been considered in Table 46.

The data represented in Table 46 are somewhat contrasting to that of Table 44. The amounts transported (column 10) are still low, indeed a fair amount lower. This is explainable by the fact that the highest discharge levels during the sampling of the experiments were greater in Experiment 4 than in 5, and so, as transport rate of any given size would increase with discharge, an increased mean would result. Also, the amount of fine sand transported is, on this occasion, less than the amount of medium sand transported. This could be explained by the amount of material of fine sand size becoming exhausted, and indeed there probably is a slight increase in the grain

Table 46. Determination of volume of sediment lost during experiment 5. See text for explanation.

Discharge of, or greater than, $m^3/sec.$	6.7	7.8		1
Size grade transported	Fine Sand	Medium Sand		2
Duration during 20 days of experiment, hrs.	42	27		3
Duration during passage of peak, hrs.	13	8		4
Vol. of sediment of tracer size transported during passage, of peak, m^3	0.017	0.024		5
mean vol. of sediment of tracer size transported, $m^3/hr.$.0013	.0030		6
Vol. of sediment of tracer size transported in 20 days, m^3 : 6×3	.055	.081		7
% of tracer of actual size grade	100	26		8
Vol. of sediment moved of total size range in 20 days, m^3 : $\frac{7 \times 100}{8}$	0.055	0.092		9
Mean vol. of sediment lost of total size range during duration of flow, $m^3/hr.$: $\frac{9}{3}$	0.0013	0.0034		10

size of bed sediment in the experimental stretch during the period of Experiments 4 and 5. However, for the calculations of both experiments, the same value for percentage weight of sand of tracer size to total sediment was used.

The variation (i.e. reduced transport rate) could possibly be a true variation due to some change in channel characteristics; for instance a constriction in the channel downstream of the sampling point may cause a hold up of water in the sampling stretch which would consequently increase the cross-section area and reduce the flow at bed level. However, it may also be a reflection of the accuracy of the method. Indeed, the amount of tracer used in Experiment 5 was less than for Experiment 4, and this itself would probably tend to a greater degree of accuracy in Experiment 4.

Conclusions on Experiment 5

Experiment 5 has provided some more data on bed load transport in the experimental stretch:

1. The threshold discharge value for the commencement of transport of medium sand is more accurately determined to within $1\text{ m}^3/\text{sec}$ of $7.5\text{ m}^3/\text{sec}$.
2. The threshold discharge value for transport of coarse sand is greater than $8.8\text{ m}^3/\text{sec}$. This agrees with data collected from Experiment 4.
3. Data from all experiments so far conducted indicate that transport values for fine and medium sized sediment are low, and occur only during conditions of non-base flow. Indeed, it is possible

that the channel here in general is one of aggradation where movement is very restricted. This is also supported by the site of the experimental stretch being an area of some alluvial flood plain development, with a meandering course.

Information from another experimental stretch with similar channel characteristics may provide some useful information.

FLUORESCENT TRACER EXPERIMENT 6. TIME INTEGRATION

Experiment 6 was conducted at a different stretch from the previous experiments. The stretch selected was immediately upstream of the three crump weir at Iping Mill (location F, Fig. 3). This site was chosen because:

- a) of the availability of discharge data;
- b) the stretch was considered to be one of non-transport at low flow, and thus similar to the previous experimental stretch;
- c) the area may be a stretch of sediment accumulation (upstream of the weir). However, samples collected from water discharging over the weir indicated the presence of tracer grains that were in fact introduced on the channel bed upstream. This indicates that some transport does occur;
- d) the data could be compared and contrasted with data collected from the other experimental stretch further downstream.

The stretch is one of a fairly straight channel 16.5 m wide and of variable depth, from 0.6 m to 1.3 m at the thalweg.

The procedure was similar to that of other time integration studies; the tracer being introduced as a line source across the channel, and

samples being collected 30 m from this origin.

Table 47 shows the amounts, and size range of tracers used, and these were mixed together before being introduced on the river bed at 14.30 on 11th January 1973.

Results of Experiment 6

Fig. 38 shows the hydrograph that prevailed during the experiment and the position of the peak of tracer concentrations of different sizes is plotted. Although coarse sand tracer was introduced, none was recovered in any subsequent downstream samples, and so it can be considered that none was transported completely through the experimental stretch.

Medium sand - grains 30-60	5,000 g
Fine sand - grains 60-120	5,000 g
Total	10,000 g

Assuming that the total amount of tracer of medium and fine sizes introduced was transported past the sampling section, then the peaks plotted in Fig. 38 represent transport rates of

.28 m³ of medium sand (Mesh 62-60) in 11 hrs

.167 m³ of fine sand (Mesh 60-120) in 17 hrs

which represent mean transport rates of 0.0254 m³/hr for medium sand and 0.0098 m³/hr for fine sand (Table 48, column 6) during the duration of the threshold of greater discharge. Threshold values have been determined as in the region of 6.1 m³/sec for medium sand and 4.3 m³/sec for fine sand.

Within certain restrictions, e.g. difference in hydrograph peak height duration etc., column 10 of Table 48 is comparable with that of Tables 44 and 46 and indicates that more sediment of medium size is transported past this stretch at Iping than is at Easebourne. The fine

Table 47. Weight of fluorescent tracers introduced onto the channel bed during experiment six.

S I Z E Grade	Mesh	Colour	Weight introduced
Coarse sand - grains 25-30		Red	246 g
Medium sand - grains 52-60		Blue	3,000 g
Fine sand - grains 60-120		Red	<u>3,000 g</u>
		Total	6,246 g

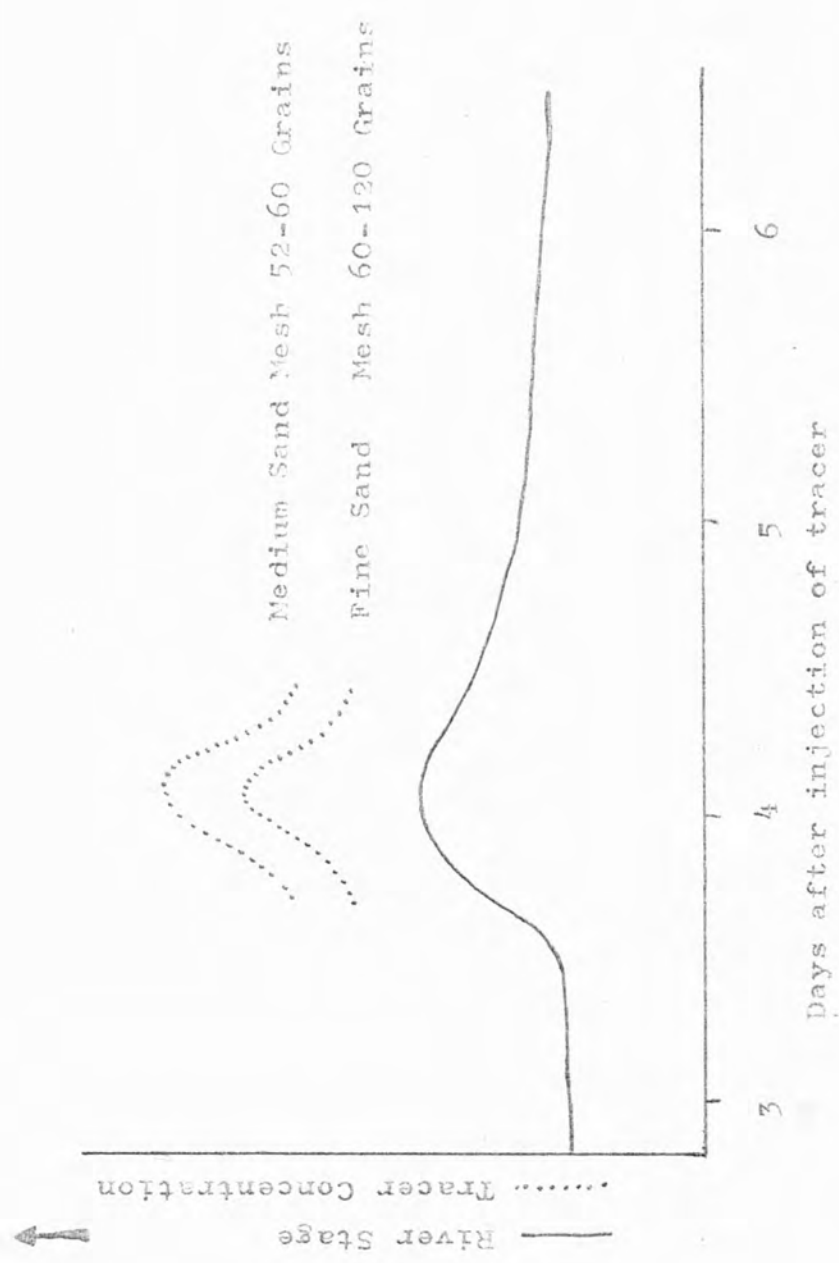


Fig. 38. Sixth experiment- Time Intergration, variable flow. Tracer concentrations at 30m from origin. Peaks only plotted.

Table 48. Determination of volume of sediment lost during experiment 6. See text for explanation.

Discharge of, m^3 or greater than, m^3 /sec.	4.3	6.1	1
Size Grade transported	Fine Sand	Medium Sand	2
Duration during 20 days of experiment, hrs.	22	12	3
Duration during passage of peak, hrs.	17	11	4
Vol. of sediment of tracer size transported during passage of peak, m^3	0.167	0.280	5
Mean vol. of sediment of tracer size transported, m^3 /hr.	.0098	.0254	6
Vol. of sediment of tracer size transported in 20 days, m^3 : 6×3	.2156	.3048	7
% of tracer of actual size grade	100	37	8
Vol. of sediment moved of total size range in 20 days, m^3 : $\frac{7 \times 100}{8}$	0.2156	0.8219	9
Mean vol. of sediment lost of total size range during duration of flow, m^3 /hr. : $\frac{9}{3}$	0.0098	0.0684	10

sand size, however, for Iping has a transport value between that of the two values for Easebourne. This is probably indicative of a more complete transport through the system of sand of fine grain size, i.e. much will be transported through the system and the amount entering any stretch is more comparable to that leaving the stretch for finer sizes than for coarser grains, e.g. the limited data suggest that medium sand passing Iping Mill may accumulate downstream of the Mill and not be entirely removed past Easebourne, if indeed it reaches this stretch.

Conclusions of fluorescent tracer Experiment 6

Data collected from a time integration study on the channel at Iping Mill supports the low transport rates of river bed sediment indicated at Easebourne. Other conclusions from the experiment are:

1. For the experimental stretch, threshold discharge values for the commencement of transport are lower than for Easebourne:

Medium sand - $6.1 \text{ m}^3/\text{sec}$

Fine sand - $4.3 \text{ m}^3/\text{sec}$

2. This would mean that differential transport rates occur along the main stream, and whereas during the passage of one storm hydrograph medium sand is capable of being transported at Iping, it is not necessarily so at Easebourne. When this does occur, some aggradation of sediment must occur somewhere between these two stretches.

3. Once threshold discharge values have been reached, transport rates of bed sediment at Iping are in the region of, or greater than:

.0098 m³/hr for fine sand
 and .0684 m³/hr for medium sand

The experiments so far conducted have given some indication of bed load transport within the main channel of the Rother at two locations. However, there is still some problem as to the accuracy of methods used as transport rates obtained by spatial integration studies are much greater than for time integration studies.

Weight
introduced

FLUORESCENT TRACER EXPERIMENT 7. SPATIAL INTEGRATION

This experiment was conducted on the experimental stretch at Easebourne, and was expected to provide some more information, and an indication of the accuracy of the method.

Table 49 indicates tracers used in this experiment that were introduced as a line source onto the channel floor at Easebourne on 28th February 1973.

The experiment was, like others, hindered by lack of a storm; for the remaining part of the winter only two storms were to occur. Consequently, available data from this experiment are limited. However, transport of medium sand sized tracer did not occur during the first of these two storms which peaked at a discharge of 6.9 m³/sec. This again indicates that transport of this sized material starts at a discharge of greater than 6.9 m³/sec.

Indeed, very little transport occurred at all, only some very tentative movements of medium size tracer during the passage of the second flood. Consequently, determination of transport rates are confined to non-transport of all sizes greater than medium sand, and

Table 49. Weight of fluorescent tracers introduced onto the channel bed during experiment seven.

Grade	S I Z E	Mesh	Colour	Weight introduced
Medium sand - grains		30-60	Red	3,800 g
Coarse sand - grains		16-30	Blue	1,513 g
Very coarse sand-grains		8-16	Yellow	760 g

velocity, v , the u_{*c} values of the three sites are 11, 20 and 23 cm/sec. The u_{*c} values for the three sites are 11, 20 and 23 cm/sec. The u_{*c} values for the three sites are 11, 20 and 23 cm/sec. The u_{*c} values for the three sites are 11, 20 and 23 cm/sec. The u_{*c} values for the three sites are 11, 20 and 23 cm/sec. (i.e. the u_{*c} values for the three sites are 11, 20 and 23 cm/sec. The u_{*c} values for the three sites are 11, 20 and 23 cm/sec. The u_{*c} values for the three sites are 11, 20 and 23 cm/sec. The u_{*c} values for the three sites are 11, 20 and 23 cm/sec. The u_{*c} values for the three sites are 11, 20 and 23 cm/sec.

It is possible that the threshold values presented are somewhat high, as they were determined by using the discharge level occurring when there was an abrupt increase in tracer concentration at the

very limited movement, if any, of medium sand.

DISCUSSION

Despite the seven tracer experiments being hindered by prolonged base flow conditions of non-transport, some useful data have been collected, but several assumptions and theoretical decisions have had to be made. The author considers that the errors brought about by these assumptions are small in comparison to other natural variations of bed load transport.

Up to the present, nothing has been said of mean particle velocity. With reference to time integration Experiment 4, the centroid position of the tracer cloud of any given grain size was at zero metres up until the time of commencement of movement of tracer particles. Similarly, if the peak concentration for each tracer size, as it passes the sampling point, is considered as the centroid of the cloud, then the time at which the centroid was at 30m from the origin is known (i.e. the time of highest concentration). Similarly, if the threshold discharge values for commencement of movement of different size values, as indicated by Experiments 4 and 5, are taken as correct (Table 44, column 1, and Table 46, column 1), then the number of hours of particle movement of any particle size prior to the centroid reaching 30m can be determined (Tables 44 and 46, column 4). Mean particle velocity can thus be determined (Table 50).

It is possible that the threshold values presented are somewhat high, as they were determined as being the discharge level occurring when there was an abrupt increase in tracer concentration at the

Table 50. Determination of mean particle velocity.

1st. position of centroid	Size	Threshold discharge, m ³ /sec.	Duration of threshold discharge prior to centroid's 2nd. position	2nd. position of centroid	Mean particle velocity, once movement commenced
0 m	Fine sand	6.7	4 hrs.	30 m	7.5 m/hr.
0 m	Medium sand	7.5	25 hrs.	30 m	1.2 m/hr.
0 m	Coarse sand	10	13 hrs.	30 m	2.3 m/hr.
0 m	Very coarse sand - aggregates	10.5	10 hrs.	30 m	3.0 m/hr.
0 m	Very coarse sand - grains	11	11 hrs.	30 m	2.7 m/hr.

for any given grain size.

The mean particle velocities shown in Table 50, which are only the mean for the particle sizes listed, are calculated by dividing the sampling points from discharge with a greater value than the threshold value. Obviously the higher the discharge, the greater the velocity. For example, medium sand is shown as having a mean particle velocity of 1.2 m/hr; whereas coarse sand has one of 2.3 m/hr. For any given

sampling locality. Obviously, however, there is a time lag between the commencement of transport at the origin, and the sampling of the tracer at 30m from the origin. If transport velocities are low, then this period would be quite long. This would result in a reduction of the mean particle velocity.

The possibility that the mean particle velocity could be used as centroid velocity in an equation similar to that for spatial integration methods (equation 16) was considered. Here, however, a consideration of the percentage of tracer size in the moving sediment (p_m) should be included, and the resulting equation would be:

$$q_s = \frac{ut \phi B p_m}{100} \quad (25)$$

However, the determination of p_m would involve a representative sample of moving sediment, which itself is problematical, and is partly the cause of the tracer approach applied here. Normal samples collected from the river bed would not be ideal for determination of p_m as these would include a coarser fraction that may not necessarily be moving. However, disregarding this, if river bed samples are used to approximate values of p_m then transport values would still be well below $1m^3/hr$ for any given grade size.

The mean particle velocities shown in column 6, Table 50, are only the mean for the period prior to the peak concentrations reaching the sampling point, when discharge was a greater value than the threshold value. Obviously the higher the discharge, the greater the velocity. For example, medium sand is shown as having a mean particle velocity of 1.2 m/hr, whereas coarse sand has one of 2.3 m/hr; but when the

coarse sand moves at 2.3m/hr, the medium sand will be moving at a velocity greater than this.

The accuracy of the threshold discharge values for commencement of transport is somewhat variable. Fig. 39 has been constructed with strong emphasis being placed on the threshold discharge values for mesh 120 and 160, which are the most accurately determined. Also, the author considers that the values for mesh 16, grains and aggregates are more accurate than that for mesh 30 which was arbitrarily determined during Experiment 4. Indeed, this value does, if the graph is correct, appear to be an over estimate. The line of the curve as drawn defines a sharp delimitation which naturally does not exist. It should be considered as a wider zone where movement commences, and depends not only on discharge, but on local factors changing the local velocity, e.g. eddies, vortices, etc. (Water velocities for any given discharge can be obtained from Fig. 29).

The most obvious contrast of the two curves on Fig. 39 is the lower threshold values at Iping. This is the result of different channel and hydraulic characteristics at Iping causing higher velocities for the same discharge, and the resulting effect of this difference would be a net accumulation of sediment between the two experimental stretches. This, however, would not apply if, once transport commenced at the downstream station (Easebourne), the transport rates were higher than at the upstream station (Iping). This, however, seems not to be the case. The net accumulation of sediment is supported by the presence of a more extensive alluvial flood plain, and a more sinuous course of the Rother between the two

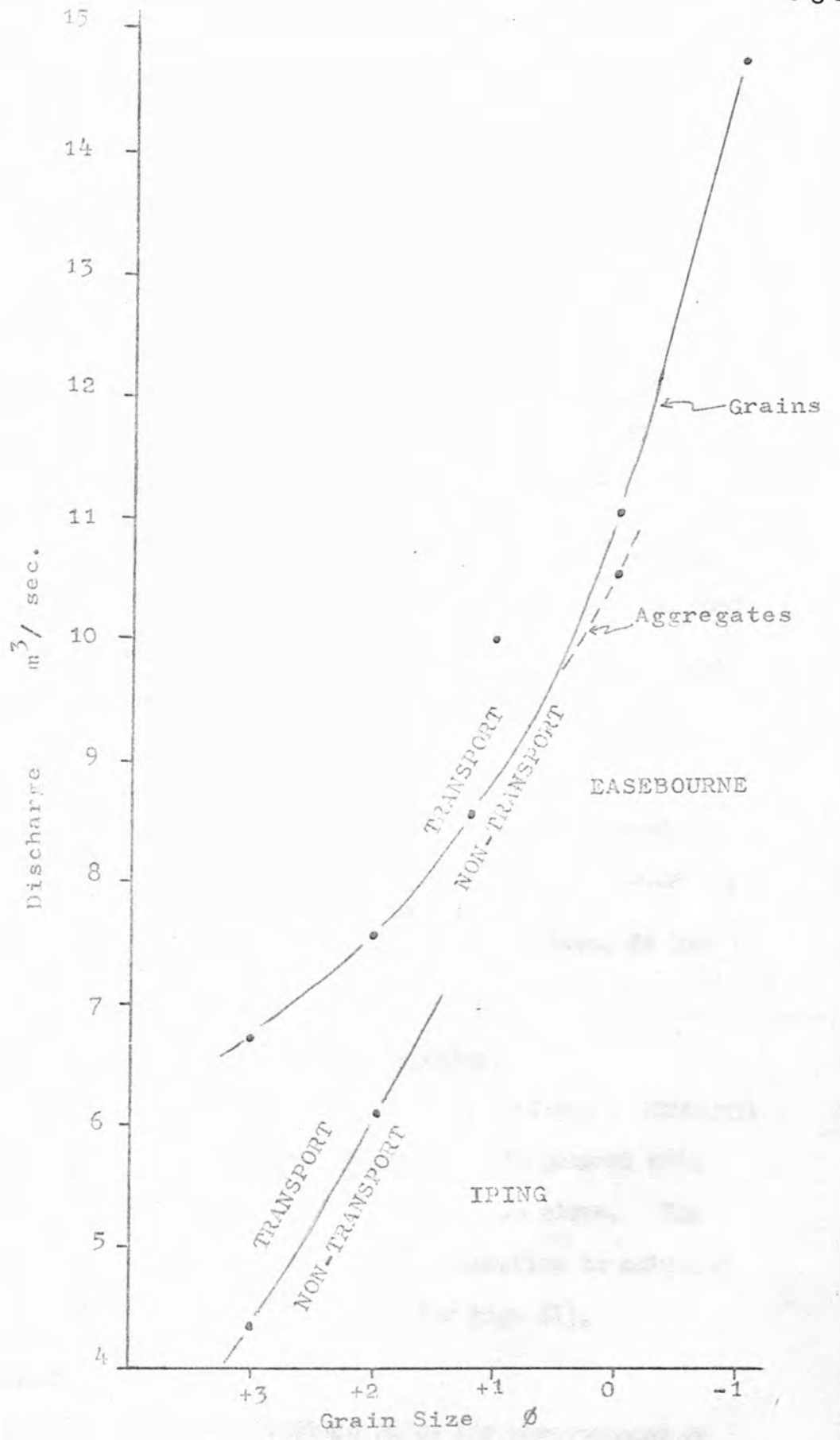


Fig. 39. To show threshold values for the commencement of bed-load movement at Easebourne and Iping Mill.

stretches than for the stream above Iping.

In fact, this difference in bed load transport between the two experimental stretches is probably a reflection of a general downstream decrease in bed load transport rates that occurs along the main stream, and perhaps its tributaries. Despite water discharge becoming less further upstream, channel depth and width generally decrease, with a resulting increase in current velocity. It is this current velocity that is the dominant factor controlling bed load transport rates.

Once threshold discharge values for the commencement of bed load transport have been determined, the next stage is to determine bed load transport rates. Figs. 40 and 41 have been constructed in an attempt to give a general picture of the relationship between bed load transport, river discharge and grain size. The author wishes to stress that the vertical scales are only a tentative approximation to reality, and more detailed studies are required to attain more accuracy.

Problems arising during the construction and use of Figs. 40 and 41 include those concerned with:

1. Construction of the scale for bed load transport.

Accurate data are lacking here, and indeed, in reality, a different scale would probably be required for each grain size, in general with larger intervals per unit for progressively larger grain sizes. The vertical scales presented are determined with consideration to column 6 of Tables 44 and 46 (for Fig. 40) and Table 48 (for Fig. 41).

2. Threshold values.

For any given mesh size, the threshold value for commencement of

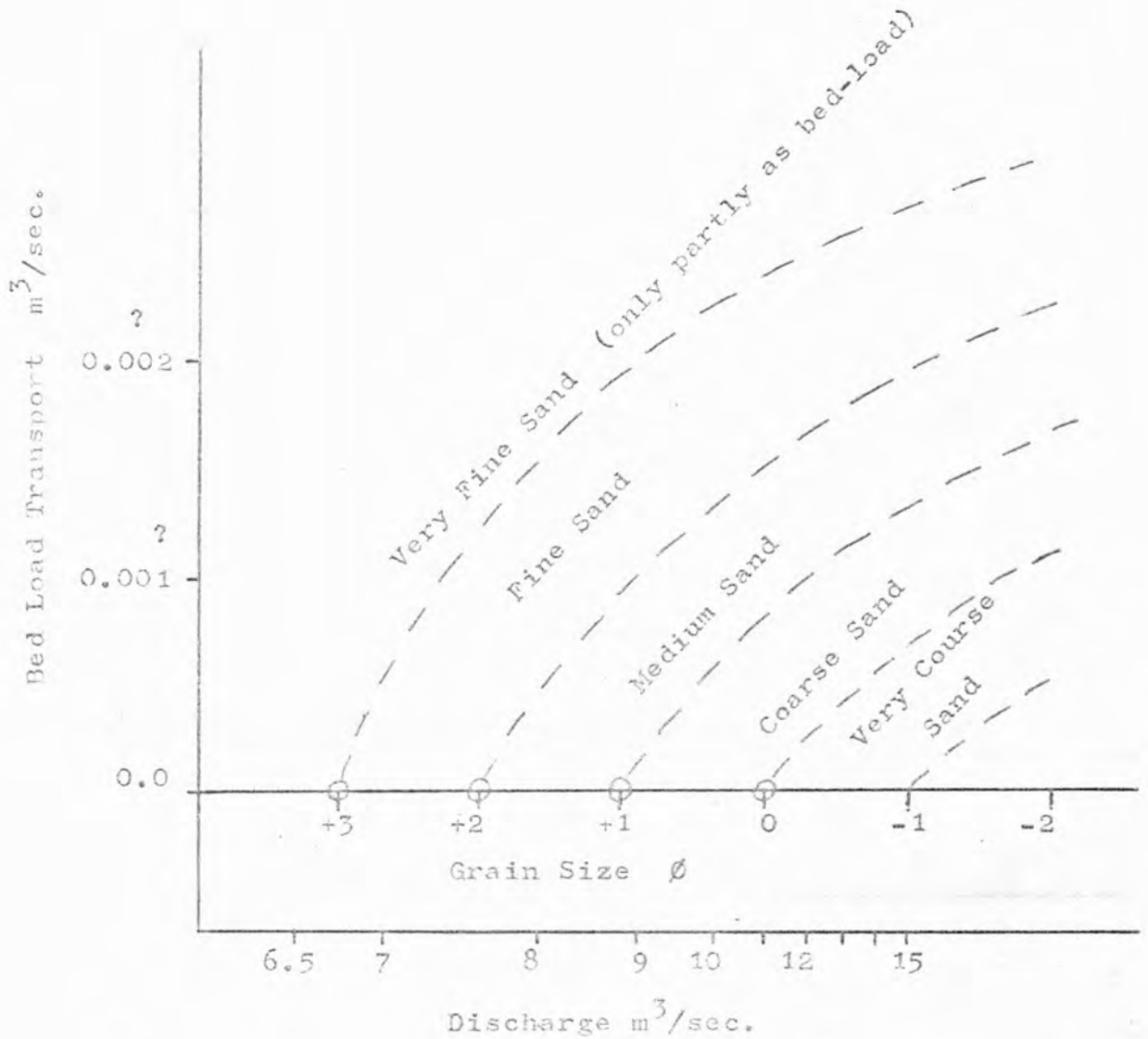


Fig. 40. Relationship between bed-load, grain size and discharge, Basebourne. Use 5 readings/ ϕ unit.

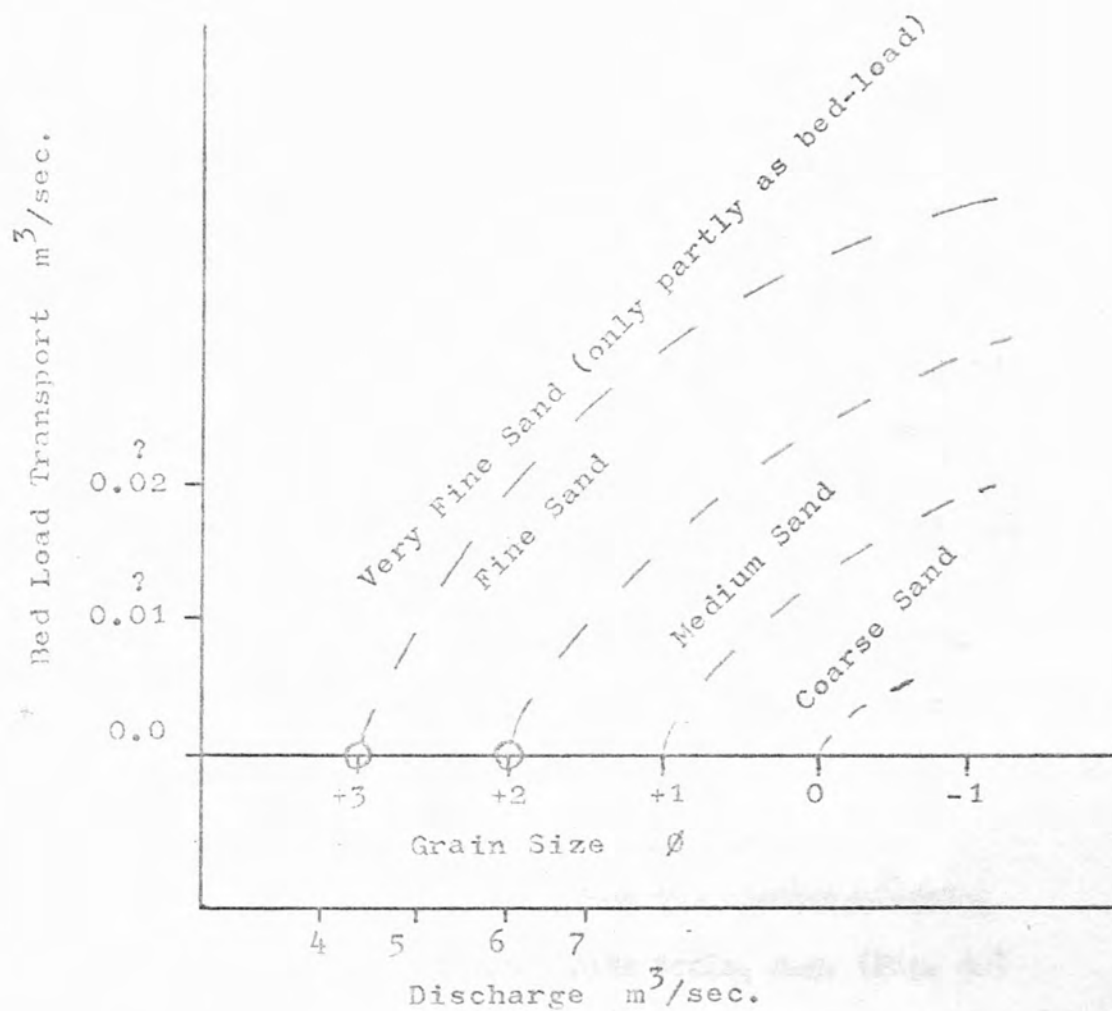


Fig. 41. Relationship between bed-load, grain size and discharge, Iping Mill. Use 3 readings/ ϕ unit.

bed movement would vary slightly with local features in the channel and hydrological regime and also upon variable factors between individual grains, notably shape and specific gravity.

3. Curve for any individual grain size.

Example curves have been drawn on the graph for mesh 120, 60 and 30. These are somewhat arbitrary, and indeed, it is unlikely that the curves are necessarily parallel. It is probable that they would diverge somewhat with increased discharge values, in that, for example, the mesh 120 curve would be steeper than shown for the higher discharges. This would, of course, be dependent on the availability of sediment of this size.

4. Use of graph.

The main purpose of the graph is to provide an approximation of the proportions and amounts of various sizes of sediment in transport for any given discharge.

a) To determine sizes capable of being transported.

Construct an imaginary vertical line from the discharge scale, at the desired discharge level, to the grain size scale, e.g. (Fig. 40) a vertical line from $9\text{ m}^3/\text{sec}$ will pass the grain size scale at a phi value of +0.9. This means that all sizes smaller than +0.9 ϕ are capable of being transported.

b) Information on one particular grain size.

Construct an imaginary line from the relevant point on the grain size scale parallel to the dotted lines shown, until it intersects with an extension of the imaginary vertical line drawn up from the discharge scale through the grain size scale. Now, assuming $9\text{ m}^3/\text{hr}$, and if discharge is $6\text{ m}^3/\text{hr}$, then the intervals determining

the vertical scale to be correct, a horizontal line to this scale from the intersection will provide bed load transport data for the discharge concerned.

A question arising here is, if information is required on the total size range being transported, at what size intervals should estimations of transport rates be taken. Obviously, with only one vertical scale, the total transported would depend on the number of intervals used, i.e. the smaller the intervals of grain size, the greater the total transport.

It is suggested that for any figs. of this sort, the number and size of intervals to be used is determined by the size range of tracers concerned:

e.g. 1. (Ref. to Fig. 40). If tracer sizes are:

Fine sand	- mesh 120-60
Medium sand	- mesh 60-30
Coarse sand	- mesh 30-16

If discharge is $11\text{m}^3/\text{sec}$ then intervals for determining bed load transport should be 1 phi unit apart and taken:

1	at	3.5ϕ
1	at	2.5ϕ
1	at	1.5ϕ
1	at	0.5ϕ

e.g. 2. (Ref. to Fig. 41) If tracer sizes are:

Fine sand	- mesh 100-120
Medium sand	- mesh 52-60
Coarse sand	- mesh 25-30

i.e. approximately one third of the total size range for each grade, and if discharge is $6\text{m}^3/\text{hr}$, then the intervals determining

bed load transport should be of $2/3 \phi$ values to progressively smaller sizes from $+2 \phi$.

In other words, as the vertical scale has been constructed on information collected from tracer experiments, it should vary according to the size range; the larger the values of the units on the vertical scale, then the less the number of intervals on the grain size scale from which readings are taken. Also, such intervals should be equally spaced, and include all sizes capable of being moved by the discharge concerned. So, for Figs. 40 and 41, 3 readings per phi unit should be used, as in example 2.

A comparison of Figs. 40 and 41 again shows the two major points indicated earlier; that is the greater transport rates and lower threshold discharge values for transport at Iping, and the implications of this have been outlined above.

CONCLUSIONS

Despite the experiments with tracers on bed load transportation being hindered by lack of non-base flow discharges, some useful information has been forthcoming:

1. With spatial integration experiments the author found it more convenient, for the purpose of this study, to use the suggested equations:

$$q = pt \phi B \quad (19)$$

$$\text{where } pt = \frac{\int_0^{\infty} gt x dx}{\int_0^{\infty} gt dx} \quad (20)$$

$$\text{and the equation } q_r = q^{t_2} - q^{t_1} \quad (21)$$

This could then provide transport data for each flood hydrograph.

2. The equation

$$q_s = \frac{ut \phi B p_m}{100} \quad (25)$$

is suggested as a possibility of determining transport rates of different sized sediments using mean particle velocity (ut) obtained from time integration studies.

3. Results indicate that data obtained by the time integration method were more accurate than data collected by the spatial integration method. The former data were more agreeable with suspected rates of transport (very low), and with data reported elsewhere, and with data determined by equation 25 (using approximate values for p_m).

Difficulties associated with the spatial integration method include:

- a) accurate determination of depth of mixing; if estimation is too great, the transport determinations will be too high;
- b) each survey should in reality cover sufficient length of stretch so that the farthest travelled tracer grain has the chance of being recovered;
- c) there is difficulty in determining accurately the amount of tracer left at the origin.

4. Threshold values of discharge for commencement of bed load transport are in the region of: (from Fig. 39)

6.7 m³/sec for +3 ϕ at Easebourne
 7.5 m³/sec for +2 ϕ at Easebourne
 8.8 m³/sec for +1 ϕ at Easebourne

- 11.0 m³/sec for 0 ϕ at Easebourne
- 14.7 m³/sec for -1 ϕ at Easebourne
- 4.3 m³/sec for +3 ϕ at Iping
- 6.0 m³/sec for +2 ϕ at Iping

The threshold discharge values may be greater after the long summer period of non-transport, during which compaction and growth of weed may have some effect.

5. Transport rates at both Iping and Easebourne are very low, and are characterised by prolonged periods of non-transport during conditions of base flow.

Transport rates are well below 1 m³/hr for even fine sand during the peak conditions of a storm.

6. Threshold values are at lower discharges at Iping than at Easebourne, which is associated with higher transport rates at the former and more upstream locality. This suggests an overall condition of aggradation somewhere between Iping and Easebourne, particularly for sediment of medium size and larger.

Bed load transport is a complex situation in the simplest of cases. But in the complex and variable setting of a natural channel it is hoped that these data will be of some use in its understanding.

SECTION III

SEDIMENT BUDGET AND SOURCE

SECTION III

SEDIMENT BUDGET AND SOURCE

It has been shown that the determination of a) the relative yield by each parent rock type to the river sediment (Section I), and b) the rate of sediment loss from the catchment (Section II) are both very problematical. Some discussion on these topics, and on the results obtained by the present study are given in the appropriate chapters, along with the conclusions. It is now proposed that the information should be brought together and commented on briefly.

The various rock types within the catchment were each found, by heavy mineral analysis and X-ray diffraction analysis, to have a characteristic mineralogy. Also, the mineralogy of the river sediment, bed load, and suspended load, was often found to vary as the channel traversed from one rock type to another, according to the mineralogy of the strata concerned. This variation appeared to be stronger in the suspended load however.

For both suspended load and bed load, a quantitative assessment of the relative yield to the sediment from each source rock is not possible. For suspended load, this was because of the sediment leaving the catchment

as a whole being dominated by quartz, (a mineral present in all rocks of the catchment) and determination of proportions of other characteristic and diagnostic minerals was not possible. For bed load, the quantitative assessment was not attempted for two reasons. The mineralogy of each source rock was not sufficiently variable for the determination of useful diagnostic minerals once the rock occurred in a sediment. Also, the study indicated that sufficient understanding of the processes of sorting and transport is lacking, even if diagnostic minerals could be determined.

Spatial variations in the mineralogy of river sediment were determined. For suspended sediment, the main cause of this variation appeared to be variable mineralogy of individual rock types and of soils developed on the rock types: whereas with the bed load, the spatial variation is also very much dependant on sorting on the basis of specific gravity, and to a lesser degree, shape.

Studies of the pebble sized fractions of river sediment indicate that sources of this material are the Lower Greensand (for sandstone fragments), and probably superficial flint gravels (for flint fragments). Some spatial variation, namely between the Hammer Stream and the main stream, was determined. Data indicate that little material of pebble size is supplied to the main

stream by the Hammer, draining from the Weald Clay areas.

So, little information of sediment yield from each rock type is available, except that more coarser sediment will obviously be derived from the coarser beds. Also, much movement may be occurring of material derived from all rock types, but much of this would be held in store within the catchment and may not be passing the lower limit of the catchment. Indeed, many mass movement processes were seen to occur during the study period, and little of this would be removed entirely from the catchment for very many years.

Educated guesses would suggest that almost all of the Weald Clay, Atherfield Clay and Gault that is lost, is removed as suspended sediment, whereas almost all of the Lower Greensand, with the exception of some fines, is transported as bed load. The Upper Greensand is probably transported by both mechanisms, both as fragments and grains in bed load, and also as very fine fragments and clay minerals (resulting from weathering) as suspended load. All of the Chalk would be removed as dissolved load, except for minor amounts of precipitated calcite held in suspension.

Estimates of the rate of sediment loss were, in general, more successful than was the determination of

sediment source. Erosion rates of calcium carbonate for the catchment above Iping Mill as a whole (for the 1971-1972 water year) are in the region of 39.8 tonnes/km^2 , but as most of this dissolved calcium carbonate would be Chalk the erosion rate for the area of Chalk outcrop would be well over $150 \text{ tonnes/km}^2/\text{year}$. An important point here is that, whereas removal by the river of material derived from all other rocks in the catchment generally involves a surface lowering, the solution of Chalk by waters entering the Rother occurs dominantly below ground.

Work on the suspended load of the Rother has indicated the necessity for rating loops for accurate determination of suspended sediment loss. Also, a change in the shape of the rating loop for each subsequent storm may occur, resulting in a reduced hysteresis effect, and lower suspended sediment concentration, and therefore, lower rates of sediment loss. There is no evidence of hysteresis in bed load transport of the Rother, and if indeed it is present, which is possible because once a grain is set in motion it can continue to be carried at velocities lower than that necessary to initiate motion, it will be very small. Similarly, with bed load there is no evidence of reduced rates of sediment loss for the same discharge of subsequent hydrographs for material of medium sand size or larger.

The total suspended sediment lost over Iping Mill weir in 1972 was 2,182 tonnes, of which 1,720 tonnes is non-organic. This gives an erosion rate of $14 \text{ tonnes/km}^2/\text{year}$ of which $11 \text{ tonnes/km}^2/\text{year}$ is non-organic. Much of the suspended sediment would initially be derived from soils, and these, originally derived from the bed rock.

Experiments with bed load transport on the main stream of the Rother have enabled a tentative relationship between river discharge, grain size and sediment loss, to be drawn up (Figs 39, 40 and 41). Threshold discharge values for the commencement of movement of different grain sizes have been determined, and Figs 40 and 41 can be used to give an indication of bed load loss during any one hydrograph. The loss is well below $1 \text{ m}^3/\text{hr}$. for even fine sand during peak flow conditions of a normal storm hydrograph. Most of the sediment transported as bed load would originally be derived from the Lower Greensand, and a high proportion would be from soils developed on these. However, field observations suggest that some would be derived directly from rock exposures on the channel sides.

Experiments on bed load transport at Iping and Easebourne suggest aggradation of material of medium sand size and larger between these two points.

The magnitude and frequency of individual storm

hydrographs is very important in the Rother Catchment. It has been shown that during base flow conditions there are prolonged periods of a) non-transport of bed load, and b) suspended sediment concentrations of less than 5 mg./l. (most of which is probably organic). It is only during the storm hydrograph that transport of clastic materials become important, and consequently, the major controlling factors of clastic sediment loss from the catchment are the frequency of hydrographs, their peak discharge levels, and their duration. These three factors will also have control on the rate of removal of Chalk in solution, but even at base flow some solution of Chalk will occur as the water issuing from the Chalk springs indicates.

With reference to the two experimental stretches, Iping and Easebourne, material of very fine sand size is lacking in the river bed sediment, and is generally transported as suspended sediment. Similarly, material of medium sand size is absent from suspended sediment and is transported as bed load. Material of fine sand size is capable of being carried as both bed load and suspended load, and often will be, depending on the conditions of flow.

CONCLUSIONS

Many conclusions were drawn during the study of the

catchment, and these are indicated at the ends of the relevant chapters. So, it remains only for a few words to be added :

1. The mineralogy of clay and silt sized material of source rocks is reflected to an extent in the suspended sediment of streams draining over them. This spatial variation however, is not sufficient for a quantitative assessment of the source of suspended sediment for the catchment as a whole.

The suspended sediment lost from the catchment as a whole is dominated by quartz, and clay minerals form only a small proportion of the total.

2. The heavy mineral assemblages of the source rocks are variable, but not sufficiently so for the determination of useful diagnostic minerals suitable as indicators of the rock occurring as river sediment. Analysis of river bed samples indicate that for a quantitative assessment of sand supplied by either a) certain rock types, or, b) a certain tributary, it appears that sufficient understanding of the processes of sorting and transportation is lacking. The methods of sampling and use of samples, needs some revision, and a comparison of two river bed samples should be confined to samples collected from identical hydrological conditions. This throws some doubt on the value of the hydraulic ratio method of Bittenhouse (1943 and 1944).

The author tentatively suggests that sorting on the basis of specific gravity, and to a lesser degree, basis of shape, will result in the formation of three zones of different mineral assemblages that are transitional with each other. Zone A is an upstream zone with a relatively greater proportion of the heavier heavy minerals than zone B. Zone B is a downstream zone with relatively greater proportion of lighter heavy minerals than zone A. Zone C is a transitional zone between A and B. Such zones may coincide with areas of aggradation (zone B) and degradation (zone A).

3. The majority of the material of very fine pebble, fine pebble, and medium pebble sizes, in the sediment that is lost from the catchment is derived from the Lower Greensand, and to a lesser extent, from the Upper Greensand and the superficial flint gravels of the area. Very little is supplied from the Weald Clay and Atherfield Clay.

As with heavy minerals, the processes of sorting are not completely understood.

4. Studies of the Ca^{2+} and HCO_3^- concentrations in the waters leaving the study catchment indicate that the majority of these ions are derived from the solution of the CaCO_3 of the Chalk. Some variations in concentrations were noted, and these appear to be controlled by discharge, and waters passing Iping Mill are saturated with Ca^{2+} with respect to CaCO_3 .

The erosion rate of CaCO_3 for the catchment above Iping Mill as a whole for the 1971-1972 water year is approximately 39.8 tonnes/km^2 . The erosion rate for the area of the Chalk outcrop would be much greater.

5. The construction of rating loops for the determination of suspended sediment loss is necessary for accurate estimations to be made. The rating loops often exhibit hysteresis and this effect is greatest for the first large storm of the water year, and becomes generally reduced through the winter. Major factors controlling suspended sediment concentrations are discharge, duration of hydrograph, frequency of hydrograph, length of recovery time for re-accumulation, and time of year. Concentrations for the same discharge become reduced, if successive hydrograph peaks follow in rapid succession, due to exhaustion of material. However, the data indicates that only a short period, (approximately 5 days, depending on certain factors e.g. controls of weathering) is necessary for re-accumulation of suitable material for suspension.

Very little vertical concentration gradient was determined in the suspended sediment. This is due mainly to mixing by the turbulent nature of the river. A general decrease in suspended sediment concentration occurs downstream, but this does not necessarily imply a downstream decrease in total suspended sediment lost.

(Figs 25, 26 and 27), and transport rates are well below

An estimated 2,182 tonnes of suspended sediment was lost in 1972, of which 1,720 tonnes is non-organic. This gives an average erosion rate for the catchment above Iping Mill as a whole of 14 tonnes/km.²/year, of which 11 tonnes/km.²/year is non-organic.

6. The author suggests that the equation

$$q = pt \phi B \quad (19)$$

is more suitable, for use in some spatial integration studies for the estimation of bed load, than those equations indicated by Crickmore (1967). This would provide transport data for each flood hydrograph.

The equation

$$q_s = \frac{ut \phi pm}{100} \quad (25)$$

is also suggested as a means of determining transport rates of different sized sediments using mean particle velocity as ut .

Threshold discharge values for the commencement of transport of river bed sand of different grades have been determined at two localities (Iping and Easebourne), and these indicate the probability of aggradation of sizes of medium sand and larger between these two stretches.

Tentative relationships between river discharge, sediment discharge, and sediment size can be drawn up (Figs 39, 40 and 41), and transport rates are well below

1 m.³/hr. for even fine sand during the peak conditions of a normal hydrograph. The author suggests that for figures of this sort (Figs. 40 and 41), the compiler should indicate the number of readings per phi unit that are necessary for estimation of sediment loss for the different size.

7. Sediment transport rates are very low in the River Rother, and are confined to conditions of non-base flow. This gives the channel a characteristic situation of prolonged periods of non-transport.

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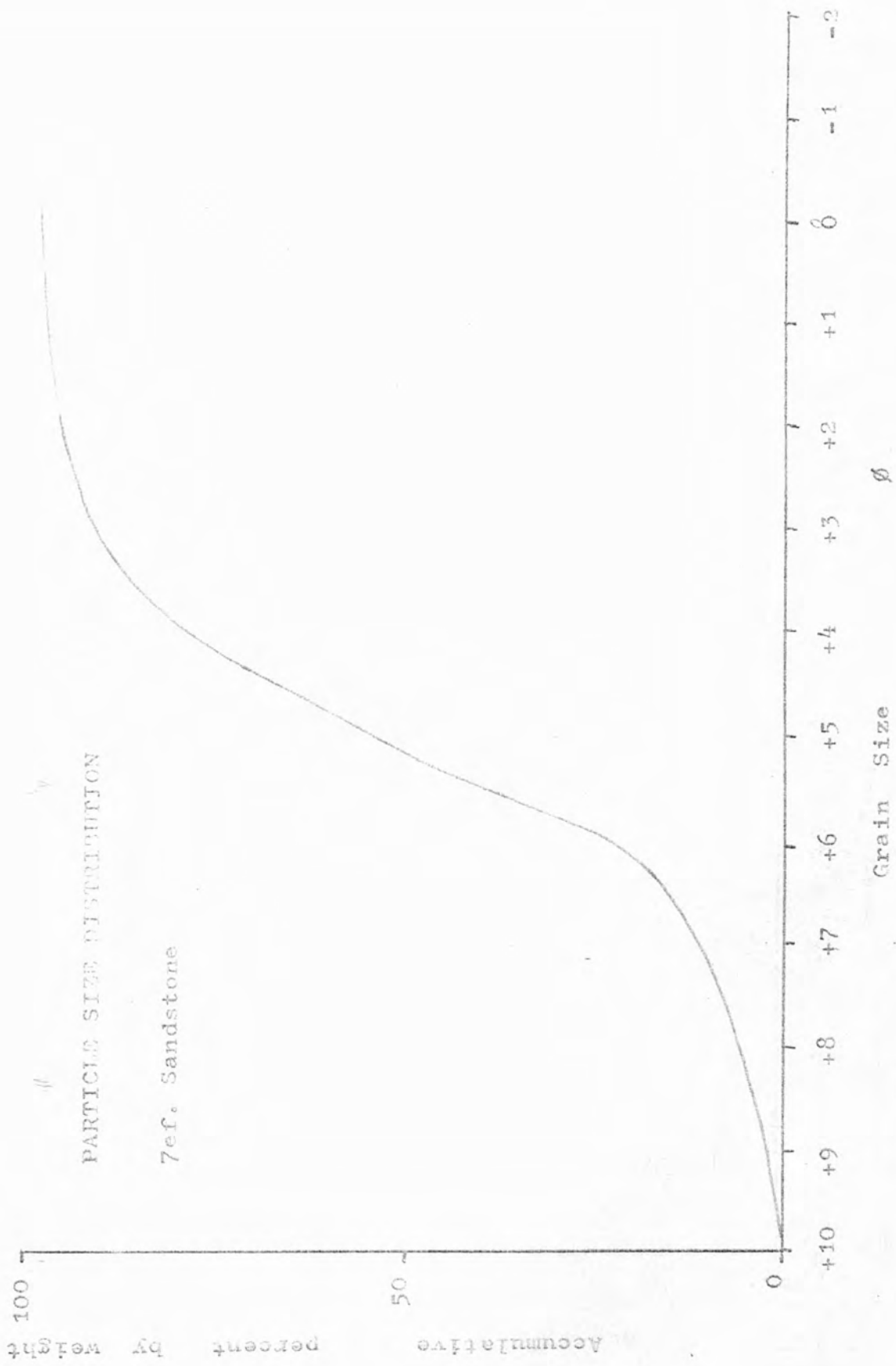
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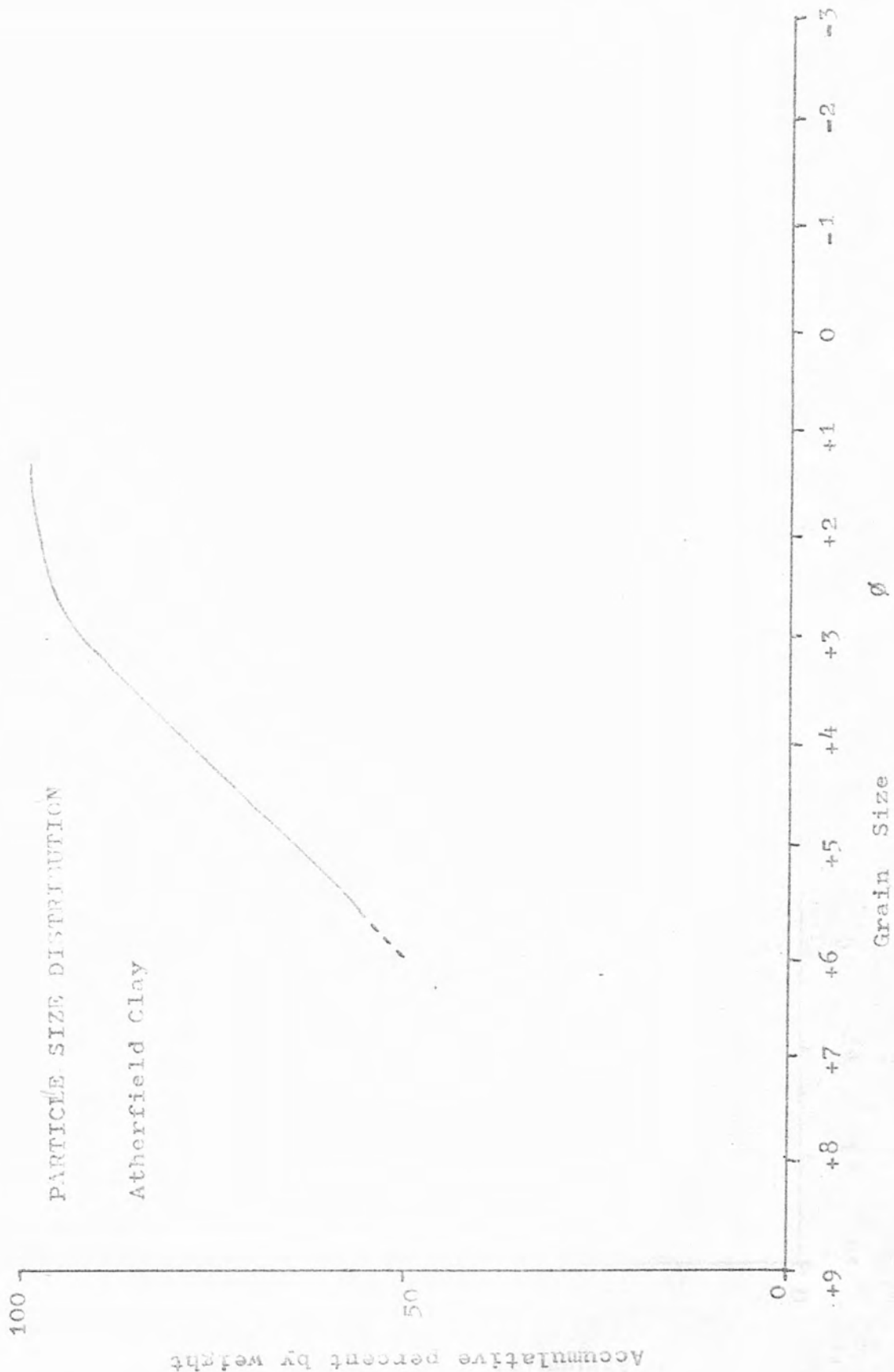
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APPENDICES

**APPENDIX 1 - Particle size distribution of
source rocks.**

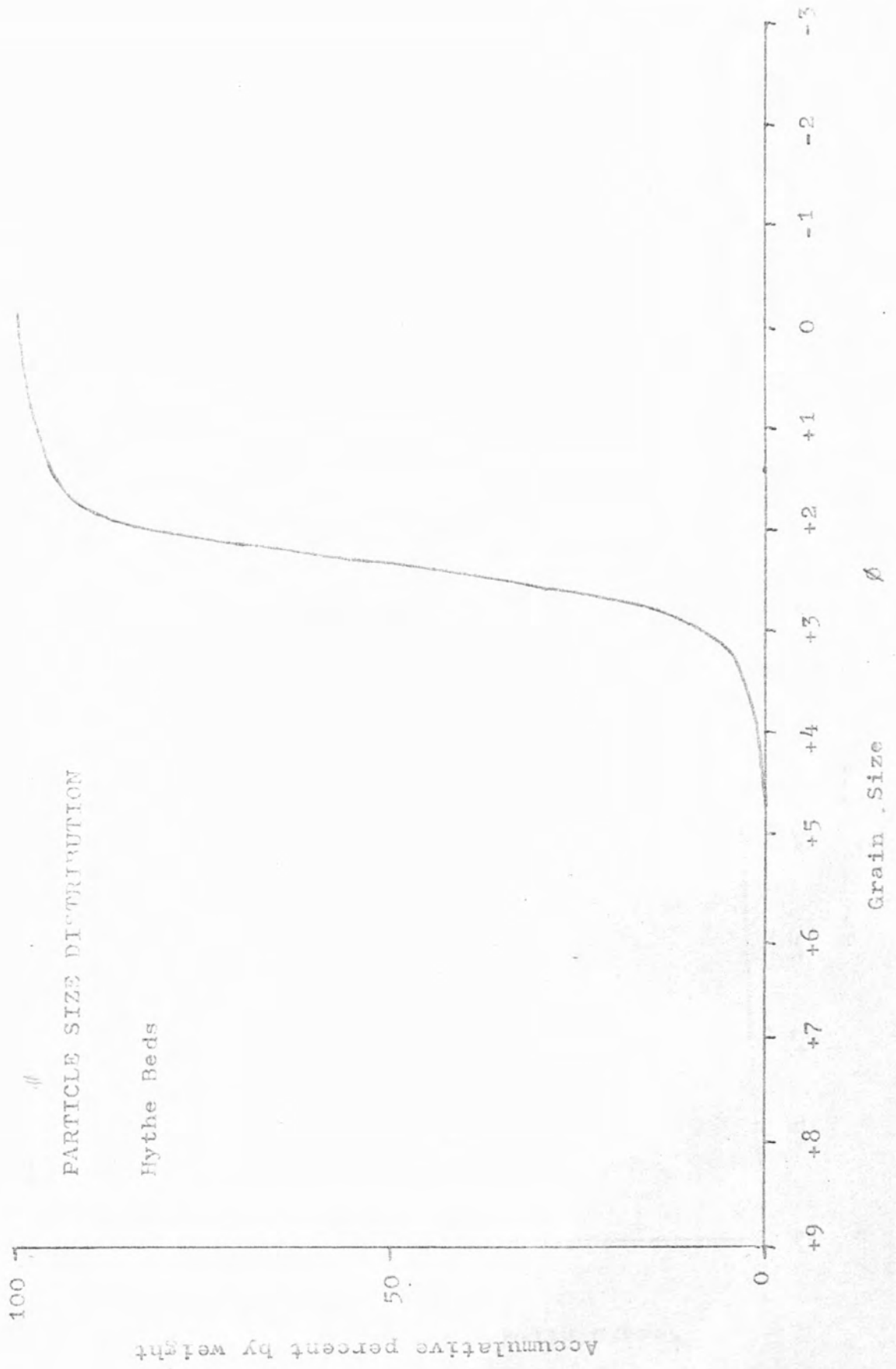
APPENDIX 2 - Explanation of symbols used in text.

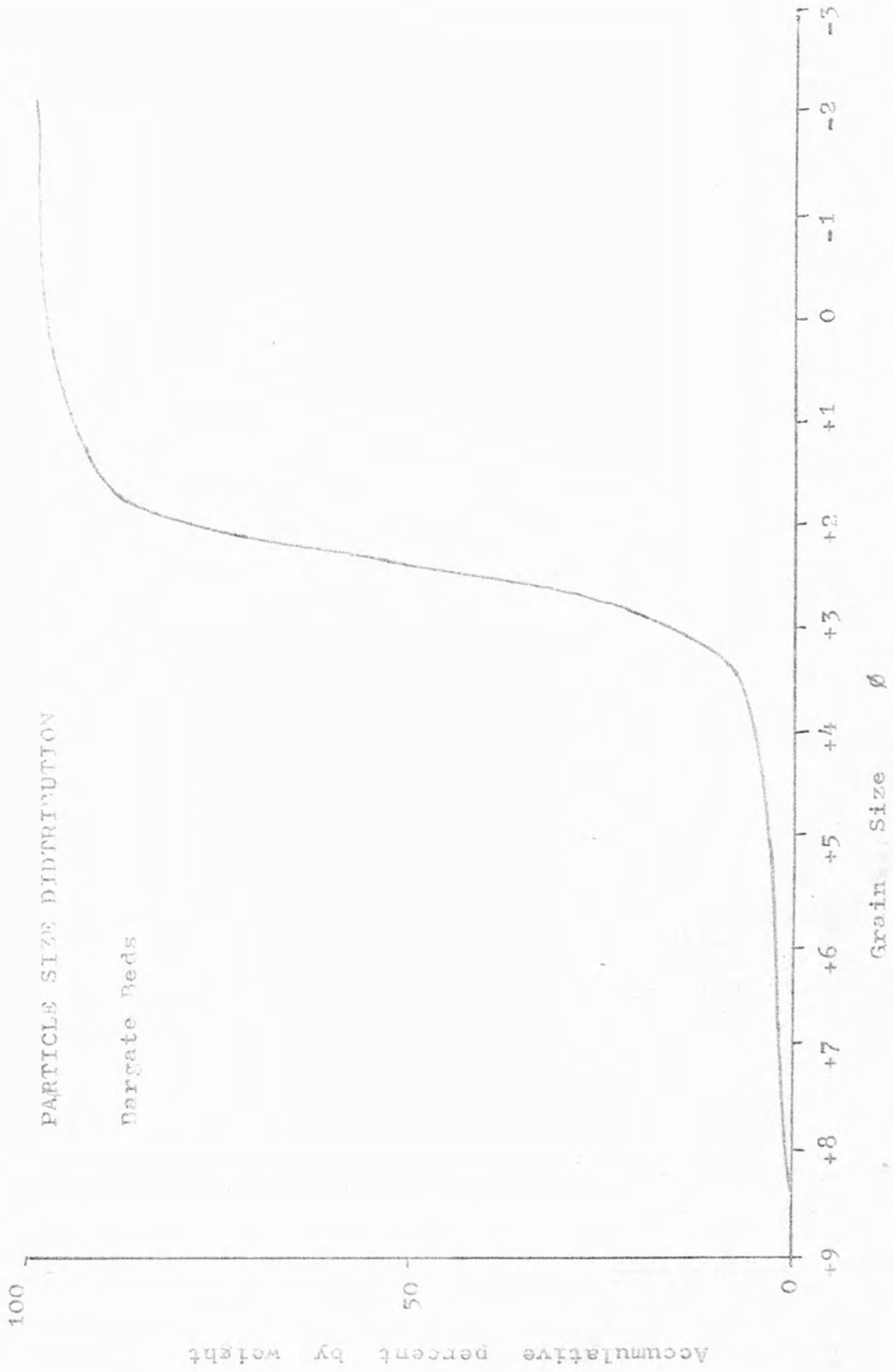


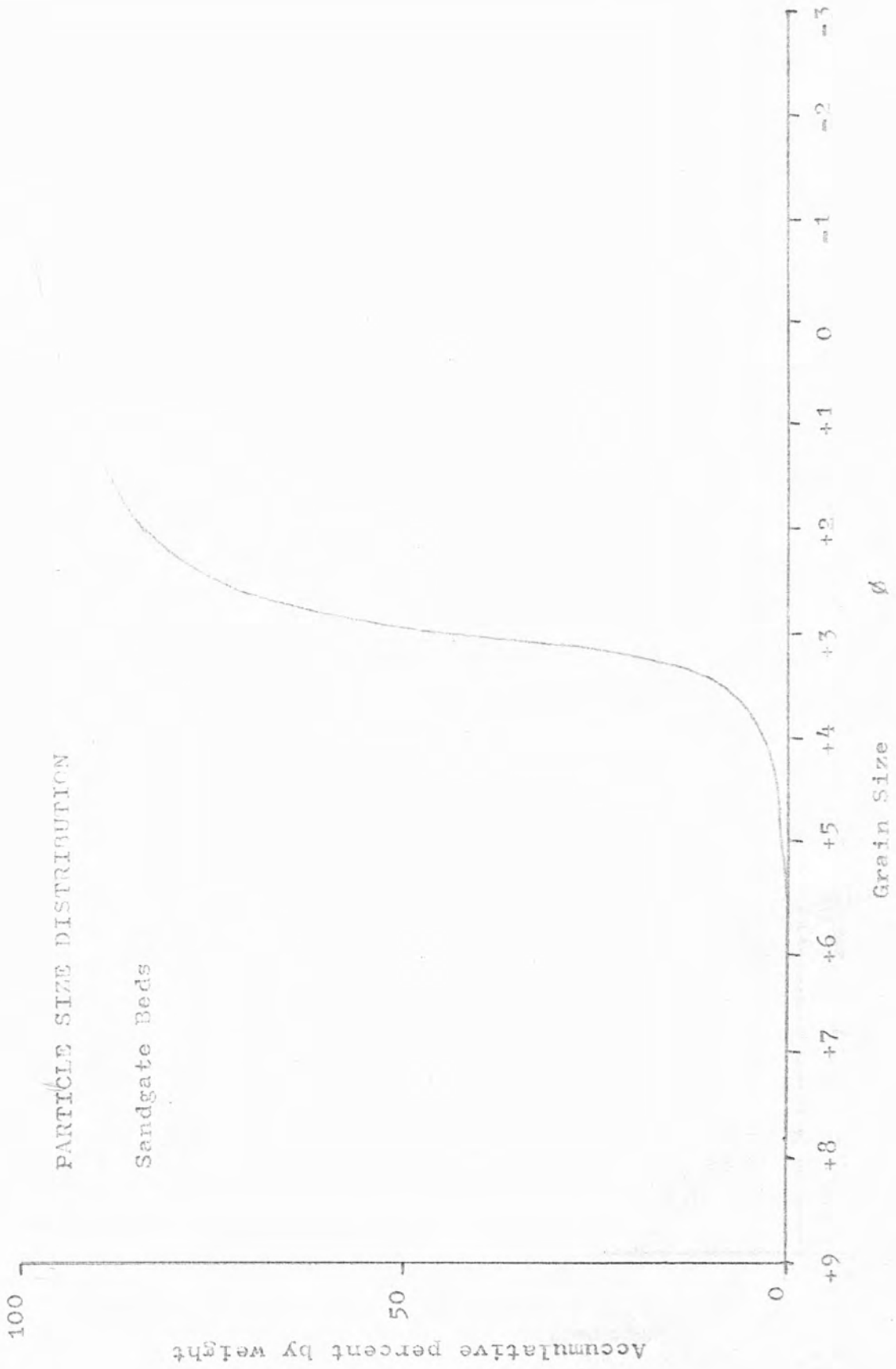


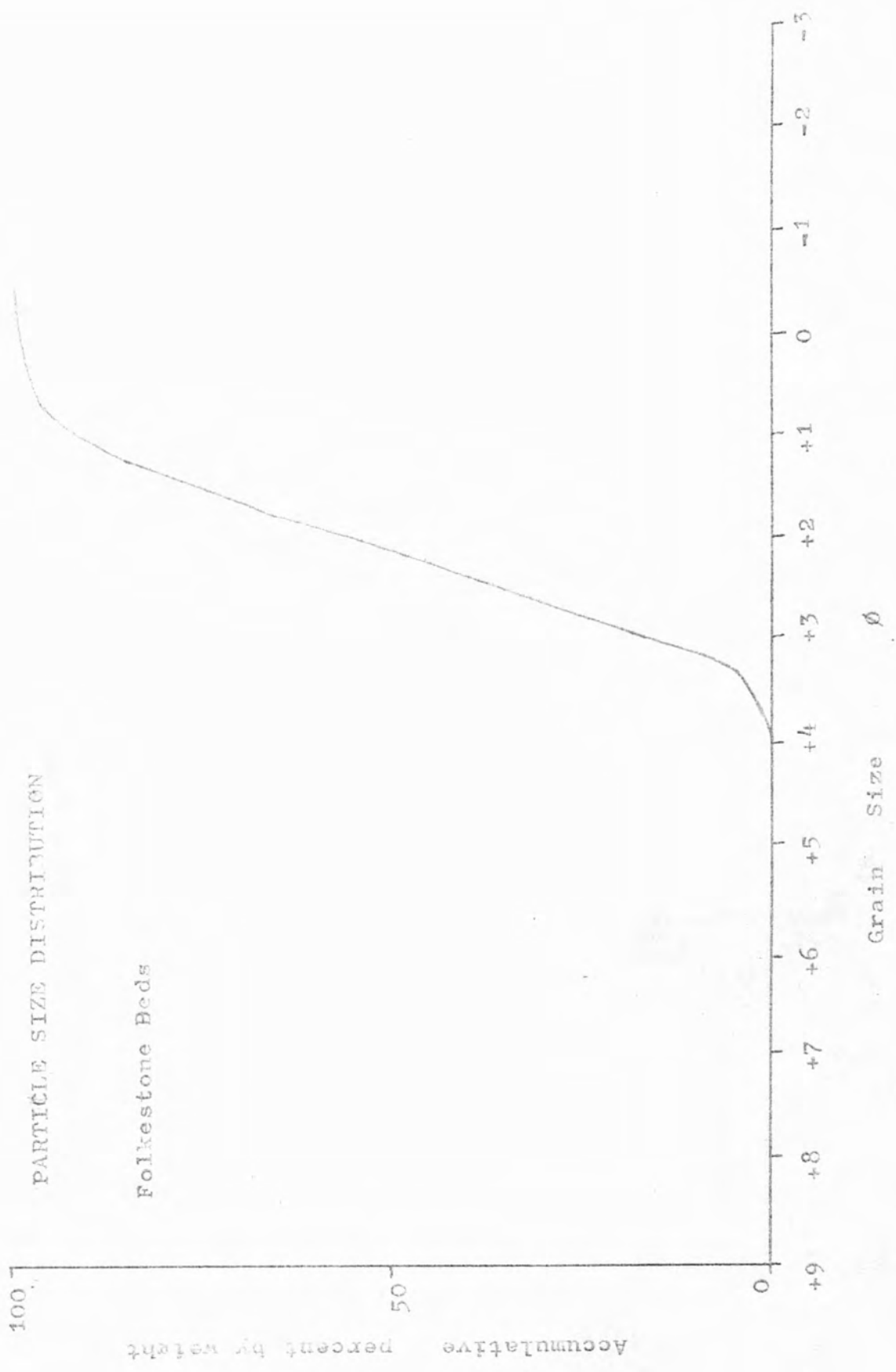
Accumulative percent by weight

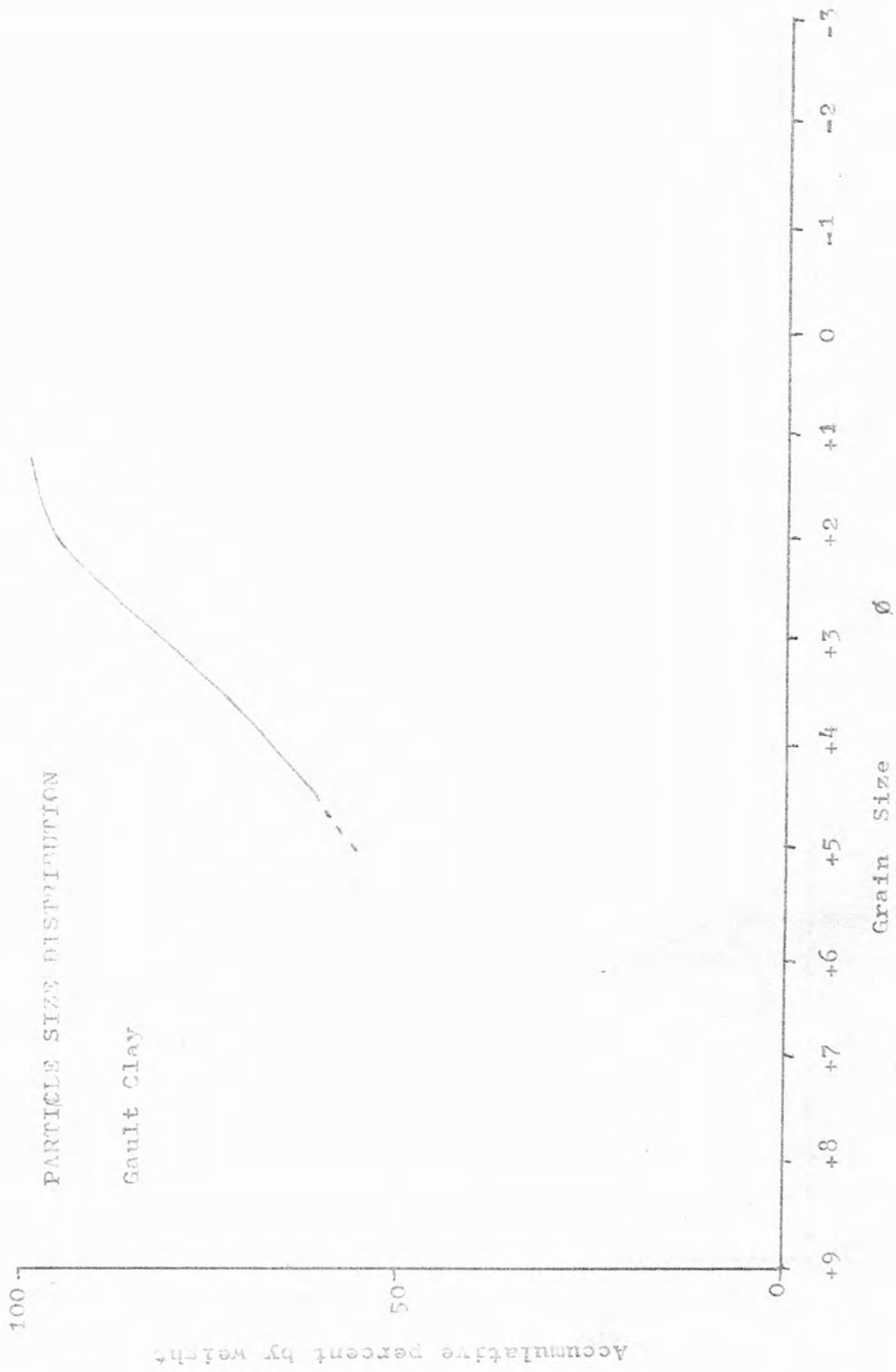
Grain Size ϕ

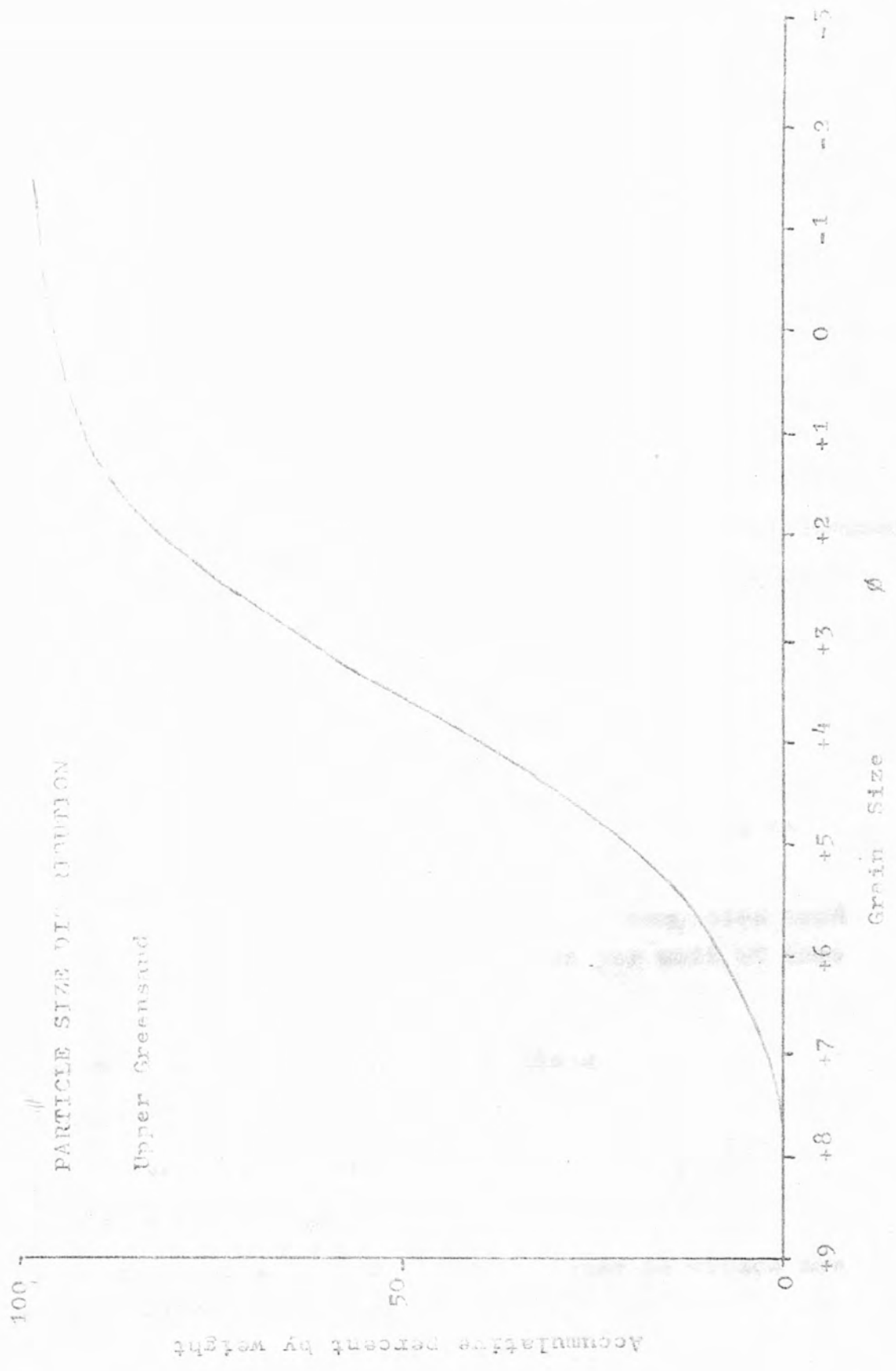








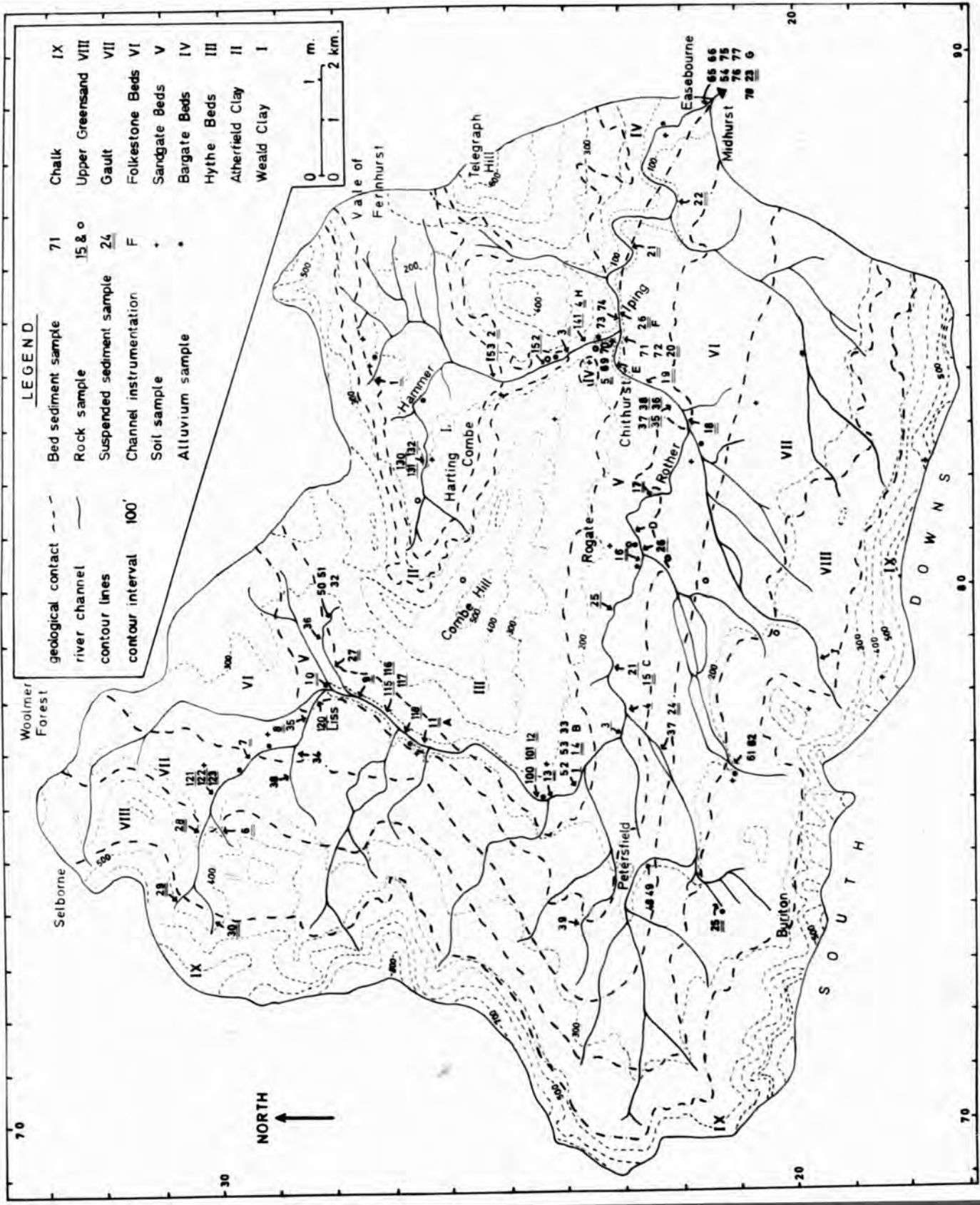




APPENDIX 2

Explanation of symbols used in text.

B	channel width
c	concentration of tracer
cf	concentration of tracer by volume
Cs	steady concentration
gt	weight of tracer per unit length
pm	percentage of particles of tracer size in moving sediment
pt	distance of centroid of tracer cloud from origin
Q	volume of discharge
q	transport over period since injection of tracer expressed as volume of compacted sand
q'	injection rate of tracer
qr	transport between successive surveys expressed as volume of compacted sand
qs	mean transport expressed as volume of compacted sand occurring over entire channel width per unit of time
t	time
ut	velocity of centroid of tracer cloud
v	volume of tracer sand injected
vf	volume of marker fluid
X	distance from origin
ø	mean depth of bed through which tracer particles are distributed



MAP OF STUDY CATCHMENT TO SHOW GEOLOGY, TOPOGRAPHY AND SAMPLING LOCATIONS

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