AN INVESTIGATION OF THE SOURCES AND SUPPLY OF COARSE SEDIMENT INPUT TO A SEMI-ARID CHANNEL REACH

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requirements for the degree of

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by

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ABSTRACT

This study comprises an investigation of the source and supply of coarse sediment input to a semi-arid channel reach. Despite a growing body of literature documenting research of various aspects of sediment response in semi-arid areas, few studies attempt to integrate processes active in specific source areas with sediment supply to the channel. Detailed in the present study is an account of the processes active in the study area, identification of source environments, a discussion of some of the factors affecting supply, a comparison of the effectiveness of gravitational and fluvial supply processes and an estimation of the time sequence of sediment supply to and removal from a channel reach. The above aspects of sediment supply are embodied in the aims set for the study.

The study is conceptualised within the framework of a coarse sediment supply model. The model is formulated from supporting literature and tested in the light of the results obtained through an investigation of the above aspects of sediment supply in the specific study area. The model is primarily a qualitative one and the data collected intended to strengthen the qualitative nature of the model, while at the same time add at least some measure of quantification.

Several reasons for studying coarse sediment behaviour in semi-arid areas are identified and include the need to improve the present lack of understanding of the relationship between supply and removal of sediment, the temporal distribution of sediment discharge and the relative contributions of coarse sediment to the overall load of rivers.

The study area is located within the semi-arid Ecca basin north-east of Grahamstown. A specific channel reach is chosen within a sub-catchment (catchment B) of the Ecca catchment area as it has a variety of channel bank environments, is accessible through the entire reach, and the proximity of a raingauge and flow measuring weir provide the necessary hydrometeorological inputs.

The methods of observing sediment response from five data collection sites include the use of slope or bank base sediment traps, erosion pins, tracer particle monitoring. sequential photographic surveys, and channel bed surface profile surveys. Hydrometeorological data is provided by records drawn from the data bank at the Hydrological Research Unit. Rhodes University. All rainfall records as well as channel flow data are available in the form of continuous records. Rainfall amount and intensity for any period could be extracted from these records. Data collection is confined to a period of two years, during which time the study area was visited on an approximate monthly basis. The index of erosivity (EI_{30}) could also be calculated from the hydrometeorological records and has been used as an integrated measure of rainfall intensity over the monthly period between site visits.

The results are presented on a sample day for sample day basis. The sediment response data together with hydrological data is represented graphically for each sample day, of which there were nineteen. Discussion and interpretation of the results is left to a separate chapter. The interpretation of the results are based largely upon graphical representation of data time series and of interrelationships between some of the variables measured. The limited number of sample days together with the assumed auto correlation present in much of the data precluded the use of simple statistical testing procedures. The use of more complex procedures is not considered worthwhile and is unlikely to add to the interpretation of the results.

Bedrock weathering is found to be a fairly active producer of coarse sediment on exposed shale bedrock outcrops through which sections of the channel are cut. The transport of the weathered detritus to the channel is attributed to a combination of gravitational and fluvial transport processes, with each process dominating at different times, depending on the magnitude of the climatic input. A tentative comparison of the effectiveness of the two processes reveals that both are capable of transporting similar amounts of sediment but on different time scales. The trends of sediment supply from the various bank environments display remarkable similarity, suggesting a measure of consistency of response to climatic input through the entire reach.

Source areas of coarse sediment identified were limited to a small percentage of the total valley area and consisted almost entirely of the immediate channel environment. A tributary gully appears to be an important source of coarse sediment during fluvially dominated supply episodes, while the channel banks supply sediment on a quasi-continuous basis. The total yields for each source environment were extrapolated from the sampled amounts. revealing that channel banks are the predominant source environments. An attempt is made to assess the role of various factors which might affect sediment supply. The factors include rainfall amount and intensity. channel flow. geology/lithology, dip of strata. aspect of channel banks and size of weathered material. The findings. though not conclusive. do give some indication of the role of the above factors. It is suggested though that this particular aspect of sediment supply receive further attention in future research. Discussion on the time sequence of supply to and removal from the channel draws attention to a pulse-like movement of sediment 'waves' through the channel, and two scales of removal-accumulation cycles are identified.

Finally the validity of the model is assessed and with the exception of a tributary inflow process not envisaged in the original model. is found to be an accurate representation of sediment supply in semi-arid areas. in both its static and dynamic phases. The suggestion is offered that future research on the sediment supply system. in all climatic regimes, can be conceptualised within the context of the basic model proposed in the present study. Specific components of the model should be quantified by numerous individual research efforts, and in this way, serve to build up the model into a widely applicable tool with which to interpret sediment supply.

1. INTRODUCTION

1.1 Field of Research

A great deal of literature has been published on research work concerning the transport of sediment in streams, the characteristics of that transport under different hydrological conditions, and the ultimate deposition of that sediment. Research undertaken on sources and supply processes of sediment deals with an aspect of sedimentology seldom researched per se, although often referred to by geomorphologists. Authors in general refer to the source of sediment in terms of some geological formation in an upstream location. Relatively few research efforts have examined the processes responsible for the transport of that sediment, from a specific source location with respect to the channel, to the channel itself.

The term 'source' as referred to in the literature often has a threefold meaning. Firstly, sedimentary material can be defined in terms of its geological composition, the particle size and shape, and degree of sorting (Allen, 1965; Lewin, Cryer and Harrison, 1974). Secondly, source can refer to the location of the material in terms of its geographical location with respect to the channel bed or banks (Dickinson and Wall, 1977; Lewin and Wolfenden, 1978; Walling, 1983). Thirdly, some authors refer to certain processes as sources of sediment (Brune, 1950; Colby, 1963; Coldwell, 1957; Harvey, 1974; Schumm, 1956; Walling and Webb, 1982). The weathering processes making material available are just as important in a study of the origin of sediment as is the 'source location' and 'source material'. So too are the transport processes operating on channel banks and adjacent slopes.

Given that a description of the material and location components of sediment sources incorporates the processes supplying material to the channel, it is proposed that the term 'sediment supply' can be used. The research detailed in the present study covers an account of the following aspects of sediment supply in a mid-latitude semi-arid channel reach:

a) source location of sediment
b) source material

c) processes making material available as sediment
d) processes transporting material to the channel, and
e) the relationship between channel sediment input and removal.

1.2 Reasons for study

Despite the volume of literature published on sediment movement in channels, especially in humid regions, comparatively little research has been undertaken identifying precisely the source areas from which sediment is derived. The neglect of semi-arid sediment research in particular extends to the spatial and temporal variations of sediment supply processes and their integration with sediment production from differing geological and geomorphological environments. Possible reasons for this apparent neglect of semi-arid sediment studies could be;

a) the hostile conditions and inaccessibility of many semi-arid areas,
b) the infrequent and discontinuous occurrence of channel sediment transport,
c) because of b) above, the long time-span required for data collection, and
d) semi-arid areas have not been subjected to the same research pressure because they are not as densely occupied as humid regions.

Gregory and Walling (1973) identify three main reasons for the geographical study of rivers. Firstly, their mere existence in the physical landscape and consequent ability to produce fluvial landforms. Secondly, their indirect importance in relation to many other geomorphological processes in fluvially dominated landscapes. Thirdly, their significance in relation to human need and activity. Understanding sediment behaviour can give insight into the manner in which rivers are able to produce fluvial landforms. The study of sediment behaviour therefore constitutes an important component of geomorphology in terms of both process and landform response.

Several reasons for studying sediment behaviour in semi-arid areas can be identified:

a) As a result of poor vegetation cover, which is sensitive to over exploitation and not able to recover quickly, semi-arid areas can be susceptible to accelerated erosion.
b) High intensity rainfall can occur in association with a) above thereby increasing the potential for accelerated erosion.
c) The relationships between sediment supply and removal on a catchment basis are poorly understood.
d) There is a current lack of understanding of the temporal distribution of sediment discharge.
e) The relative contributions of coarse and suspended sediment to the overall load of rivers is poorly understood.

The present study is confined to studying coarse sediment behaviour in the immediate channel environment. Although broader studies are important they would be unlikely to produce results in the short time period and with the limited resources available.

1.3 Aims of the study

The main objective of the present study is to formulate a model describing the behaviour of coarse sediment in a semi-arid environment. The initial model conceptualisation is based on previously documented literature. The ability of the model to represent observed processes of coarse sediment supply is then tested by collection and analysis of field data. The model is intended to account primarily for coarse sediment. For the purpose of this study coarse sediment is defined as particles with a diameter larger than the threshold size of particles whose settling velocity can be described by Stoke's Law:

$$V = \frac{2/9\ g\ (d_1 - d_2)\ r^2}{\mu}$$

(Krumbein and Pettijohn, 1938)

where $(d_1 - d_2)$ is the difference in density between particles and liquid, r is the radius of the particle, g the force due to gravity and μ the fluid viscosity. The threshold radius is approximately 80 microns for non-cohesive sediments.

The following are the specific aims of the study :

i) "To investigate the processes involved in the supply of sediment to the channel".

The above aim involves the following :

a) identifying processes active in the study area, and
b) classifying processes according to whether they are making sediment available for transport to the channel, or whether they are transporting the available sediment to the channel. Weathering of shale for example, makes material available, while talus creep may actually transport the debris to the channel.

ii) "To identify the source areas of coarse sediment for a channel reach".

To achieve this aim it is necessary to know which type of sediments are present in the channel. Sampling of the channel sediments can give an indication of the type of surficial material present in the channel. Such samples should indicate the type and proportion of channel bank environments acting as source areas of sediment for the channel reach. However, there are inevitably sediments present in the channel reach which are derived from up-channel locations and deposited during previous flow events. These channel deposits can serve as sources of sediment during subsequent events.

iii) "To establish the intrinsic and extrinsic conditions of the semi-arid environment most favourable to coarse sediment supply to the channel".

In order to achieve the above aim it is necessary to establish which factors could influence the availability and movement of sediment to the channel. It is suggested that the following factors could fit this category :

a) Geology / lithology,
b) Dip of strata,
c) Aspect of channel banks,
d) Antecedent moisture conditions,
e) Rainfall amount,
f) Rainfall intensity, and
g) Size of weathered fragments.

iv) "To determine the relative effectiveness of the two major energy inputs, gravity and water, in their role of transporting coarse sediment to the channel reach".

The above aim could also be interpreted as being a comparative examination of the movement of material down channel banks under the influence of gravity or fluvial action.

v) "To establish the relationship between supply of coarse sediment to a channel reach and the subsequent transport and removal of coarse sediment from, the channel reach".

The channel reach may serve as a storage container for sediments for extended periods. However, a certain rainfall amount and intensity leading to channel flow and channel erosion might remove the sediments from the channel reach. The frequency of erosion/removal of channel sediments needs to be established as well as whether the amount being eroded exceeds that initially deposited. This will enable statements to be made as to whether the channel is aggrading or eroding.

Ultimately a model should accurately describe relative sediment supply to and removal from a semi-arid channel reach. Given 'adequate' data on the causative factors effecting sediment movement in a semi-arid catchment, it might be possible to estimate how much sediment has been delivered to the channel over a period, as well as the percentage that has been removed.

However, the limited amount of available time and data collected in this study, precludes the formulation of such a predictive tool.

1.4 Outline of the Thesis

The available literature on the subject of sediment input to a channel for all climatic regions is reviewed. A conceptual model describing the nature of sediment input to a semi-arid channel is postulated, including all possible factors which might influence this aspect of the semi-arid channel. Finally, the thesis focuses specifically on coarse sediment inputs and the processes involved in the supply of sediment to the channel. The model, formulated from the theory, is tested and reviewed in the light of the field results obtained through studies in a specific semi-arid catchment.

2. PROCESSES OF SEDIMENT SUPPLY TO CHANNELS : A REVIEW OF THE LITERATURE.

2.1 The drainage basin : A general framework.

Geomorphologists have recognized the importance of the drainage basin as a single geomorphic unit providing a framework for the study of landform development, form and process (Chorley, 1969b; Gregory and Walling, 1973). However, it should be remembered that the processes presently operating in any basin may not necessarily be the ones responsible for the formation of the landforms in that basin. If they are, then at least their rate of operation can be expected to be different from those of the past because of changing climatic inputs over the basin (Schumm and Hadley, 1957).

A central theme in geomorphology has been that landforms are the result of processes active now, or at least in the recent geologic past. Geomorphological research was previously concerned with either process or form. However, this earlier split in the discipline has largely been reconciled by the new school of process-response geomorphologists. Utilizing the process-response relationship is the systems approach in which a set of objects are inherently linked by functional and structural relationships which exist between them and modified by the processes acting on them. The drainage basin, characterised by supply and removal of energy and material across its boundaries, is an open system. Supply of energy is derived largely from the climatic inputs to the basin (Gregory and Walling, 1973). Removal of energy can be seen in the loss of water and sediment from the basin through the outlet.

As an open system, drainage basin form is controlled primarily by processes determined by inputs to the system. When inputs vary, the system adjusts through a change in the rate of processes, thereby altering basin form. Drainage basins adapt to process in time and space (Gregory and Walling, 1973), and two basins in differing climates, having different inputs and processes, will have different forms.

An advantage of the open systems approach is the emphasis it places on adjustment and the relationship between form and process. Adjustment can be brought about by changes in the system as a result of the intervention of man. The systems approach is therefore useful in an area where the activities of man are bound to play some role (Gregory and Walling, 1973).

The components of a drainage basin system may be divided into four interlinked and associated parts.

a) The hydrometeorological inputs consisting principally of precipitation and solar energy.
b) The processes of material breakdown and transport of water, solutes and sediments.
c) The drainage basin forms considered in three dimensions and including geological structure and chemistry, soil structure and chemistry, vegetation and surface geometry. The latter is considered to include the total assemblage of hillside slopes and channels.
d) Drainage basin outputs of water (surface and groundwater), solutes and sediments (coarse and suspended).

This study is concerned primarily with the components in b) as they relate to coarse sediment movement. The following section therefore reviews some of the concepts of drainage basin sediment processes. It should be noted, however, that it is not always possible to discuss the processes in isolation without referring to the components of a) and c).

2.2 Drainage basin processes.

For the present study processes are broken down and discussed in three categories: weathering; slope transport; channel processes.

2.2.1 Weathering.

Weathering processes are important insofar as they are responsible for disintegration of rocks of the earths crust. Such disintegration is mostly caused by several mechanical (physical) and chemical weathering processes (Carroll, 1970), although Imeson (1977), Guy (1970) and others add biological factors as a third cause. The resultant debris is the principle source of fragmental material that may become fluvial sediment (Ollier, 1969). Weathering includes all the changes that occur in materials at or near the surface of the earth as they respond to water, the atmosphere and living things (Judson, Deffeyes and Hargreaves, 1976). These changes in, or disintegration of rock occur in situ (Clark and Small, 1982; Carson and Kirkby, 1972). Temperature and moisture are important climatic factors determining the kind and rate of weathering, while topography might determine the exposure of rock to precipitation and solar energy (Guy, 1970). The specific mode of weathering is dependent largely on lithology, the degree of jointing in the rocks, and climate.

Individual weathering processes are widely documented by authors such as Ollier (1969), Chorley (1969a), Carroll (1970), Cooke and Warren (1973), Selby (1982) and Clark and Small (1982). Table 2.1 gives a brief summary of the most important weathering processes.

Table 2.1 Weathering processes.

TYPE	TYPICAL LOCATION	MECHANISM/MODE OF OPERATION
Frost weathering	Periglacial/High altitudes/ Mid-latitudes in winter	Freezing water/expansive forces widen joints/ break up/ angular particles
Salt weathering	Semi-arid/Arid/Salt bearing rocks	Expansive forces of salt crystallization pressure in rock pores/break up/weaken
Insolation/ Exfoliation	Deserts/continental interiors/great daily/seasonal temperature range/Mid-latitudes/Igneous and sedimentary rocks	Outer layers of rock expand/contract with heat and cool/stresses cause flaking
Granular Disintegration		Individual rock particles/dark colours/loosen when heated/cooled more frequently/fall out
Alternate wetting and drying	All climates	Rocks able to absorb water e.g. shale/expand/ dry out contract/expansive stresses cause cracks/breakdown/flaking
Biological	Any climate able to support vegetation	Roots in joints/bedding planes/widen cracks
Solution	Rocks bearing chemicals able to be dissolved/all climate regimes	Acidic groundwater/dissolves and removes chemical/weakening the rock
Carbonation	All Climatic Regimes	Calcium bicarbonate more soluble/dissolved and removed/leaving Calcium bicarbonate as residual/weaker
Hydration		Absorption of water into crystal lattice/ volumetric changes exert stress which weaken the rock
Hydrolysis		Reaction between H^+ and OH^- ions of water and ions of mineral/decomposition
Oxidation	Most prominent in wetter climates/rocks having traces of iron/mainly igneous	Oxygen dissolved in water/reduces iron minerals/rock left weaker

The end result of weathering in all its forms is soil. In humid regions, the soil is eroded by fluvial action to become part of a river's sediment load. However, very often in semi-arid regions, a lack of precipitation leads to a moisture deficiency in rock masses. The breakdown of rocks to the soil phase is seldom achieved on a large scale. The coarse residuals of partly weathered rock masses become the characteristic component of the semi-arid channel's sediment load. Although weathering processes determine the input of rock fragments into the drainage system, this input is in turn dependant on other processes which operate in the system. Carson and Kirkby (1972) indicate that where the production of debris by weathering processes is fairly rapid and the transportational processes to the stream channel fairly ineffective, debris will accumulate on the slopes and channel banks until some 'transport event' moves it into the channel. Supply of sediment can then be said to be 'transport limited', and this is usually the case in arid regions. However, where 'transport events' occur frequently and effectively, debris which can become stream channel sediment is limited by the rate of weathering. Supply of sediment can then be said to be 'weathering limited'.

2.2.2 Slope transport processes

Once a rock mass becomes broken down through weathering processes, the residual particles become potential components of a stream's sediment load. All that is required is some process to transport the material to the channel. Gregory and Walling (1973, p 145) are convinced that ".....a study of fluvial geomorphology must place particular emphasis on those processes concerned with the erosive action of water on the slopes and the supply of material to the channel at the foot of the slope". The processes involved vary from extremely large rapid movements to extremely slow micro-scale displacement (Clark and Small, 1982). Carson and Kirkby (1972) claim that the geomorphic effect of a process is decided partly by how often it occurs, and partly by how fast it operates.

Raindrop impact (rainsplash) as a transporting process has been widely documented in the literature. Raindrops falling onto a surface can contribute to the amount of sediment being transported across that surface in two ways:

a) particles can be dislodged and transported outwards from the point of impact if the forces are great enough, and

b) raindrops falling onto a saturated surface can enhance turbulent flow which is more effective than the shallow laminar-type flow on that surface (Yair and Lavee, 1976).

Sheet erosion. Sheet flow of runoff precedes concentrated or channel flow. Sheet flow is normally a shallow laminar-type flow over gently sloping areas of bare soil (Thornbury, 1969). Guy (1970) claims that purely laminar flow transports negligible amounts of sediment. However, Emmett (1970) indicates that flow can be turbulent as well, due to raindrop impact and that "closely related to the hydraulic properties of overland flow is the ability of these shallow flows to rework the ground surface over which they flow" (p A3). In so doing, sheetflow is capable of transporting considerable amounts of finer sediments to other locations on the slope or to the channel (Palmer, 1965). Sheet erosion, because of its ability to transport only the finer sediments, usually makes contributions to the suspended sediment and solute loads of a stream (Walling and Webb, 1982).

The amount of transport achieved by wash-related processes will depend on slope angle, the erodibility of the surface material, vegetation cover and the amount of water involved. An understanding of this aspect of slope processes is therefore directly linked to slope hydrology. The rate of sheet erosion is partly determined by the physical characteristics of the soil including particle size, cohesiveness, porosity and moisture content (Colby, 1963). Probably the most convincing research that demonstrates the effectiveness of sheet erosion was that of Leopold, Emmett and Myrick (1966). Working in the semi-arid New Mexico state of the U.S.A. they show that the sediment transporting process contributing the largest amount of sediment was sheet erosion.

Rilling. Sheet flow rapidly becomes concentrated into very small channels or rills (Thornbury, 1969), which are initiated at a critical distance downslope from the watershed (Horton, 1945). Rills are the first and smallest form of channel in a continuum from rills through gullies to river channels. These are all forms of concentrated flow and therefore have, on different scales, the same characteristics. Once a rill has been established, further modifications are controlled by the laws governing concentrated channel flow rather than those governing overland flow (Emmett, 1970). The water in a rill has sufficient depth for considerable turbulence to develop and rill flows can therefore entrain larger particles than sheet flow (Selby, 1982). Rilling is generally considered to be evidence of more accelerated erosion than sheet erosion (Engelen, 1973). Kirkby (1969) suggests it is only the erosive power of water flowing in clearly defined channels that is a truly effective transporting and eroding agent. The rill will carry not only the fine`grained load derived from sheet flow, but also the fine and coarse sediments that may be eroded from the bed and banks of the channels (Guy, 1970). Rills are usually only a few centimetres wide and deep, and their dimensions are controlled by the erodibility of the soil (usually fine grained) into which they are cut (Carson and Kirkby, 1972). Rills are less common on soils where there is good vegetation cover because overland flow is less frequent and intense (Kirkby, 1969).

Table 2.2 A comparison of the erosive efficiency of raindrops, overland flow (sheet erosion) and rilling.

Form	Mass*	Typical Velocity (ms^{-1})	Kinetic Energy+	Energy for Erosion&	Observed Transport$ ($g\ cm^{-1}$)
Raindrops	R	9	40.5R	0.081R	20
Overland flow	0.5R	0.01	2.5×10^{-5}R	7.5×10^{-7}R	400
Rill flow	0.5R	10	25R	0.75R	19 000

* Assumes rainfall of mass R of which 50 per cent contributes to runoff.

\+ Based on $\frac{1}{2}mv^2$.

& Assumes that 0.2 per cent of the kinetic energy of raindrops and 3 per cent of the kinetic energy of runoff is utilised in erosion.

$ Totals observed in mid-Bedfordshire on an 11° slope, on sandy soil over 900 days. Most of the energy of raindrops contributes to detachment rather than transport.

(After Morgan, 1979; p.6)

Rills seldom become well established because of the short duration of most flows (Yair and Lavee, 1977). They can be obliterated by a number of processes and Schumm (1964) describes how disturbance of the surface by animals can move material downslope and fill rills. Meyer and Monke (1965) have shown that rills are very often destroyed by deposition of sediments from inter-rill areas. But some 'master' rills may grow large enough to escape destruction (figure 2.1). The relative efficiency of the above 3 forms of water erosion are illustrated in table 2.2.

Gullying. A 'master' rill may so deepen and widen its channel that it may be classed as a gully. A gully is arbitrarily defined as a "....recently extended drainage channel that conducts ephemeral flow, has steep sides, a steeply sloping or vertical head scarp, a width greater than 0.3 m and a depth greater than about 0.6 m" (Brice, 1966; p 290). Gullies are most common in materials such as deep loess, volcanic ejecta, alluvium, colluvium, gravels, partly consolidated sands, and debris from mass movements (Selby, 1982). Unlike rills, gullies are relatively permanent features (Graf, 1979), almost always associated with accelerated erosion and therefore landscape instability (Harvey, 1974).

Gullies undergo oscillations of depth; periods of erosion are followed by periods of aggradation especially in extreme arid environments (Heede, 1974). Changes of this nature have been observed by Emmett (1974). In areas of heavy intense rainfall, gullies can supply a large amount of sediment (Grant, 1982), where they form partly in response to such high intensity rainfall events. Both rills and gullies will continue to be an important focus for sediment production in all environments.

Mass wasting. Not all slope transport processes are dependant on water to deliver sediment to the channel. Certain processes are a result of gravity alone, although moving water can be an effective trigger mechanism in many cases. The assemblage of processes dependant on gravity as an energy input are collectively termed mass wasting processes. The traditional types of mass wasting are illustrated in figure 2.2.

As Gregory and Walling (1973) indicate, "....mass movement must be included within a study of the slope phases of fluvial processes both for the

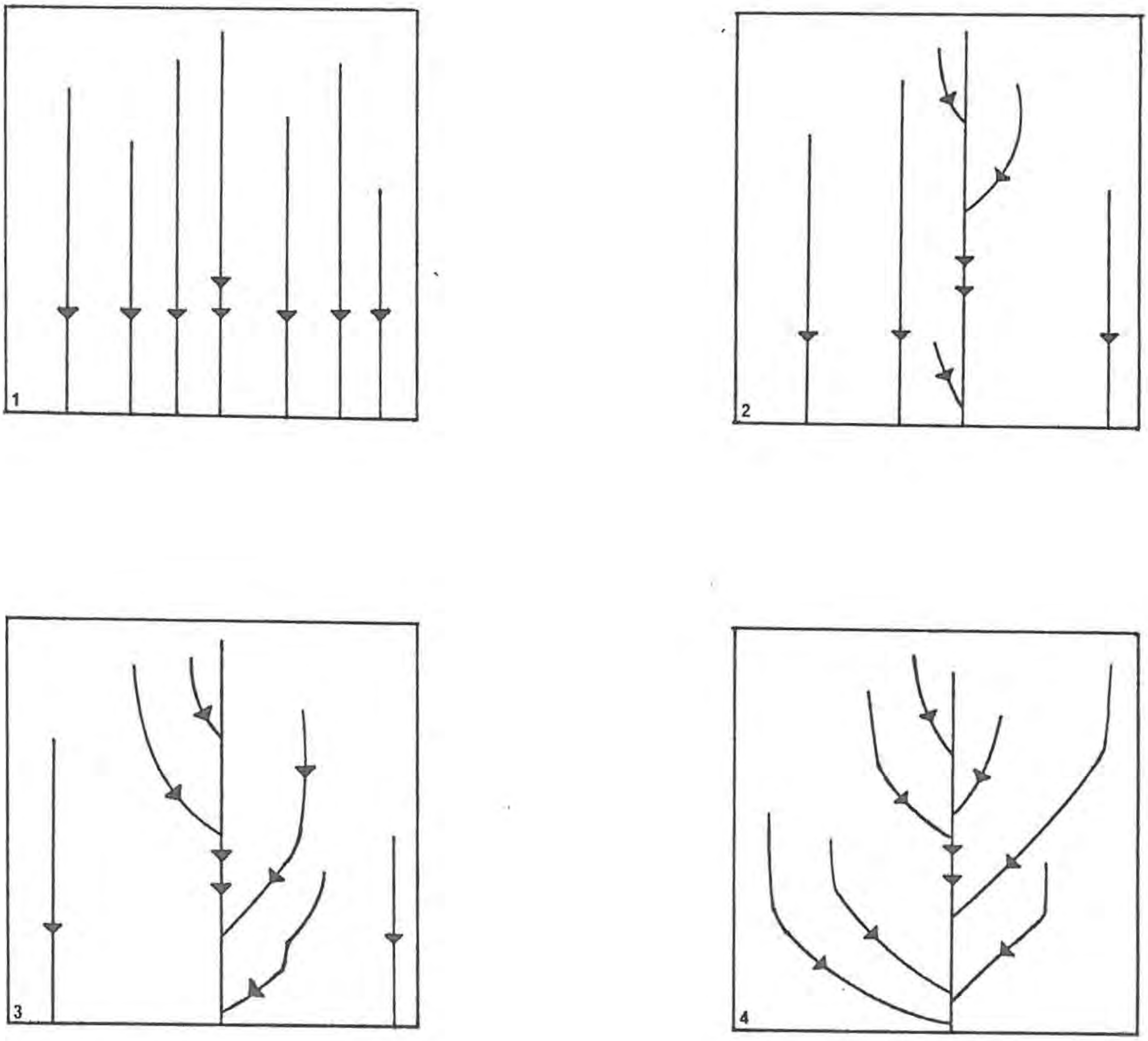

Figure 2.1. Hypothetical stages in the development of a master rill by cross-grading as it enlarges its valley. Diagrams show succesive periods of rilling, with only the master rill reforming in the same position (Carson and Kirkby, 1972. p. 194).

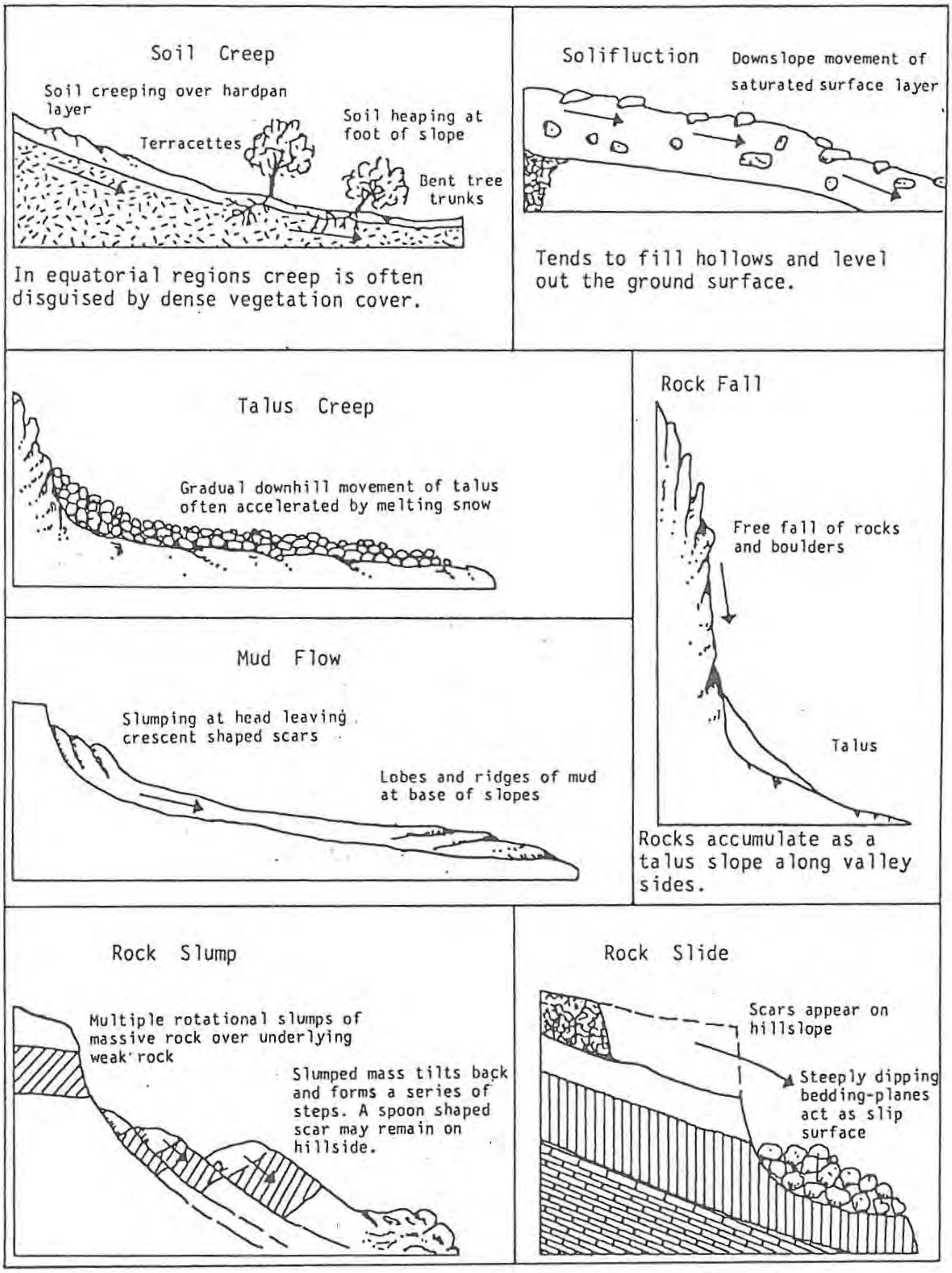

Figure 2.2. Types of mass wasting (after Buckle, 1978. p. 71).

purposes of comparison to its efficacy with sheet and gully erosion, and its capacity as a supplier of material to the stream at the base of the slope" (p 148). Mass movement will be an unimportant supply process in many areas. Emmett (1965) has shown it to constitute less than 1% of the amount contributed by sheet erosion in the south-western United States. It is in areas characterised by steep and unstable slopes that this form of supply process can deliver considerable amounts of sediments to the channel.

Carson and Kirkby (1972) have undertaken an in-depth investigation of mass movements as slope processes and their classification in diagrammatic form of mass movement processes (figure 2.3) is useful for 3 reasons:

i) all mass movements fall into three main groups - heave flow or slide,

ii) the diagram indicates relative rates of movement, and

iii) the moisture content of the movement is also indicated.

Soil creep is the slow downslope movement of superficial soil or debris, imperceptible except under long term observations (Selby, 1982). Many authors indicate a seasonal fluctuation with peak movement during the wet season, usually most marked within 1 m of the surface of soils and diminishing progressively with depth (Carson and Kirkby, 1972). Terracettes are probably the most important surface feature attributed to soil creep (Young, 1972). Measurements indicate that common creep rates downslope are between 0.1 and 15 mm. $yr.^{-1}$ in vegetated soils (Selby, 1982). Leopold, Emmett and Myrick (1966) have indicated that downhill creep is an important process capable of supplying 38,3 ton. $km.^{-2}$ $yr.^{-1}$ in semi-arid areas.

Solifluction is the downslope movement of a saturated surface layer of rock and soil debris (Rapp, 1967). It is a term usually applied in periglacial areas (Clark and Small, 1982).

Talus creep is a very slow process (Smith, 1983). Moon (1984) found talus creep to be a major process in the development of slope forms in the fold mountain areas of South Africa. It is the gradual downhill movement of talus occurring on the lower slopes closer to the channel, at times accelerated by water (Buckle, 1978).

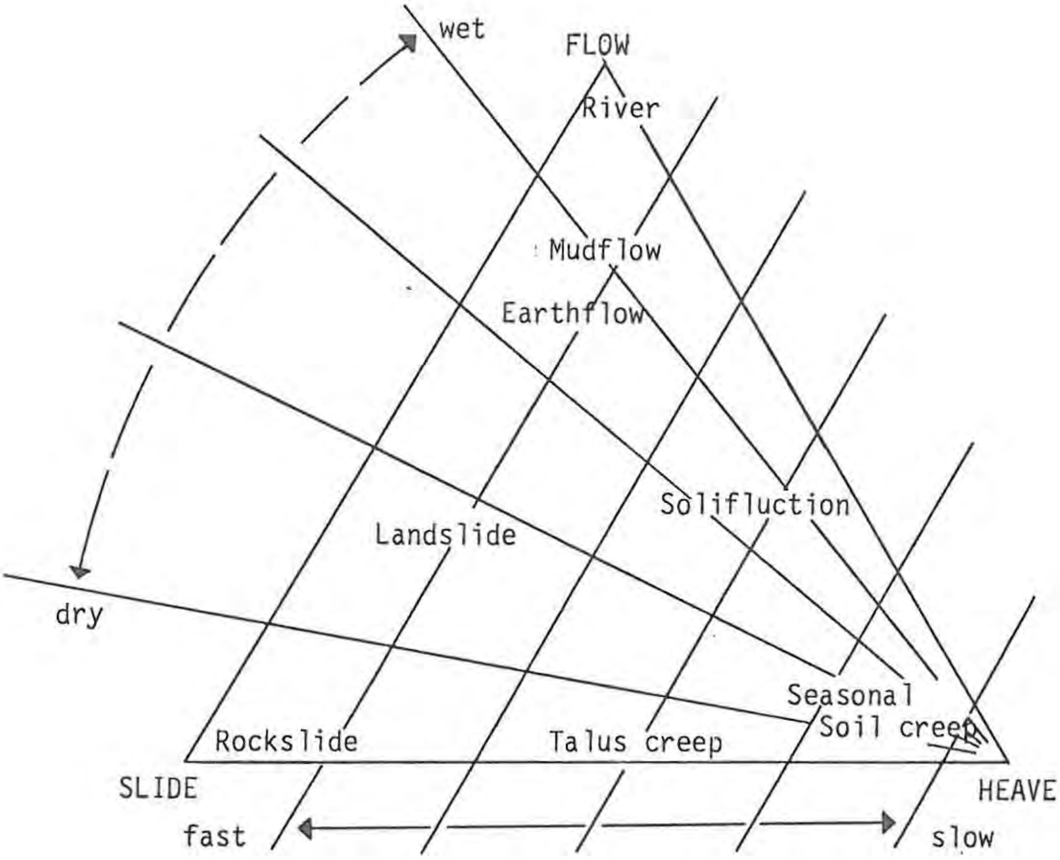

Figure 2.3. A classification of mass movements (after Carson and Kirkby, 1972. p. 100).

Mud flow has been observed in arid and semi-arid areas. It occurs when large volumes of unconsolidated material, super-saturated after heavy rain, became plastic and flow over short durations. Kelsey (1980) has documented the importance of this process in the Californian Coastal ranges where average annual sediment yield from mudflow is about 24 165 ton. $km.^{-2}yr.^{-1}$. Mud flows can also occur on steep slopes of streams and gullies draining areas where vegetation and soil have been damaged (Croft, 1967).

Slumping very often involves large masses of rock and debris, occuring usually on over-steepened slopes (figure 2.2). Where they occur on channel banks they are capable of supplying enormous amounts of sediments instantaneously (Carson and Kirkby, 1972).

Rockslide, although capable of moving vast amounts of material, do not have to be seen as the movement of large sections of a slope en masse. Very often, smaller rock particles can slide individually across dipping bedding planes in response to disturbances by wind or animals. Krammes (1960), in a study in arid California using metal troughs laid on contours, discovered that 87% of the debris moving downslope was contributed during non-rain periods by dry sliding. Because they occur more frequently after heavy rain, wetter conditions can initiate a period of landsliding (Clark and Small, 1982). Where large scale slides occur, they introduce large amounts of sediment to the channel, but on a very infrequent basis. The smaller scale sliding investigated by Krammes (1960) contributed small amounts of material but on a more frequent basis.

Rockfall and toppling take place on the steepest bare rock slopes (angles greater than 40°) and cliffs, where detached fragments will fall and bounce rather than roll or slide (Selby, 1982). Assisting this process is the rapid weathering of weak underlying rock (shale, mudstone) which leaves an unsupported overhang below the harder rock (Koons, 1955).

In all the above processes of mass wasting, it is important to realise that the critical factor determining the relative importance of events of different magnitude and frequency is the magnitude of the threshold stress, or force, necessary to initiate the process (Carson and Kirkby, 1972). Many of the processes demand a threshold stress so large that they occur only rarely and are of catastrophic nature (Coates and Vitek, 1980). The resistance of the landscape to withstand stress is often a function of time, in which the progressive weakening of a solid mass through the extension and enlargement of joints is achieved (Carson and Kirkby, 1972). It should be noted that not all the processes mentioned above are relevant in any one area. The processes dominant in one region may not necessarily be the same as in another environment.

2.2.3 Channel Processes

Documenting channel processes will allow a measure of insight into sediment behaviour in channels, and serve as a useful background to the present study. The bed and banks of river channels can serve as sediment stores of material derived from slopes which may make considerable amounts of sediment available during streamflow events of sufficient magnitude to allow sediment entrainment (Campbell, 1977a).

Channel bed erosion occurs when the flow of a stream has the ability to transport much more of the available sediment than it is already carrying (Colby, 1963). Erosion is achieved mainly through channel scour by the coarse bedload of the stream. The fine material load transported by the channel is not usually eroded from the channel bed itself, but from adjacent land surfaces by overland flow (Colby, 1963). The coarse bedload is broken down through collision by the process of attrition and thus a further source of fine material is produced (Newson, 1971). Lane and Borland (1953) have concluded that the bed of a river (in their case the Rio Grande) is generally not scoured through its entire course. They found that scour occurs mainly in the narrow sections and that most of the material thus removed is deposited in the next wide section downstream as channel bars. Thus, the sediment in a channel bed, while being highly mobile, may only be moved from one temporary storage (a channel bar) area to another, a short distance downstream, during one event.

Bank erosion can occur either directly during floods by fluvial action, or by undercutting and subsequent collapse due to gravity. The latter process is frequently observed in gullies cut in loosely consolidated material. Lewin, Cryer and Harrison (1974) have documented the process of bank collapse as a major sediment source for rivers flowing through alluvial floodplain areas. Moore (1984) has indicated that the erodibility of channel banks will increase between storms as sediment has time to dry. Many of the authors who have documented research on channel erosion worked in humid areas with gravel bed channels and unconsolidated flood-plain deposits. Bedload then often exceeds suspended load due to the limited amount of weathered material transported on the slopes and the large amounts of unconsolidated post-glacial till eroded by the river itself.

A general summary of channel`transport is given by Colby (1963). Briefly, the peak concentrations of fine sediment may not coincide with the peaks of flow, and the largest runoffs do not necessarily produce the highest concentrations of fine sediment. The concentration of coarse sediments increases as discharge increases during a single event, largely because velocities tend to be higher and flow more turbulent at high discharges. It is important to note here that channels can serve for extended periods as storage containers for coarse sediment derived from adjacent slope areas or tributary channels. This is especially true for ephemeral channels in semi-arid and humid areas alike (Rooseboom and Harmse, 1979).

Deposition occurs in the stream channel because of a local or general reduction in the transporting ability of the stream. Transporting ability is reduced where velocity and turbulence are locally reduced behind obstacles, in backwater areas or at the inner edges of bends in the stream channel. In general, deposition occurs when more sediment is brought into a stream reach than can be transported through the reach by within-bank flows. Channel deposits can act as sediment sources during subsequent high flows.

2.3 Sources of sediment

Recent investigations indicate that most sediment inputs are derived from a comparitively small area of the basin (Campbell, 1977a); Gregory and Walling, 1973). The concept of limited sediment contributing areas appears to be applicable to basins in different climatic regimes. The individual research results referred to in this section are often site specific and the present scope of knowledge on the sources of sediment does not appear to be adequate enough to enable general conclusions to be made. However, if an improved conceptualisation of the system of sediment movement within drainage basins can be determined, then the established soil loss and sediment supply models may require revision.

Until about 1960 most quantifications of sediment production re-distributed the sediment load, measured at the basin outlet, mathematically back onto the watershed (Roehl, 1962). Recently authors have become more specific about the precise location of sources. Gottschalk (1962) suggested that channel erosion is dominant in the semi-arid and arid areas of the United States, implying that the channel itself is an important source area at the time of a flow event. However the sediment which is transported to the channel during non-flow periods by rainfall events of lesser magnitude are derived from the adjacent valley sides. Therefore the channel, in semi-arid areas, seems to serve as a temporary store where sediment accumulates until a later flow event. Leopold, Emmett and Myrick (1966) report that for a semi-arid area (New Mexico), measurements have shown that by far the largest sediment source was sheet erosion operating on the small percentage of area near the basin divides. In all probability, this area served as a source at times of low magnitude rainfall events at which time sediment was transported to the channel for storage.

Carson, Taylor and Grey (1973) have observed the importance of channel bank scour in the 82 km^2 Eaton Basin in the Appalachians. Lewin, Cryer and Harrison (1974), working in Mid-Wales, report that most sediments are derived entirely from streambank bluffs cut into soliflucted valley deposits during high flows by direct bank undercutting. In the case of the Red Deer Basin (Alberta) Campbell (1977b) has recorded the relatively minor proportion of basin area from which sediment is derived. The channel banks and valley sides comprising about 2% of the basin were the major contributors. This rather restricted area of sediment yield is believed by some to be typical of most basins (Gregory and Walling, 1973). Rhoades, Welsh and Coleman (1975) found that 51% of the sediment yield in the basin they studied derived from 1% of the area. Bowie, Bolton and Spraberry (1975) have shown that about 40% of the sediments in some northern Mississippi drainage systems came solely from channel erosion.

In a study of the Hodge Beck catchment in England, Imeson (1974) refers to the important role of unvegetated areas and river channels as sediment source areas. He indicates that sediment load data may be related to specific sources, particularly in zones of accelerated erosion. However, this relationship is more difficult to define where erosion approaches the geologic norm and where several potential sediment source areas exist. Kelsey (1980), in the north coastal California area identified source areas as being the adjacent slopes on which landslide activity moved sediment to the channel. Dickinson and Wall (1977) expressed concern that the delineation of erosion source areas and sediment contributing areas are receiving only preliminary investigation. There is a need to identify the nature of these areas and their variability in space and time.

3. CHARACTERISTICS OF MID-LATITUDE SEMI-ARID ENVIRONMENTS RELATED TO SEDIMENT MOVEMENT.

When considering the specific form and composition of sediment, the movement of sediment from a specific geographical location with respect to the channel, and the various transport processes outlined in the previous chapter, it is clear that at any stage the actual supply of sediment to the channel can be affected by a wide range of factors. The discussion in Chapter 2 has already drawn attention to those factors relative to some specific processes. The present chapter summarises these factors in general before looking specifically at the characteristics of the semi-arid situation.

3.1 Summary of factors affecting sediment supply to channels.

The system of sediment supply to a channel can be investigated from two angles : The first, a) focuses on the physical factors which influence sediment supply while the second, b) examines the manner in which the physical factors in a) control the supply process at each stage of the sediment supply system.

a) Morisawa (1968) has illustrated the inter-relationships between some of the factors influencing sediment supply in diagramatic form (figure 3.1). The present study envisages a three level classification of the physical factors affecting supply. The aim of such a classification is an attempt to simplify the complex array of natural factors. Sediment supply can be seen as a chain of processes. The role of certain factors in the sediment supply chain are made more effective as a result of the inter-action of other factors higher up in the supply chain. It would therefore be inaccurate to give them equal status with those more prominent in the role of affecting sediment supply. The factors are therefore grouped into three classes, primary, secondary and tertiary sediment supply influencing factors (Table 3.1).

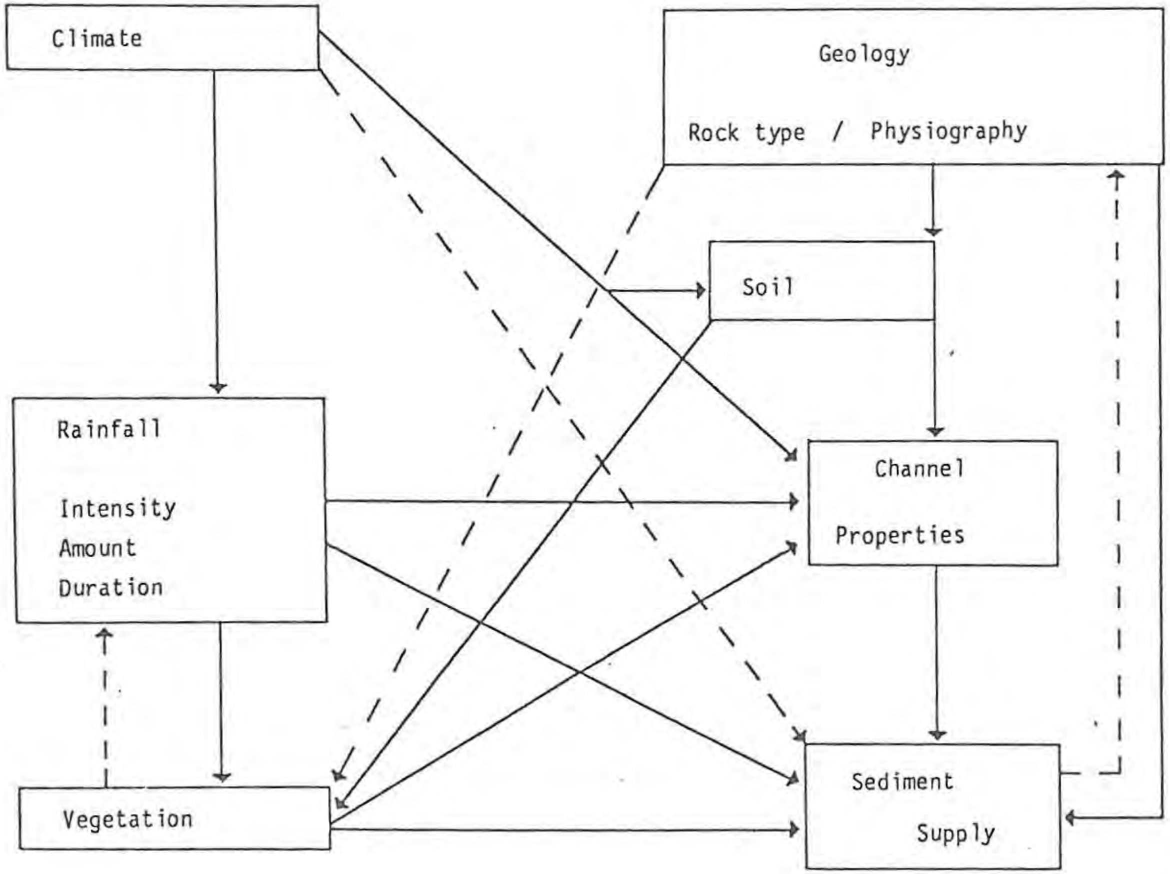

Figure 3.1. The inter-relationships between the main factors influencing sediment supply (adapted from Morisawa, 1968).

TABLE 3.1 A Three level Classification of some of the major factors affecting sediment supply.

Primary	Geology	Climate
Secondary	Soil type/Depth. Weathered material. Fauna and Flora. Rainfall intensity/amount. Drainage density/Pattern. Physiography. Dip. Aspect. Channel properties.	
Tertiary	Infiltration. Antecedent soil moisture. Raindrop impact. Ground temperature. Land use. Sediment availability. Evapotranspiration. Runoff. Soil cohesiveness and erodibility. Erosivity of rainfall. Slope angle. Kinetic energy of rainfall event.	

The primary factors are geology and climate. The inter-action of climate and geology govern the secondary effects lower down in the hierarchy of the factors influencing sediment supply.

Secondary factors are either subsets of one of the primary factors (rainfall intensity or dip for example) or subsets resulting from the interaction of the primary factors (soil type or drainage pattern for example). Tertiary effects result from interactions between any of the effects higher up in the classification. They represent the fine detail that has to be understood before sediment movement processes can be adequately characterised. Some of them are relatively time independant (slope angle for example) whereas many of them vary as climate varies over short time scales. At such scales climate is perhaps better referred to as weather.

The above hierarchical classification is only tentative and does not constitute a "complete model". It is not always simple to clearly define boundaries between what are secondary and tertiary factors. Therefore the classification serves only as an example of one possible method of categorising sediment supply factors.

Climate and geology influence sediment supply in their ability to govern vegetation cover, amount of water available for weathering, temperatures, seasonality, winds, rock chemistry, jointing, mineral composition, physiography and the ultimate form of sedimentary material. At the secondary level, soil type and depth influence the amount and ease with which sediments are able to be removed, the type of weathered material available and the susceptability of material to removal. Fauna and flora influence the surface structure, soil cohesiveness, erodibility and erosivity of rainfall events. The role of aspect and physiography are similar in their influence on ground temperature (and therefore soil moisture), slope angles and velocity of runoff. Drainage density, pattern and channel properties largely determine the ability of the drainage system to remove sediment either out of the system or to a location further down the channel reach. Rainfall intensity and amount, with soil infiltration and moisture status, affect the amount of runoff available, the energy available for sediment removal and the kinetic energy of the storm. Dip of strata determines the exposure of bedding planes and joints to weathering agents.

The factors at tertiary level are necessarily more direct in their role. The measurement and assessment of the extent of their effectiveness is often difficult to achieve. Infiltration, antecedent moisture, raindrop impact, soil cohesiveness and erodibility, ground temperature and evapotranspiration all influence the surface properties of the ground from which sediment could be supplied. The variation of slope angle, landuse and sediment availability influence the potential amount of sediment available for supply. Where these factors are favourable, more sediment will ultimately be supplied. Any variation in the kinetic energy and erosivity of rainfall events also bring about a variation in the eventual amount of sediment supplied.

The interrelationships between some of the above factors are illustrated in figure 3.2. Not all the factors are included because of the complexity of their interrelationships. The diagram illustrates how the interaction of certain factors can give rise to further factors that influence sediment supply. For example, rainfall amount and intensity determine erosivity and the effectiveness of raindrop impact. Depending on slope angle and infiltration capacity, rainfall amounts of varying intensities give rise to runoff and sediment supply. The diagram, although not pretending to be complete, is more comprehensive than figure 3.1.

b) Section a) above proposed a three level classification of the factors which can affect sediment supply. In this section a simple sediment supply system is proposed comprising 4 interleading phases of sediment supply (figure 3.3). Firstly, weathering of bedrock and the preparation of sediment for transport to the channel takes place. The second phase considers the amount and frequency of water on the slopes able to transport sediment, while the actual movement of that sediment by water or gravity falls into phase 3 of the supply system. Phase 4 details the removal of the slope transported sediment at the base of the slopes or in the channel. At each phase of the system it will be found that certain of the factors outlined in a) above could play a role. Some factors may be applicable to only one phase while others relate to more than one phase.

The two angles of investigation outlined above are part of the same sediment supply system. Table 3.2 combines the two approaches illustrating how each phase of supply in b) (above) can be influenced by the factors in a) (above).

The purpose of breaking down the sediment supply system into the 4 phases and combining each phase with possible influencing factors is twofold: Firstly, to simplify and describe what might otherwise be a complex system in order that the relationships which do exist between influencing factors at each phase of the supply system be clarified. Secondly, clarification of the above and a simple understanding of the process of supply is necessary in order that the model proposed in chapter 4 be based on clearly understood underlying relationships.

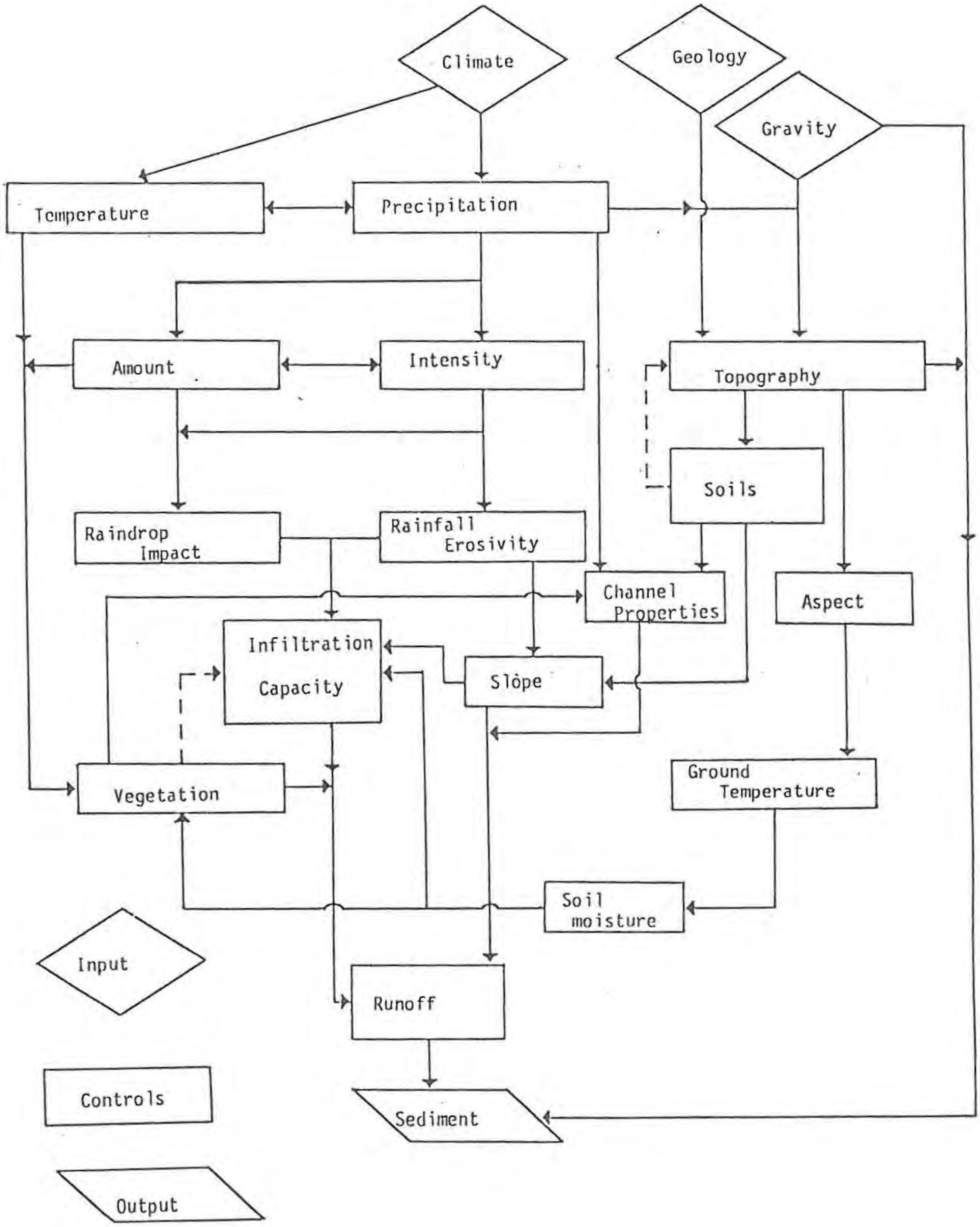

Figure 3.2. Factors influencing the amount and rate of sediment production in a fluvially dominated landscape.

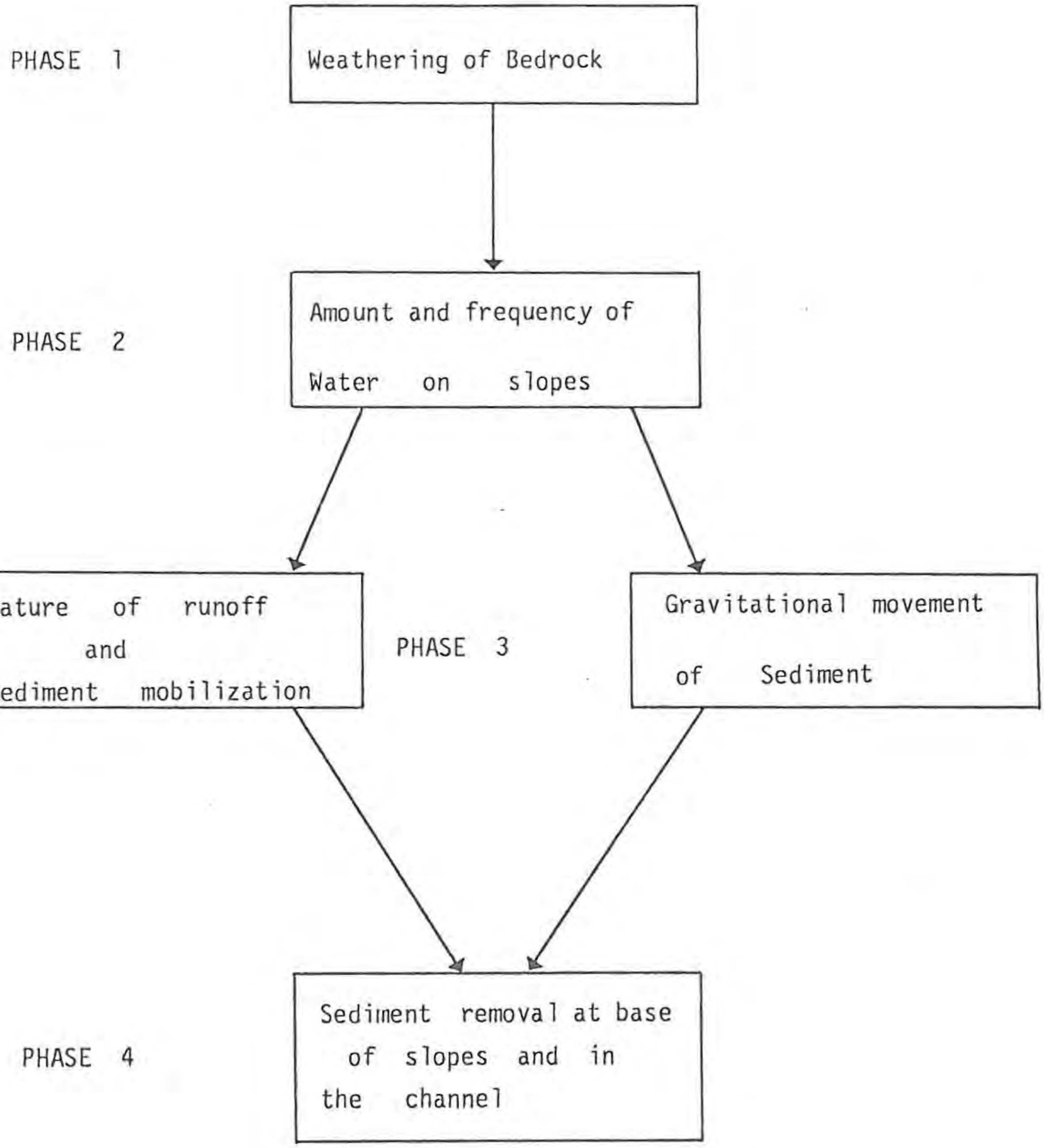

Figure 3.3. A simple sediment supply system.

TABLE 3.2 Factors influencing the supply of sediment at each phase of the sediment supply system. (See figure 3.2)

Phases of Supply Process		Factors affecting Phases	Relevent references
Phase 1	Weathering	Rock type/jointing/dip of strata biota/temperature/temperature range/moisture availability	Ollier, 1969; Chorley, 1969a; Carroll, 1970; Imeson, 1974; Clark & Small, 1982; Selby, 1982.
Phase 2	Amount & Frequency of Water on Slopes	Vegetation/temperature/rainfall amount/rainfall intensity/soil depth/topography/temperature/ physiography/micro-climate/ aspect/infiltration capacity	Emmett, 1970; Arnett 1971; Dickinson & Wall, 1977; Imeson, 1977; Kirkby, 1978; Morgan, 1979; Selby, 1982.
Phase 3	Nature of Runoff on Slopes/ Movement of sediment by Gravity	Slope angles/infiltration capacity/surface texture & armouring/size of weathered fragments/ rainfall type/antecedent soil moisture/moisture content of particles/vegetation/land use/ surface roughness/soil & particle cohesiveness/angle of repose of particles	van Burkalow, 1945; Schumm & Hadley, 1957; Allen, 1965; Kirkby, 1969; Osborne & Lane, 1969; Ahnert, 1970; Fleming & Poodle, 1970; Benedict, 1970; Imeson, 1971; Engelen, 1973; Gardner 1979; Walling, 1983; Moon, 1984;
Phase 4	Sediment removal at base of slopes & in channels	basin size/basin shape/rainfall characteristics/drainage network /stream frequency/drainage density/condition of channel/hydraulic geometry of channels	Coldwell, 1957; Maner, 1958; Gottschalk, 1964; Guy, 1970; Campbell, 1977b; Walling & Webb 1982; Carling, 1983; Graf, 1983; van Sickle & Beschta, 1983.

3.2 Characteristics of mid-latitude semi-arid environments.

The following discussion of semi-arid environments is dealt with under four major headings :

a) Rainfall
b) Evapotranspiration
c) Vegetation and lithology
d) Hydro-meteorological characteristics related to sediment movement

a) Rainfall in semi-arid environments has been shown to be of a very sporadic nature (Campbell, 1977a), while often being fairly concentrated in space (Thornes, 1977). The total amount of rain received from year to year is of a highly variable nature (Leopold, Emmett and Myrick, 1966). In general, annual rainfall totals in semi-arid areas are low and unreliable (Campbell, 1977a). Although semi-arid areas are sometimes located in winter rainfall areas where they receive rain from mid-latitude cyclonic disturbances over a wide front, the type of rain commonly encountered in most semi-arid areas is characteristically of high intensity derived from very localised convectional storms (Thornes, 1977). Convectional type rain results in higher kinetic energy values and semi-arid areas have been described as high energy environments (Campbell, 1977a). Infiltration rates can be exceeded and surface runoff on slopes appears to be a more common phenomenon than in humid environments (Campbell, 1977b). The volume of water on the slopes able to transport sediment increases rapidly, a situation which favours rapid erosion in semi-arid areas where the type of lithology and amount of vegetation are conducive to high erosion indices. The nature of surface runoff being partly controlled by rainfall type can vary considerably in time and space, so that the ground surface of semi-arid areas is constantly altered.

b) As a result of reduced cloud cover amounts in semi-arid areas, the amount of solar energy received at the ground surface is very high, especially during the summer months (Lettau and Lettau, 1973). Ground temperatures are high and in association with the dry air over these regions, potential evapotranspiration is also high (Barry, 1973). There is a general excess of potential evapotranspiration over rainfall. The high evaporation rates from both the surface and deeper soil layers through the action of capillary moisture rise, results in lowered soil cohesiveness because of the absence of the binding action of the water. Antecedent moisture levels are lowered and the ground surface is vulnerable to wind and water erosion. Thornes (1977) has noted the presence of crusts at the surface, while they may also occur at deeper levels. The infiltration capacity is reduced because of these crusts and surface runoff begins sooner, making the rainfall event more effective in its erosive ability.

c) Low rainfall and high evaporation give rise to sparse vegetation cover, little grass to bind the soil, and poor soil development. As a result, the ground surface characteristically has low infiltration rates (Thornes, 1976). Once again, high intensity rainfall leads to an excess of rainfall intensity over infiltration capacity and high levels of slope surface runoff (Yair and Klein, 1973). The ground surface is highly sensitive to erosion (Campbell, 1977b) and these regions typically display high erosion rates (Kirkby, 1969). As a result drainage densities in semi-arid areas have been found by Melton (1957) to be among the highest in the world.

d) The nature of rainfall, high evapotranspiration rates and surface characteristics in semi-arid areas results in few streamflow events each year (Slayter and Mabbutt, 1964). The runoff itself displays a highly erratic nature and runoff for a single event may exceed the total amount for all other events in that year (Görgens and Hughes, 1982). Table 3.3 illustrates the poor relationship between rainfall and runoff for semi-arid and arid basins in South Africa. The high levels of slope surface runoff and concomitant tributary flow do not necessarily lead to streamflow in the main channel (Thornes, 1977; Schumm and Hadley, 1957), as water is lost to surface retention in the dry valley areas. This apparent lack of accordance of tributaries and main channels appears to be an important characteristic of semi-arid drainage systems. Hydrologic studies in the Cheyenne River basin have shown that a large percentage of runoff from headwater areas is lost in the channels before reaching a master stream. Discharge is reduced in a downstream direction due to channel absorption (transmission losses) in the stream beds, leading to deposition of sediments as the flow is dissipated (Schumm and Hadley, 1957). The result is channel aggradation and a lack of accordance. Channel aggradation is regarded as being due to a deficiency of water in relation to sediment (Schumm and Hadley, 1957).

TABLE 3.3 The relationship between rainfall and runoff in some South African basins.

Catchment or region	Total area (km^2)	MAR* (x10^2 m^3)	MAP (mm)	MAR/MAP (%)	MAR as % of total South African MAR
Orange between Bethulie and Vaal confluence	33 605	196	363	1.61	0.38
Lower Orange	313 625	204	225	0.29	0.40
Doorn and Sout	45 765	449	188	5.22	0.88
Western Coastal Region (Namaqualand)	28 890	71	130	1.89	0.14
Breede	15 425	2 026	651	20.18	3.95
Gouritz	45 300	674	249	5.98	1.31
Gamtoos	34 500	567	277	5.93	1.11
Sundays	21 110	297	340	4.14	0.58
Great Fish	30 275	580	423	4.53	1.13

Source Görgens & Hughes, 1982.

Associated with the erratic nature of runoff, sediment yield can be highly variable (Graf, 1983) and very intermittant (Thornes, 1977). The study of sediment movement in semi-arid environments is complicated by the fact that fluvial activity is concentrated in several runoff events each year (Campbell, 1977b). Sediment appears to be moved through the channel system by a series of storm events. Each storm event entrains sediment from the stream bed, banks and flood plain, transports it some distance downstream, and deposits it again.

Thornes (1977) has documented the presence of inset channels within the main channel. Their presence is attributed to the variation in magnitude of runoff events and the intermittant nature of sediment movement (or local re-distribution of sediment) in the channel. The inset channels are most likely a response to smaller runoff events. Thornes (1977) claims furthermore that in ephemeral channels, a flow event of a different magnitude and frequency to a previous one may be instantaneously imposed on an existing morphology. There appears to be no constant time-continuous adjustment between channel form and flow, as in humid areas. Thornes (1977) indicates that ...." i) channel morphology overall is a function of a major flood; ii) detailed morphology reflects the history of scour and fill since the flood, and iii) this history is spatially variable so that morphology in one part of the channel is the response to a different history of flow events from that in another part of the channel" (p. 323)

It has been suggested in preceeding paragraphs that there appears to be a ready store of sediment in semi-arid areas. Many authors attribute the excessive amount of available sediment to an extended recovery period (Walling and Webb, 1982; Campbell, 1977b). The extended recovery period can be attributed to the sporadic nature of rainfall and runoff events (Walling and Webb, 1982). The high suspended sediment load of rivers in semi-arid areas (Renard and Keppel, 1966) supports the idea of an extended recovery period, during which sediment is made available for transport in the channel.

As a general conclusion it could be stated that runoff events are more infrequent than rainfall events in semi-arid areas (Görgens, 1983; Table 3.4). Therefore sediment movement in channels is more infrequent than sediment movement to channels (or on slopes). Recovery periods between storms are extended because of the sporadic nature of rainfall. A consequence of the above is that sediment availability could be high even after sediment removal events.

TABLE 3.4 Rainfall and Flow data for a semi-arid catchment near Grahamstown.

SUMMARY OF AVER. CATCH. RAIN ABOVE Q9M21(MM)

Period of Record Jan. 1975 to Dec. 1981

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
75	10.0	45.9	52.5	8.7	2.4	47.4	11.7	14.6	95.4	1.9	16.3	56.7	364.00
76	63.8	77.6	145.7	10.4	24.8	11.8	37.5	9.4	16.7	64.5	35.9	23.1	521.00
77	14.0	139.5	26.1	55.0	66.4	5.5	2.5	9.4	32.1	6.3	76.6	104.2	538.00
78	55.5	27.3	33.1	112.2	15.9	22.7	2.3	10.7	13.9	78.1	36.9	49.9	459.00
79	48.6	82.7	14.3	3.0	45.0	24.4	193.9	121.6	29.1	49.0	13.2	12.5	637.00
80	33.2	37.0	43.8	27.2	1.0	28.0	1.8	10.7	30.7	25.6	69.8	37.4	346.00
81	39.1	16.6	115.0	10.1	56.9	10.6	0.4	62.9	22.3	64.5	30.8	52.3	481.00
%Total	7.9	12.7	12.9	6.8	6.3	4.5	7.5	7.1	7.2	8.7	8.4	10.0	100.00

Mean Annual Rainfall = 478.0mm

SUMMARY OF OBSERVED FLOWS AT Q9M21 (THOUS.CUB.MET.)

Period of Record Jan. 1976 to Dec. 1981

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
76	5.1	0.6	67.4	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	73.00
77	0.0	12.5	15.5	0.5	28.8	0.0	0.0	0.0	0.0	0.0	0.3	7.4	65.00
78	3.2	0.0	0.0	17.5	0.0	0.0	0.0	0.0	0.0	0.1	0.3	0.0	21.00
79	0.0	2.2	0.0	0.0	0.0	0.0	444.6	405.5	138.9	11.8	3.5	0.0	1007.00
80	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	2.0	3.00
81	0.0	0.0	5.0	0.0	0.3	0.0	0.0	0.5	0.7	6.7	0.3	3.9	17.00
%Total	0.7	1.3	7.4	1.5	2.5	0.0	37.5	34.2	11.8	1.6	0.4	1.1	100.00

Mean Annual Runoff = 197.7 THOUS.CUB.MET.

Source: Görgens, 1983

4. A QUALITATIVE MODEL OF COARSE SEDIMENT SUPPLY TO A SEMI-ARID CHANNEL REACH.

The problem of modelling semi-arid catchment sediment responses to rainfall inputs is one which has been receiving attention in recent literature. Thornes (1977) has drawn attention to the various techniques and approaches adopted in the past (p. 329). Walling (1983) has indicated that the simple sediment delivery ratio which expresses the ratio of sediment yield to gross sediment production within a basin (Gregory and Walling, 1973; p. 204), must be replaced by a more realistic model. Such an approach should recognize the various processes involved in the movement of sediment from the source area through the basin system to the outlet, and take account of spatial variability within the system and various time constants involved. Wolman (1977) claimed that in 1977 there was still some way to go before attaining such a goal, but that it was then possible to specify processes that must be included.

Two models which can serve as examples of earlier approaches are referred to here. Fleming & Poodle (1970) drew up a model of sediment transport processes from source areas to the channel and then out of the basin (figure 4.1). However. sediment movement and transport sequences are likely to be more complicated than this model suggests. Fleming & Poodle do not take account of sediment storage in the various locations, which if included would lead to a more comprehensive model. Selby (1982) has modelled an erosional system on rock slopes which takes more factors into account. Selby's model is particularly fitting for use in semi-arid regions because the lithologies are often characterised by bare rock or talus mantled rock slopes (figure 4.2). Selby's model, however, does not allow for any variation in the rates of process operation. the amounts of sediment going into storage with each event nor the amount of rainfall required to initiate the various processes. As such it lacks a dynamic component.

The model proposed in the present study, while initially a static one, incorporates a dynamic component. A static model could not possibly describe the variation of magnitude and frequency of rainfall and runoff events outlined in the previous chapter. If however a dynamic component is added, it becomes possible to vary the scale of the event by adjusting the

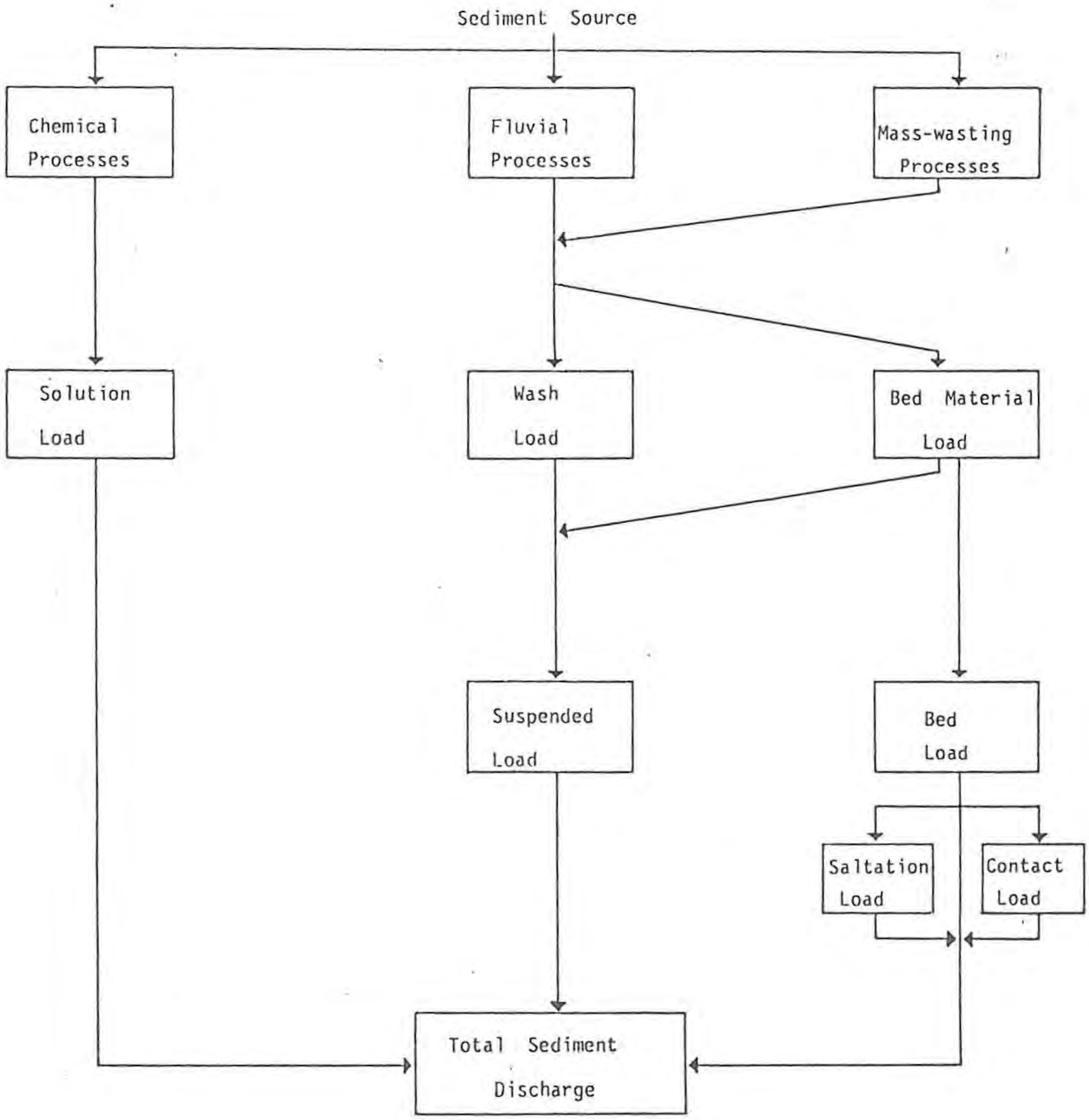

Figure 4.1. Sediment transport processes (after Fleming, 1970. p. 434).

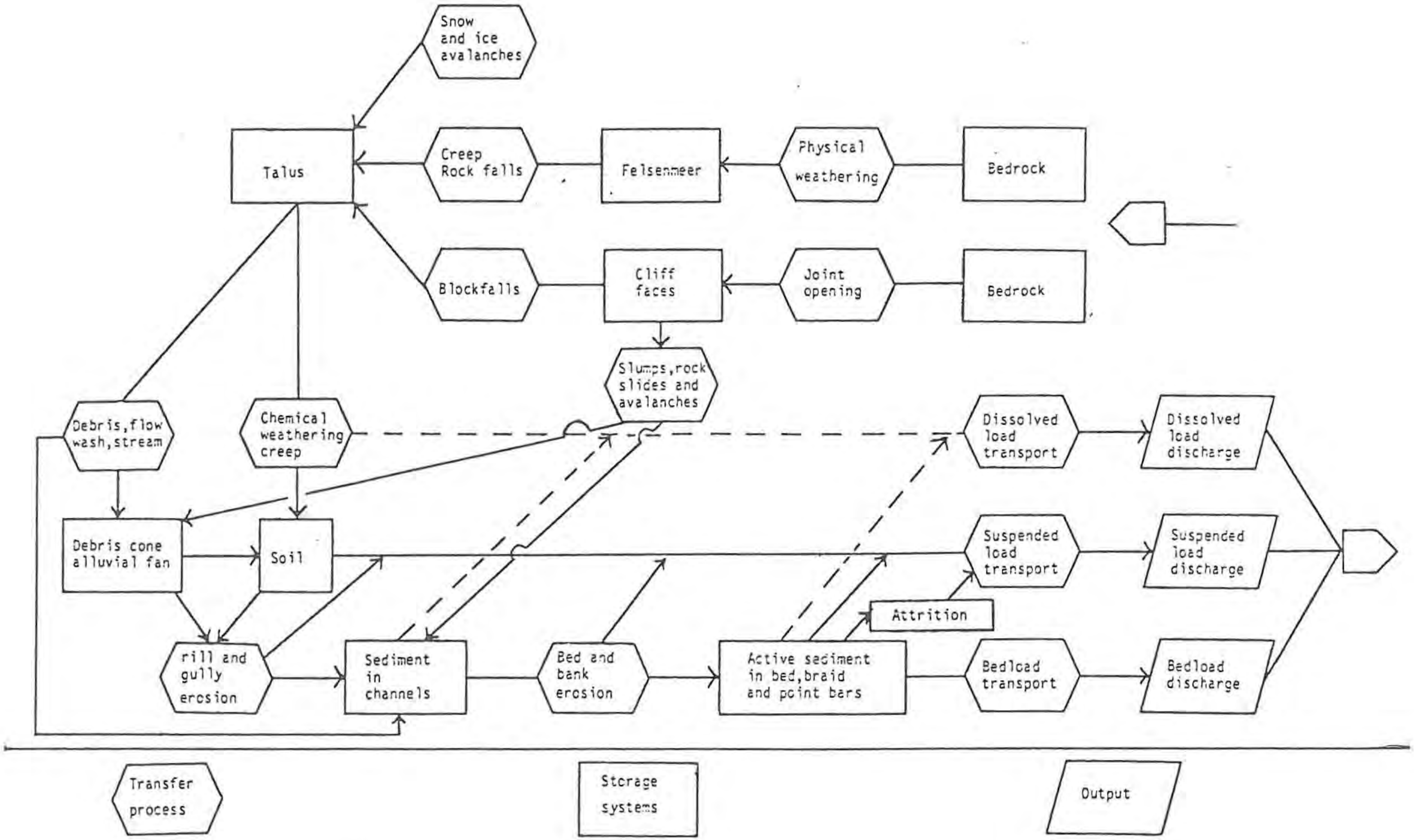

Figure 4.2. The system of stores and transfers on rock slopes (after Selby, 1982. p.2).

level of processes, additions and removals from stores and sediment transport.

In order to formulate the desired model, firstly an understanding of the internal conceptual structure of a sediment supply system and how it operates under different types of external processes is required. This has largely been outlined in chapters 2 and 3. Secondly, in order to include a dynamic component, an understanding of the effects of a sequence of events (time series) of external forces (e.g. rainfall) is needed. These are inferred from supporting literature.

The model proposed (figure 4.3) concentrates on representing the system of sediment supply as an association of inputs, processes, stores and outputs. It is a conceptual representation similar to approaches used elsewhere, particularly in hydrology (Stanford Watershed Model, Crawford and Linsley (1966)). Lewin and Hughes (1980) have applied a similar conceptual approach to water movement on flood plains during overbank inundation.

The model proposes four initial inputs. Climatic inputs act on geological inputs through weathering processes to produce <u>in situ</u> storage. No transport processes are involved at this stage. The processes of slope transport (gravity and fluvial) then operate to deplete the <u>in situ</u> storage. It should be noted that the distinction between gravity and fluvial processes is not always clear as water can influence gravity movements (chapter 2), and fluvial processes themselves are not independent of gravity. Transport processes move sediment down through a series of secondary slope storages until eventually sediment reaches the channel storage element.

The channel storage component can be incremented by bank erosion which can act on <u>in situ</u> slope storage, secondary storage and flood plain stores. The bank erosion process described in figure 4.3 is over-simplified for convenience.

The output or channel phase of the model is specified as being out of the channel reach. By implication, channel sediments can be transported to stores further down the channel and not necessarily out of the channel system. In this way, the intermittant nature of channel sediment movement

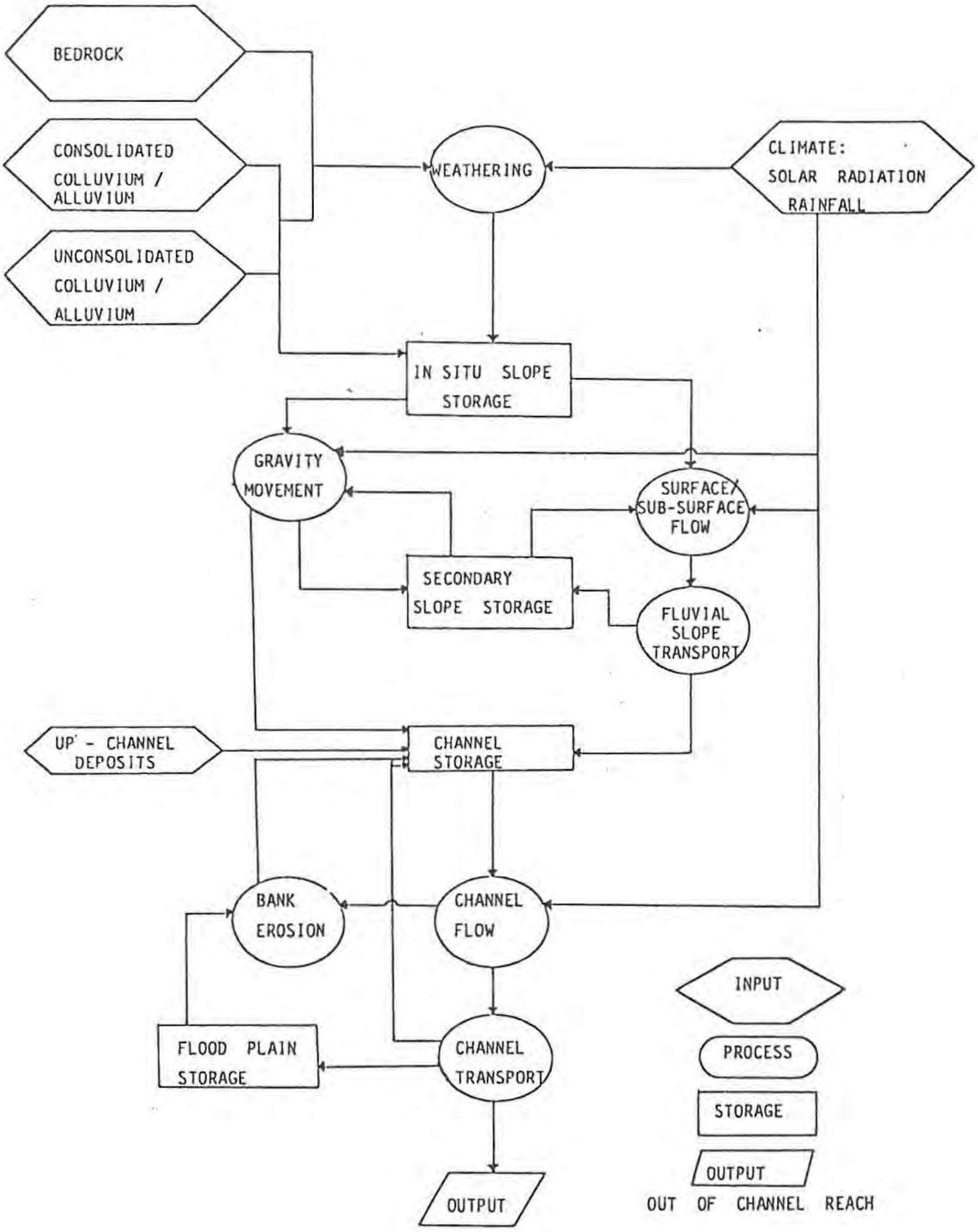

Figure 4.3. Coarse sediment supply model for a channel reach.

is recognized, allowing for the possibility of a further source of sediment to increment channel storage, that of up-channel deposits.

The number of components in the model that can be affected or brought into operation during any given 'event' depend largely on the magnitude of that 'event', as well as antecedent moisture conditions and antecedent sediment storage conditions. Figures 4.4 a - d illustrate the level of operation of the various components during the hypothetical 'event' types A - D which are defined below. These 'event' types represent the dynamic component of the model and should be seen only as examples in a continuum of possible 'event' types. Furthermore, the shading is used to indicate relative levels of activity and should not be interpreted in a quantitive manner.

A-type event. (figure 4.4a) An A-type event represents the system during ineffective or no-rainfall periods. Weathering and gravity movement (possibly through channel bank collapse) are the only active components. Net addition to stores occur.

B-type event. (figure 4.4.b) These events have an insufficient amount of rainfall to generate flow in the main channel. Various processes are active in moving weathered material downslope through a series of stores and eventually to the channel. Sediment availability is increased.

C-type event. (figure 4.4.c) Channel flow occurs after a substantial period of negligible channel activity. The accumulated stores are largely depleted and because of a high sediment availability factor, sediment loads are high.

D-type event. (figure 4.4.d) A significant main channel flow event occurs after an earlier channel flow event of a magnitude sufficient to remove a large part of the accumulated sediment. The semi-depletion of the stores in the previous event leads to a lowered sediment availability factor. The resultant stream load may therefore be considered as being more 'availability' limited than 'transport' limited, a situation which can lead to channel erosion. However, addition to slopes continues to take place due to slope processes remaining active during such an event.

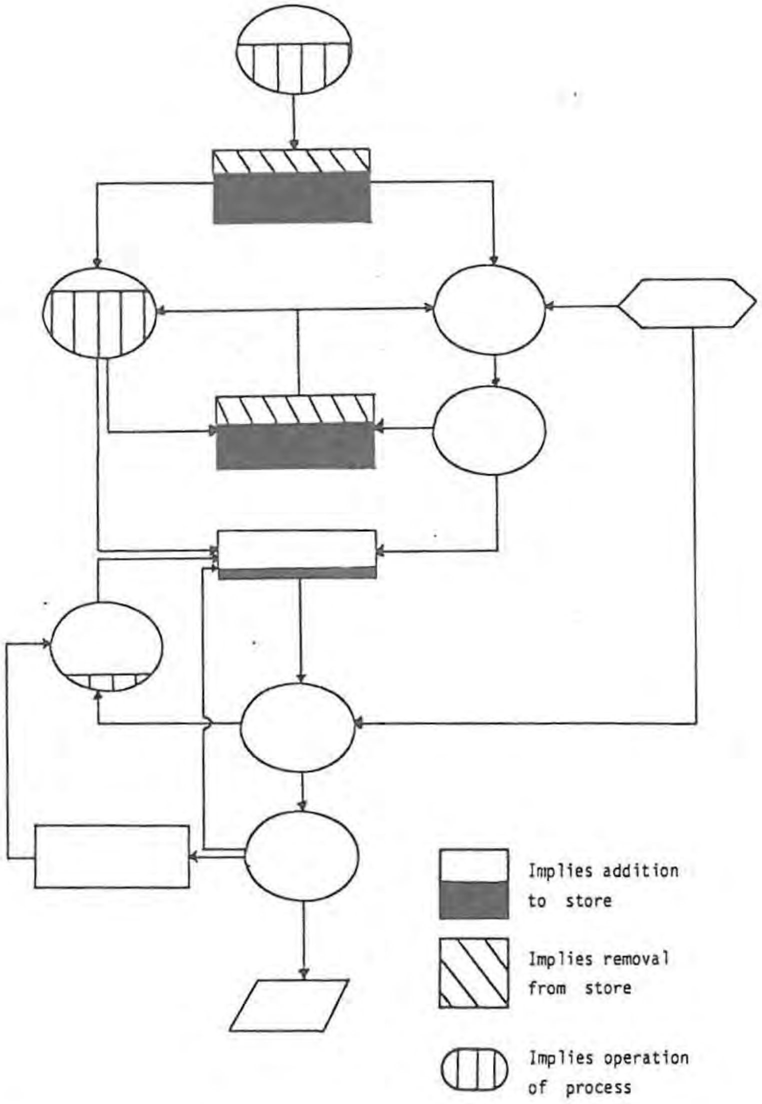

Figure 4.4a. No rainfall period.

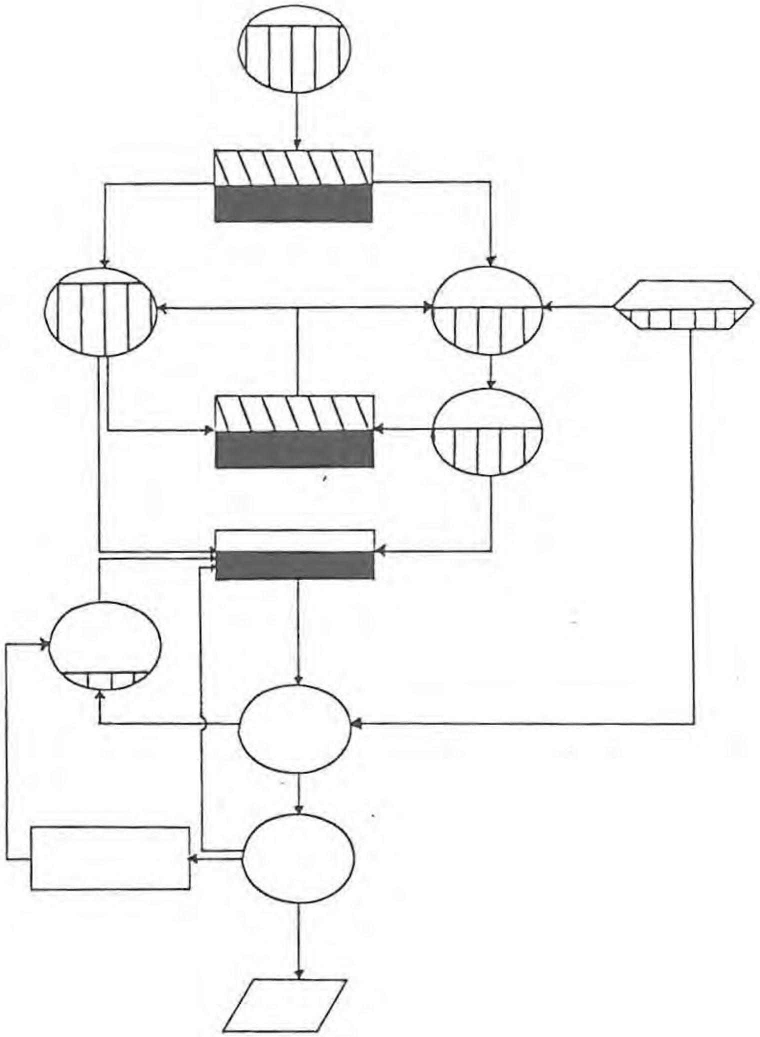

Figure 4.4.b. Low rainfall events but negligible flow in the channel.

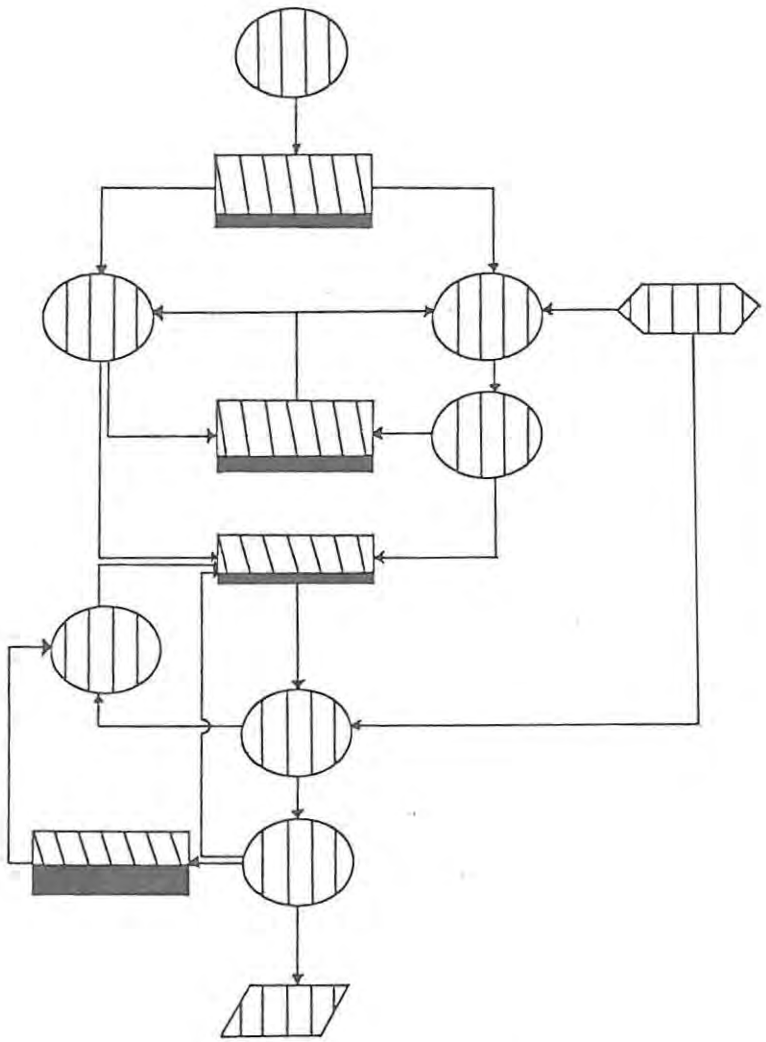

Figure 4.4c. A streamflow event following a period of little channel flow activity.

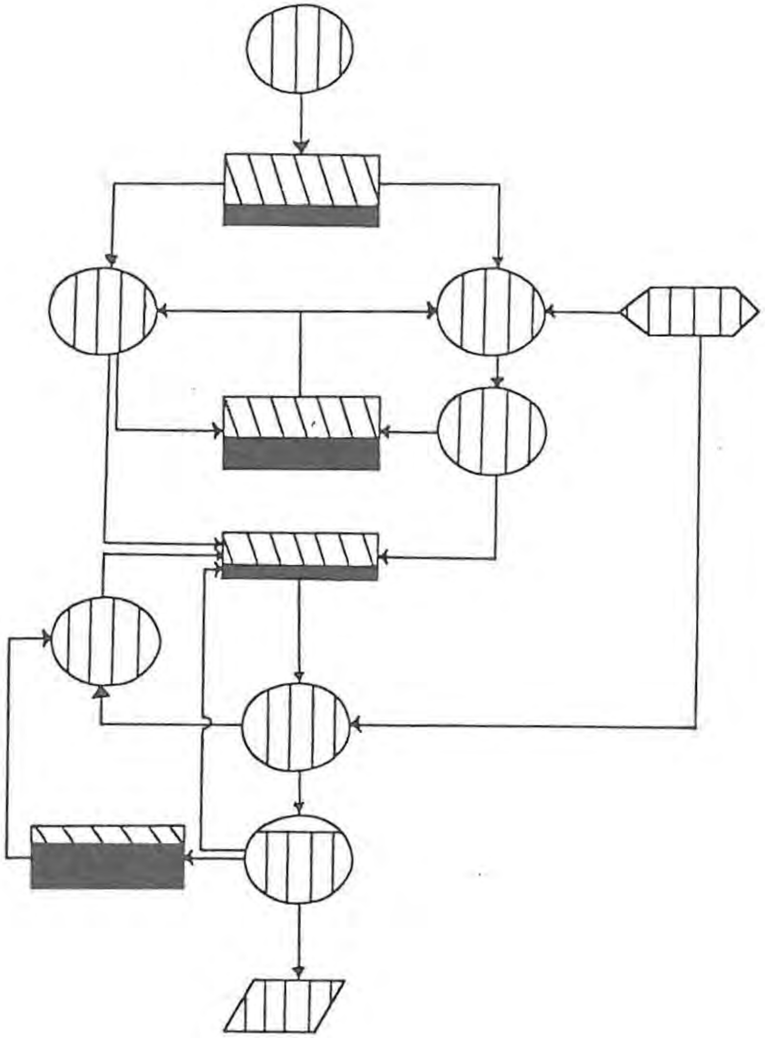

Figure 4.4d. A streamflow event following soon after a previous event of active channel sediment movement.

The model described above is very generalised and makes no reference to the magnitude, frequency and duration of 'events'. Thus the situation is avoided in which an individual rainfall event in its own right could constitute a model, relevant only to that specific rainfall event. However, equally important is a consideration of the sequence of events, which in the semi-arid situation can be highly erratic. Figure 4.5 illustrates a possible sequence with reference to the event types A - D above.

With the passage of time the storage component increases whilst A- and B-type events occur (see figs. 4.4a and 4.4b), until such time as a C-type event (figure 4.4c) occurs. Depletion of stores takes place with concomitant high sediment yield from the channel reach. Further A- or B-type events serve only to modify the recovery of the storage component. A subsequent D-type event yields less sediment as less is available from the various stores, which are further depleted. Sediment availability (i.e. storage) is an important consideration because as Walling and Webb (1982) explain "....(the) model should incorporate a time-variant measure of sediment availability to take account of exhaustion effects operating both within multiple events and during a sequence of events" (p.335).

The sequence of events and their respective outcome outlined above are broadly supported in work published by researchers such as van Sickle and Beschta (1983), Moore (1984) and Walling and Webb (1982). The amount of sediment available to the first C-type event is not unlike the situation in truly seasonal regimes. The first event of a season could have a larger amount of sediment available than latter events (van Sickle and Beschta, 1983; Walling and Webb, 1982). The model would therefore appear to be applicable to erratic regimes as well as truly seasonal ones.

The following conclusions can be drawn for this chapter.

a) The model is qualitative and conceptual.
b) It is based on relatively well-documented ideas about processes as well as observations about the non-linearity and lack of fixed relationships between channel flow and sediment yield.
c) If such a model is to be used as a predictive tool it would need to be paramatised in mathematical form, calibrated and tested using a great deal of field data.

d) Consequently, this study is limited to collecting data that should help to confirm or deny the conceptual structure. The limited programme of field data collection that is possible during this study may indicate the relative scales of operation, but will not be adequate to totally quantify the model.

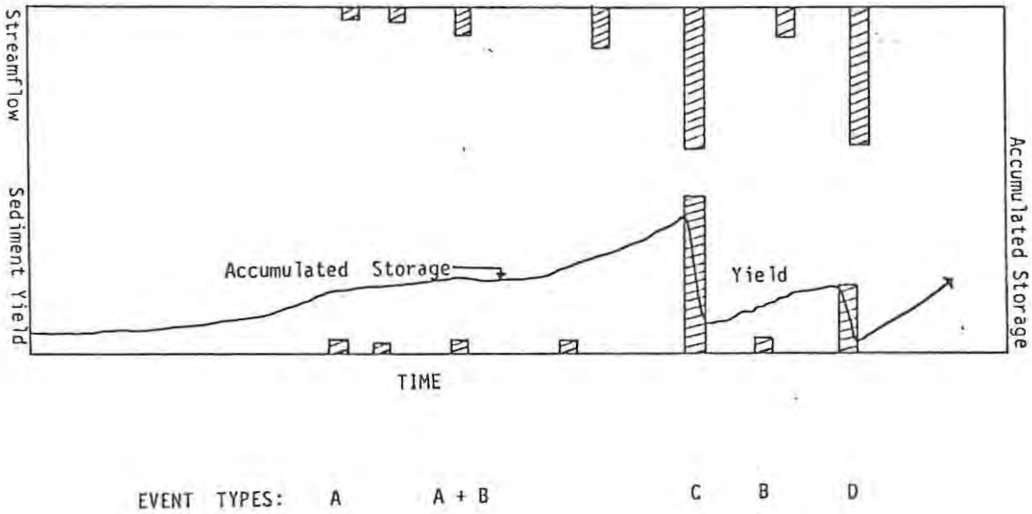

Figure 4.5. Possible sequence of event types (see text)

5. STUDY AREA.

5.1 Reasons for the choice of the study area.

The most important factors considered in the choice of a study area were:

a) The area should have a semi-arid climate with ephemeral channel flow but with well defined channel reaches.
b) The area should be well instrumented so that the hydrological input can be readily quantified.
c) The channel reach under study must be accessible.

A set of five nested gauged catchments on the Ecca river were established in 1975 by the Hydrological Research Unit (H.R.U.) of the Department of Geography at Rhodes University. The gauging network was set up in this area as part of a research project financed by the Water Research Commission to study rainfall-runoff relationships in semi-arid climates. The Ecca river is a tributary of the Great Fish River and the catchments are situated approximately 20 km north of Grahamstown in the Eastern Cape Province. (fig. 5.1). The catchments were initially instrumented with five flow measuring structures, ten continuously recording raingauges and two evaporation pans. Since 1975 the project aims have been broadened slightly to investigate processes of sediment production and water quality. The main consequence of these new aims with respect to the study reported here is that sediment accumulation behind the flow measuring weirs is monitored.

This area adequately satisfied the first two criteria referred to at the beginning of this section and it was straight forward to select a reach that satisfied the third criterion. The section of channel studied in detail is illustrated in fig. 5.1 and is immediately upstream of the gauging weir Q9M21. A continuously recording raingauge is located close by at BP02. The records from this station provided the rainfall amount and intensity data necessary for the study.

The entire Ecca catchment area has been well documented in terms of soils, vegetation, physiography and geology by Roberts (1978) and Görgens (1983).

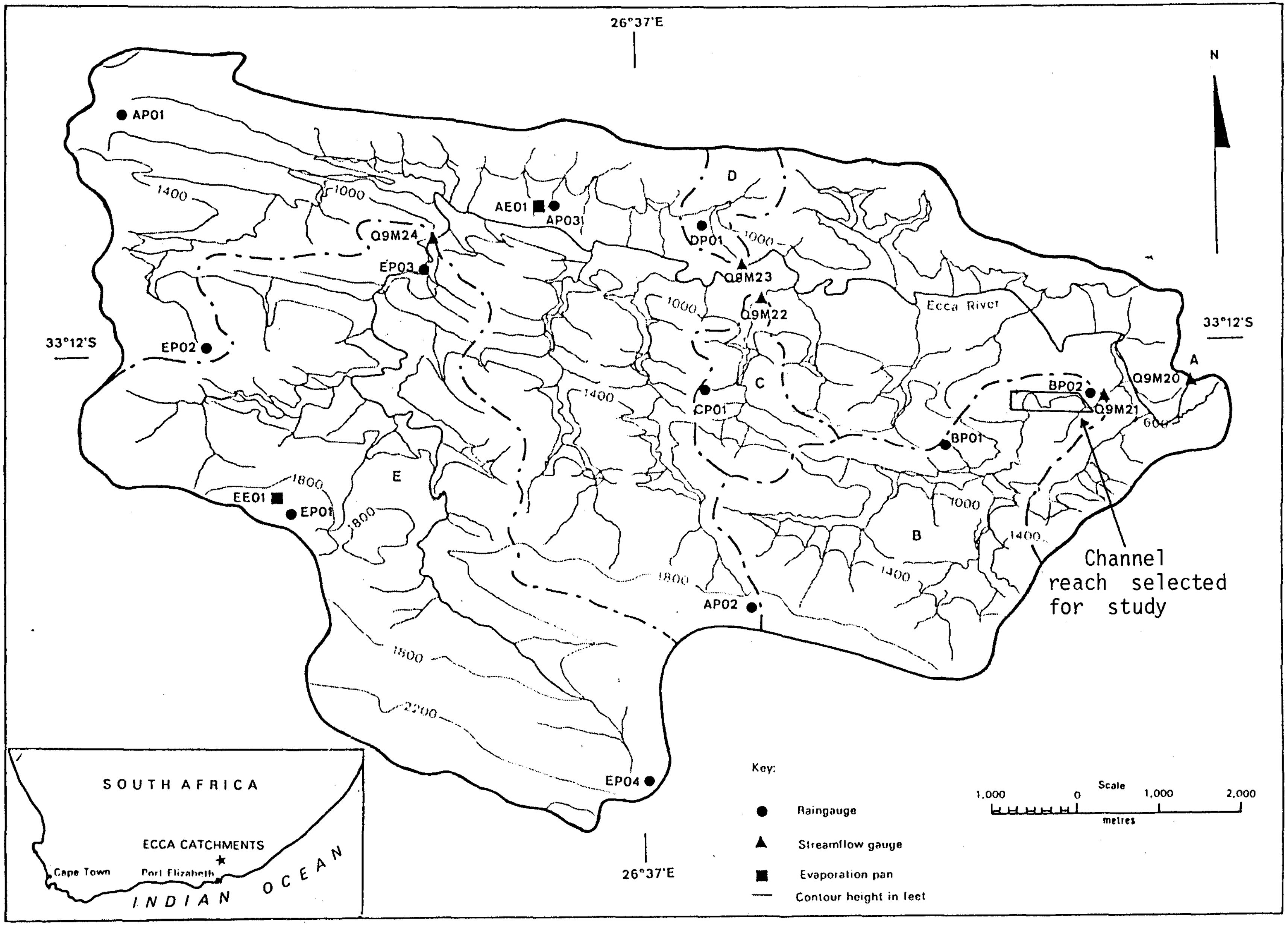

Figure 5.1. The Study Area (After Görgens, 1983).

The following description has been drawn from these two sources.

5.2 A brief description of the Ecca Catchment.

The complete Ecca catchment covers an area of approximately 73km^2 (Roberts, 1978). Three major rock units underly the region, the Witteberg group of the Cape Supergroup, the Dwyka formation and Ecca groups of the Karoo Supergroup (fig. 5.2). The channel reach chosen for the present study is underlain predominantly by hard grey siliceous shales of the Ecca group (fig. 5.3). The Ecca group does not consist entirely of shales, but also has alternating bands of sandstone (the Rippon formation), mudrock and shale. The area is characterized by extensive outcrops with only thin soils on the valley sides and hilltops. Relatively deep alluvial and colluvial soils occur in patches within some of the wider valley bottoms.

The area is highly dissected with steep valley side slopes. The main channels flow parallel to the strike and the tributaries form deeply incised valleys at right angles to the strike (Roberts, 1978 and figures 5.1 and 5.2 of this thesis). The slope categories for sub-catchment Q9M21, in which the present study reach is located, are shown in figure 5.4. Roberts calculated hypsometric curves for each sub-catchment and these are shown in figure 5.5.

The vegetation of the catchment has been described as Valley Bushveld (Karoo and Karroid Bushveld Types IV, Acocks, 1975). It consists mainly of tall sub-succulent woodland which thins to a low succulent scrub on the flatter areas, and appears to be reasonably uniform in type and density over the catchment (Roberts, 1978).

The climate over the catchment is relatively severe, with large differences between both daily and seasonal extreme and average temperatures. The mean annual rainfall is approximately 480 mm (with a standard deviation of 100 mm) while the mean annual free water surface evaporation has been estimated at 1362 mm (Görgens, 1983). Most of the rainfall (60% MAP) occurs in the summer during the months October to March. The winter rainfall is generally associated with large-scale frontal systems which move along the southern coast of the Southern Africa sub-continent. Much of the summer rainfall

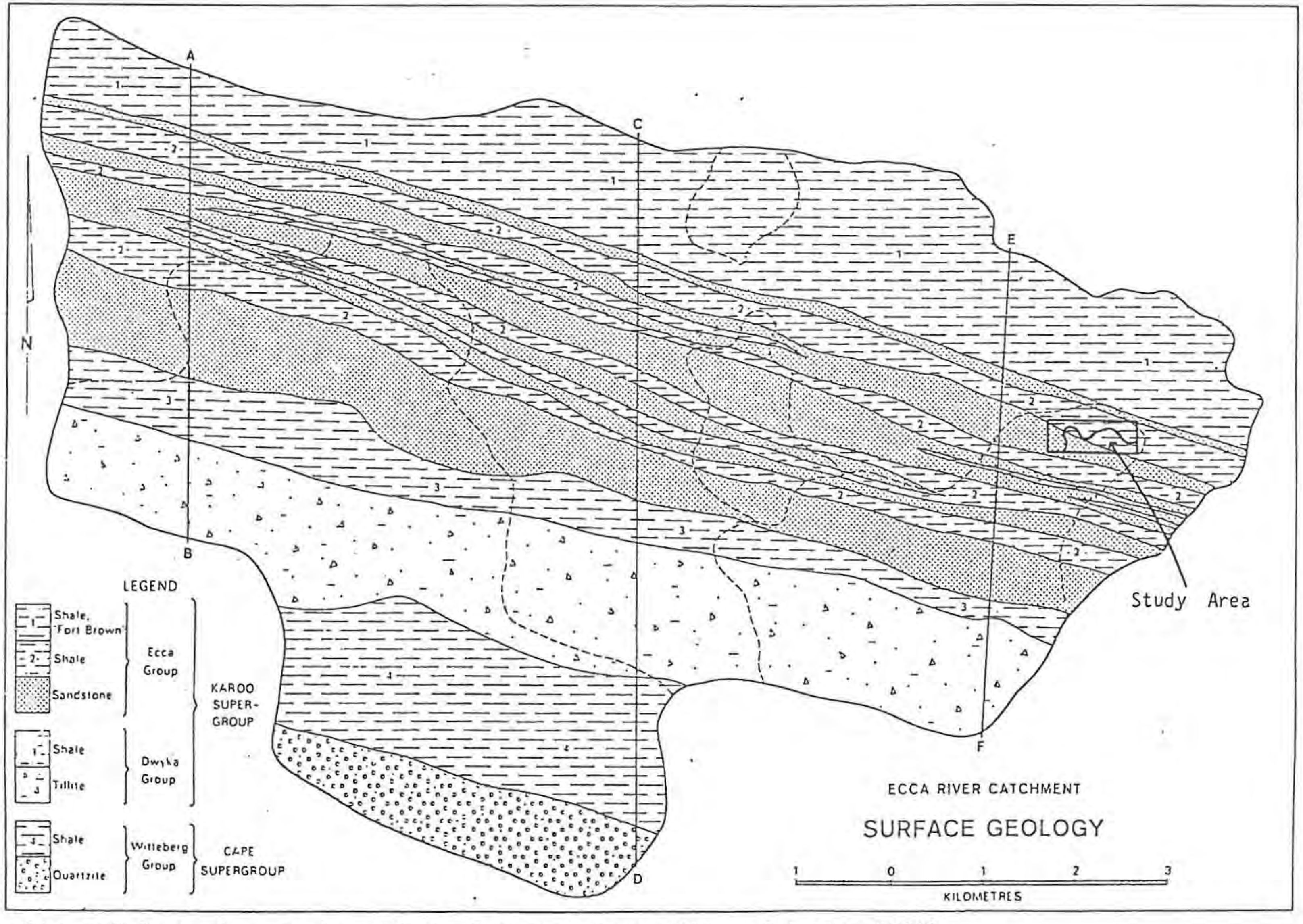

Figure 5.2. Surface geology of the Ecca catchments (After Roberts, 1978)

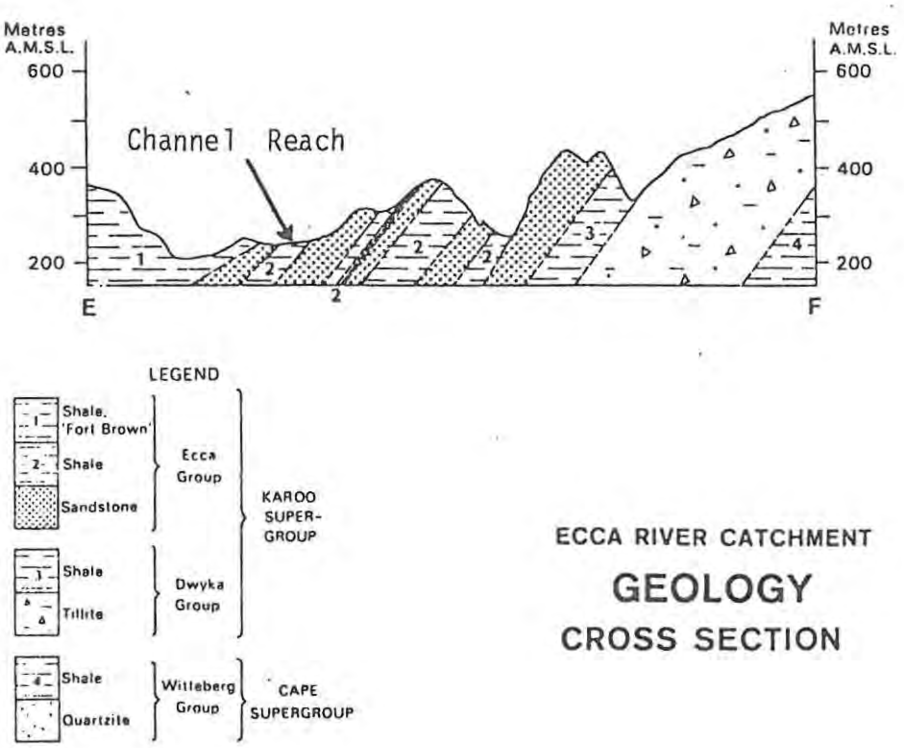

Figure 5.3. Geological cross-section of study area (after Roberts, 1978. p. 41).

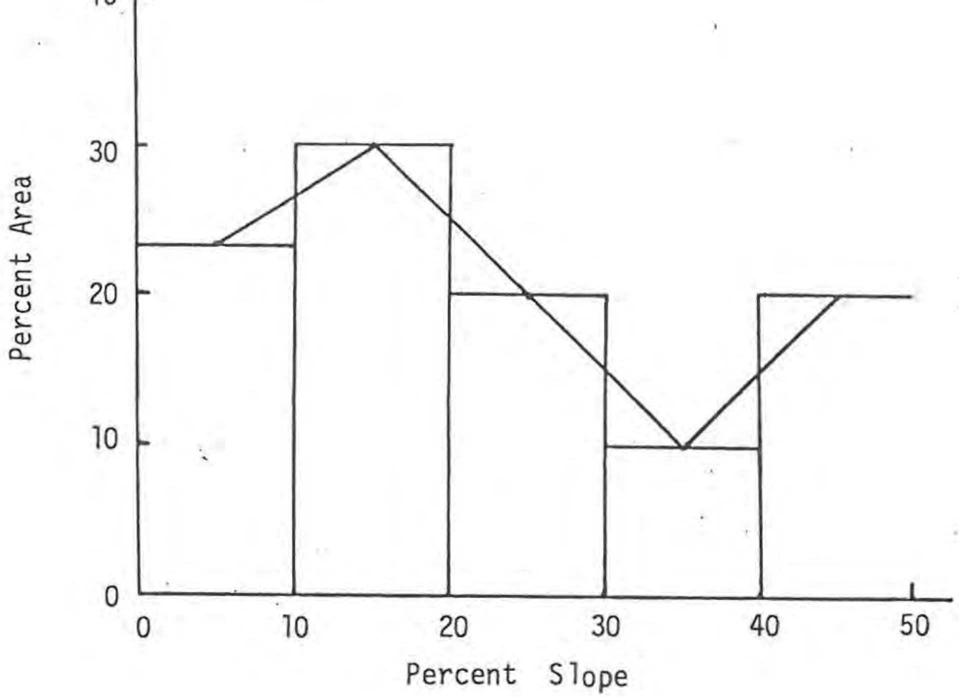

Figure 5.4. Slope categories for catchment Q9m21 (After Roberts, 1978. p.51).

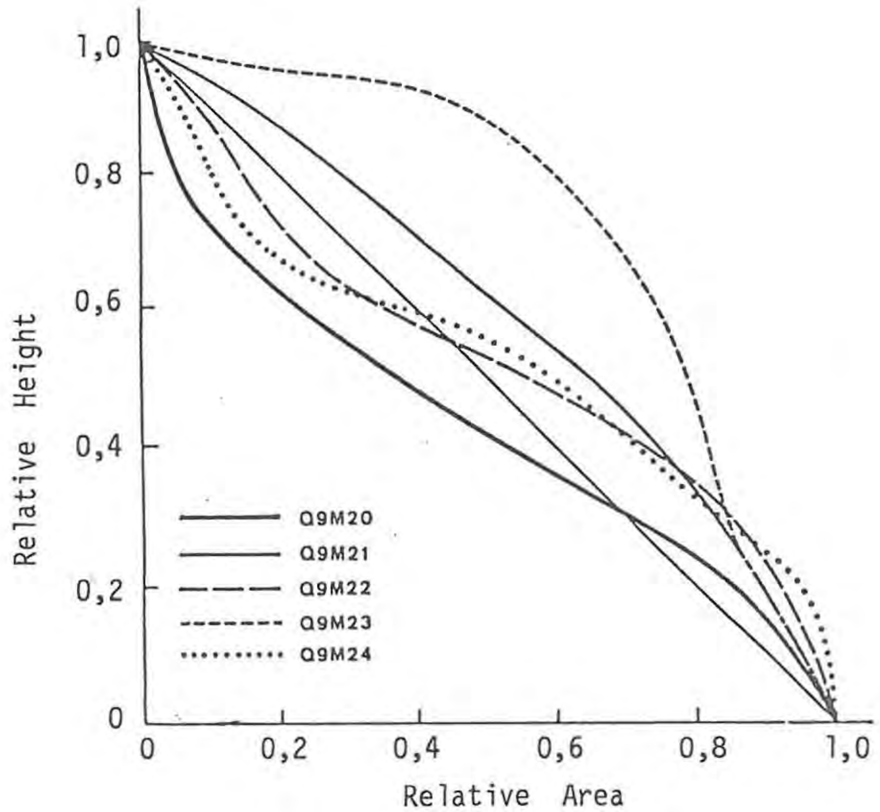

Figure 5.5. Hypsometric curves for the Ecca Catchments (After Roberts, 1978. p. 47).

occurs during convectional thunderstorms which often give rise to short duration but high intensity falls. The highest single storm rainfall amounts are associated with advected air moving in from the Indian Ocean and caused by offshore high pressure systems. These storms usually have lower intensity falls than convectional storms but are of much longer duration and have been the cause of the major flow events measured in the catchment since 1975. The available data from both Grahamstown and the Ecca catchments suggest that such storms can occur in any season (Hughes, pers. comm.).

5.3 The choice of a specific channel reach.

A channel reach within catchment Q9M21 was chosen as the specific reach for study due to the following reasons :

a) Experience within the HRU as well as data given in Görgens (1983) suggests that flows from Q9M21 occur more frequently than from other Ecca sub-catchments. It was therefore expected that a greater amount of channel sediment movement would occur during the study period within this section of channel.

b) The channel is readily accessible along the entire lower reaches.

c) The channel reach is located upstream of a flow measuring weir where limited sediment data is being collected.

d) The reach offers a variety of channel bank environments from which sediment might be produced.

e) The proximity of a raingauge and flow measuring weir provide the necessary hydrological inputs.

Figure 5.6 illustrates the section of channel with the specific sites chosen for detailed study. Cross-sectional profiles and the geological content of the banks are also given in figure 5.6 for each of the sites.

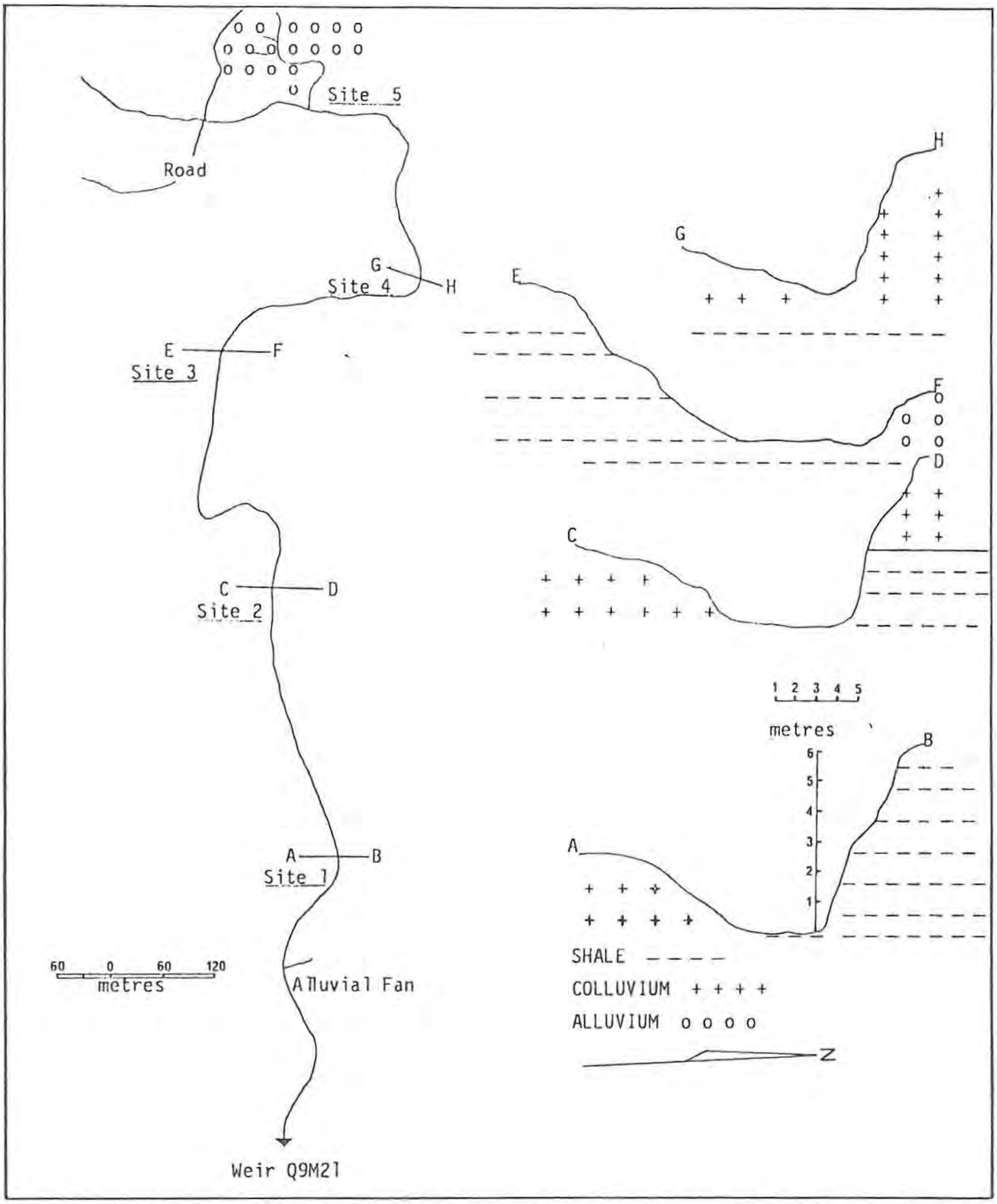

Figure 5.6. Channel reach under study showing location of data collection points and the channel cross-sectional profile.

Plate 5.1. A view of a section of the channel reach under study.

6. METHODS OF STUDY AND DATA COLLECTION.

6.1 Introduction

It remains a difficult task to achieve a comprehensive quantification of even a short reach of channel in terms of sediment production without disturbing the environment and therefore the sediment production to some degree. It is consequently necessary to achieve as much as possible with minimum disturbance of the sediment producing areas and processes.

A number of different methods have been employed by earlier workers to identify and measure rates of sediment movement. Patterns of sediment removal or accumulation can be detected by sequential photographic surveys but any quantification of amounts is difficult without sophisticated stereoscopic equipment (Lewin, Cryer and Harrison, 1974). Some measure of quantification can be achieved by the measurement of surface cross-sections and the geometry of channel beds and banks at regular intervals (Campbell, 1970. One common method of catching sediment has been in traps at sample locations (Krammes, 1960; Schick, 1967; Kellerhals and Bray, 1971; Gregory and Walling, 1973 and Harvey, 1974) while the use of erosion pins to measure both accumulation and erosion has also been a popular technique (Emmett, 1965; Leopold, Emmett and Myrick, 1966; Evans, 1967; Rudberg, 1967; and Gardner, 1979). A method of monitoring the movement both in the channel and on the banks, has been to mark loose accumulations of sediment or individual stones for use as tracers (Hadley, 1967; Rapp, 1967; Lewin, Cryer and Harrison, 1974 and Lewin and Wolfenden, 1978).

Studying sediment sources and movement in the field and especially designing a statistically valid sampling procedure is difficult unless the researcher has prior knowledge of the system and its operation. The best one can achieve, in a limited amount of time, is to sample points which are representative in terms of slope geometry, geology and active sediment producing areas. The measurement techniques used here are believed to be appropriate considering the limitations imposed upon the study by the environment as well as available resources. For example, in the present study area it is not possible to knock pins into solid rock or walk over steep slopes littered with loose shale.

The major aim of the fieldwork is to gather data that confirms or suggests modifications to various aspects of the model proposed earlier. If any measure of quantification of sediment production is possible and the relationships established are able to be quantified, this will enhance the value of the study. However, it must be remembered that while the conceptual model should be generally applicable, the specific quantitative results from this study may not be. Such results may be representative of other areas where the assemblage of factors affecting sediment movement operate in a similar way and at similar scales as in the Ecca catchment. Extreme care should be taken though in attempting to extrapolate quantitative results from one area to another when the system involved is complex.

The following sections discuss the data that are available in the study area, as well as the methods used to collect and analyse further information relevent to identifying several aspects of coarse sediment movement. The data collection methods were established in the Ecca catchment in order to monitor sediment movement over a two-year period. It was envisaged that the study area be visited on an approximate monthly basis in order to collect data. The data and methods are discussed under three headings; climate and catchment outflow data, in-reach sediment information and sediment particle characteristics.

6.2 Climate and catchment outflow data

The climate and channel flow data have been collected by the HRU as part of the rainfall-runoff hydrological research project. All rainfall records as well as channel flow data are available in the form of continuous-flow records. Autographic raingauges and water level recorders were established in the catchment in 1975 (fig. 5.1). Rainfall amount and intensity for any period can be extracted from the above records. They can be related to findings from sediment movement experiments in the present study to determine whether any relationships exist, thereby allowing for the verification, modification or rejection of the model.

An erosivity index (EI_{30}) is used in the present study as an indication of rainfall intensity. The erosivity index is calculated as follows: The kinetic energy values are calculated for each day of rainfall using the following formula:

$$KE = (8,7319 \times \log_{10} I + 11,8975) * I.T ;$$

where I is the rainfall intensity and T the time over which that intensity is constant. All the KE values are added up for the day and multiplied by $I_{30}/1000$, the maximum 30 minute intensity, hence EI_{30} values. The EI_{30} values for each day of rainfall between sample days are summed to give a value for the period, and recorded on the latter sample day. No EI_{30} values are recorded for days with rain of less than 12,5mm unless the maximum 15 minute intensity is greater than $6,3mm.hr.^{-1}$.

The sediment collected behind the weir at Q9M21 and periodically surveyed by the HRU provide approximate estimates of the value of coarse sediment transported between survey dates. This only applies if none of the coarse sediment is washed over the weirs. The only situation when coarse sediment can be lost downstream is if the weir pool becomes full of material and therefore loses its intended ponding effect. A limited amount of suspended sediment data is also available on an event basis from the HRU. Prior to 1982 only occasional grab samples were taken but since 1982 a number of regular interval samples, taken using automatic pump samplers during events, are available.

6.3 In-reach sediment information

The sub-sections below outline the different methods that were adopted in order to obtain information about the movement of sediment within the environs of the chosen channel reach.

6.3.1 Gully and slope base sediment traps

Sediment traps are intended to provide information relating to the volume and frequency of sediment movement or supply from anticipated source areas. The traps consisted of galvanised iron boxes (1m x 0,5m x 0,1m). They were installed at the base of banks, cut into the slope to form a lip enabling sediment to drop freely into the pan. Two pans were installed in-line at the mouth of the tributary gully system. The up-channel sides were cut and the downbent lip inserted into the channel bed sediment, allowing free entry of fluvially-borne sediment. Drainage holes were drilled into the down-channel side to allow water to drain through the traps. All traps were held firmly in place by short iron rods driven into the bed and banks on 3 sides. The traps were visited and the contents collected on a more or less monthly basis, regardless of the amount of rainfall during the preceding period. The amount of sediment trapped at each collection point in time, should reflect the variation of conditions at that location which affect the movement of sediment above the trap. A comparison of the contents of different traps might indicate which lithology or slope is more active in the production of sediment.

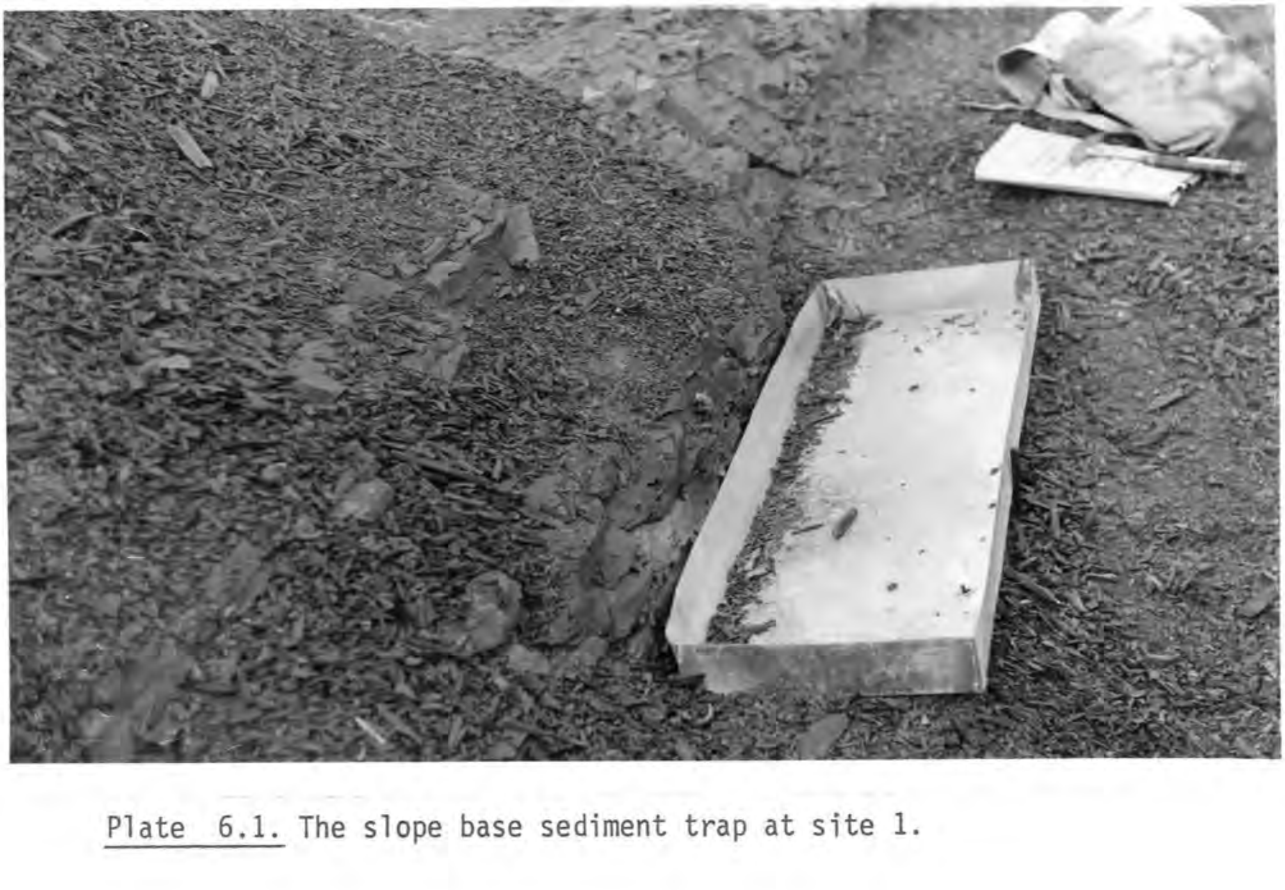

Plate 6.1. The slope base sediment trap at site 1.

The fixed position of box traps does impose limits on their usage in semi-arid areas in that sediment movement and supply is characteristically variable in space. A box might trap a considerable amount of sediment during one event, but very little during the next event of equal magnitude. Traps also need to be well drained as any water collecting in them can attract animals which disturb their position and the sediment above the trap.

Sediment traps were located at the base of what appeared to be 'active' slopes (plate 6.1) as follows: one each at the bases of a south-facing shale bank, a north-facing shale bank, an alluvium/colluvium bank (sandstone pebbles and cobbles) and two at the mouth of a tributary gully (fig. 6.1).

6.3.2 Erosion pin studies

Erosion pins driven into slopes, banks or the channel bed can give an indication of the depth of removal or accumulation of sediment during any sediment transport event. The pins were surveyed on each sample day. During a no-rainfall period, any variation in the height of protrusion could be attributed to processes unrelated to fluvial action. At times of significant rainfall and possible fluvial action, the amount of accumulation or removal registered by the pins can be compared with that during no-rainfall periods. One advantage of pins over box traps is that they can be spread over a wider area thereby sampling sediment behaviour more comprehensively. However, pin experiments should not be conducted in isolation but in conjunction with tracer particle experiments and sediment box traps in order to gain insight into the locations from which or to which sediment is moving.

An initial limitation in the use of pins is disturbance of the surface into which the pin is driven. Furthermore, they serve as obsticles in the path of moving sediment and tend to cause artificial sediment accumulation. Pins nevertheless remain a simple and effective experiment to maintain (Leopold, Emmett and Myrick, 1966). Pins were deployed on channel banks to record sediment movement to the channel during both rainfall and non-rainfall periods, as well as in the channel to indicate accumulation or removal of sediment (fig. 6.1)

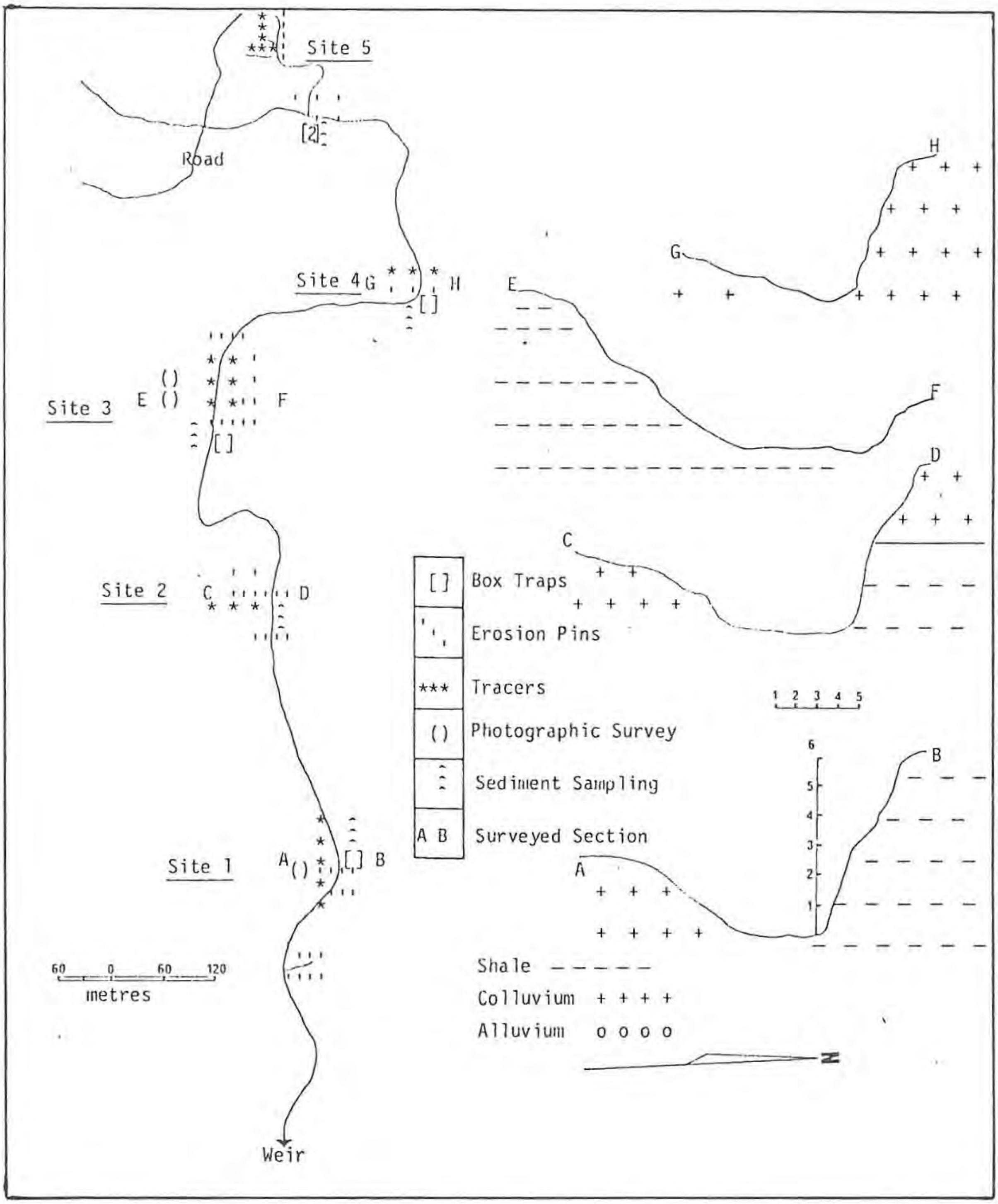

Figure 6.1. The study area illustrating the various data collection techniques at the data collection points.

6.3.3 Channel-bed surface cross-sections

One of the methods which can be used to determine whether there has been any significant sediment removal or accumulation in the channel is by regular survey of the channel bed surface. Any flow event should impose its own morphology on the existing channel morphology (where the channel bed consists of loose unconsolidated material). By surveying the depth of the channel from one transport event to the next, it might be possible to determine whether, at that particular cross-section, sediment is being removed or deposited and on what time scale. The extent of removal or accumulation of sediments in the channel might be related to the scale of the meteorological input. A relationship might well exist between the magnitude of the meteorological input and the extent of either removal or accumulation, which in turn might highlight the role of the channel as a dynamic storage container. The method utilized is illustrated in figure 6.2.

The channel section studied by the above method was surveyed only at times when visual inspection indicated some form of sediment movement by channel flow or tributary channel in-flow. The experiment was conducted at the inlet of a tributary gully system simultaneously monitored by erosion pins, sediment traps and tracers.

6.3.4 Monitoring tracer particle movement.

Visual inspection of a channel reach can give some clue as to which channel bank environments appear to be contributing significant amounts of sediment to the channel. Once they have been identified, some method of confirming the authenticity of their role as source areas needs to be employed. Marking a sample of the sediment particles on the banks and monitoring their subsequent movement is one of these methods. Commonly referred to as tracer experiments, the method involves selecting a representative sample (size, shape, distance from the channel need to be considered and varied), carefully removing them, painting them and returning them to their original position.

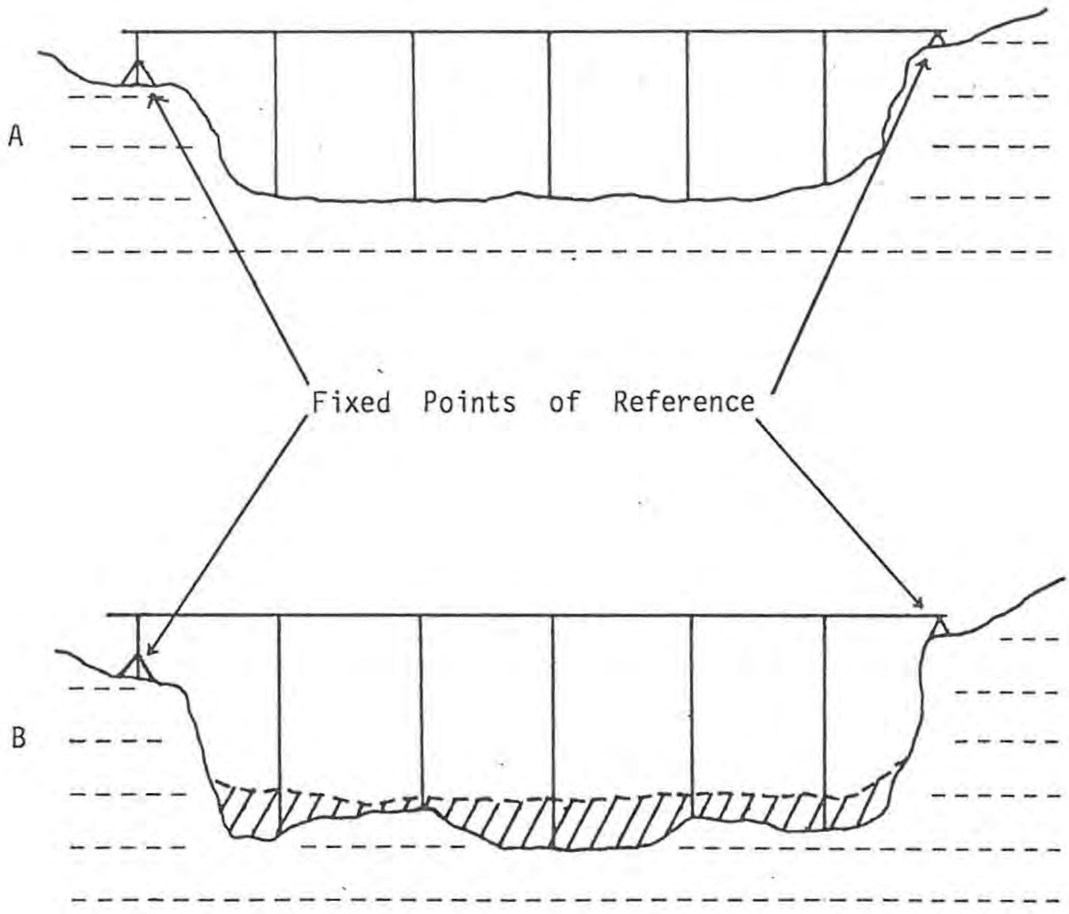

Figure 6.2. An illustration of the method used in doing channel bed surface profile studies.

A - Before major event

B - After major event

▨ - Amount of material transported out of channel reach

Tracer experiments can be carried out on both the banks and in the channel. Channel tracers should preferably be numbered allowing later measurements of distances transported to be made. Where two tracer experiments are conducted in close proximity, it is imperative to use more than one colour to avoid confusion. Tracer experiments are not limited to individual stones, but can be adapted to monitor the break-up by weathering of bedrock outcrops. The resultant sediment particles which move downslope are easily identified as they are painted on one side only.

Tracers on channel banks are susceptible to movement by gravity, wind and animals, and for this reason need to be monitored regularly. Channel tracers however need only be monitored after flow events. The movement of tracers is measured from a fixed point (erosion pin for example) up-slope or up-channel of the tracers. No control over their path of movement is possible and particles sometimes work their way into positions where accurate measurements of their movement are impossible. In addition, tracers can become buried or break up which makes further monitoring of their movement difficult or impossible.

The problems mentioned above do not usually detract from the effectiveness of the experiment if the sample of tracer particles is large enough to absorb losses. One of the foremost advantages in using tracers is their adaptability to location. In the present study tracers were used in the channel, in gullies and rills and on a variety of channel bank environments.

6.3.5. Sequential photographic surveys

Sequential photographic surveys cannot measure amounts of sediment removal from a particular location. They can, however, illustrate changes in various channel environments. Photographs are used in this study to illustrate bedrock weathering and hopefully give some indication of the rate of weathering and subsequent particle movement downslope. Photographs can also illustrate gross changes in accumulation or erosive stripping.

The implementation of sequential photographic surveys requires that photographs of the same area or subject are taken from the same point. Any change in the subject of the photograph (for example a channel bank, sand bar or pebble bar) should then be readily noticeable. It then remains to interpret the photographs and seek some form of process-related explanation for the changes observed.

Although the experiment outlined above was attempted in the present study, it was carried out on a very limited scale. Whilst the method remains a qualitative one, it is not to be ignored as a valuable source of information.

6.4 Sediment particle characteristics.

The sediment collected from the sediment traps as well as from other sample locations need to be quantified in terms of size and shape. Sediment accumulations in the base traps or in the channel need to be analysed in order to determine their mean particle size and sorting values. Both these parameters can be used for a comparison of sediments supplied at different locations, or at one location over time. Any variation in the value of the parameters could indicate a different process responsible for suppply, or a greater or lesser degree of activity for the same process. Gravity supplied sediment might be found to differ in terms of mean grain size and degree of sorting from fluvially derived sediment. Thus it might be possible to differentiate between sediment accumulations (fluvial, gravity) on the basis of their particle size and shape characteristics. Sediment accumulations on banks need to be compared with accumulations in the channel, in order to determine the extent to which channel processes modify the character of the sediment. It might be possible on the basis of grain size characteristics to distinguish further between bank derived sediment stored at the base of a bank not moved by flow in the channel, and sediment accumulations in the channel as a result of a previous flow event, e.g. a gravel bar.

Sediment collected in the present study was analysed by standard sieving methods (Folk and Ward, 1957; Blatt, Middleton and Murray, 1972). Grain size parameters, although not directly significant in terms of the model proposed, might contribute some information about the effect of rainfall amount and intensity variations on the nature of the sediment supplied.

7. RESULTS

7.1 Introduction

This chapter presents the results of the data collection techniques referred to in Chapter 6. As these results represent a variety of monitoring techniques it is not easy to present them visually in an integrated way. An attempt is made to present the data from all measuring sites for each sample interval so that comparisons can be made and consistency of response assessed. The discussion and interpretation of the results is left largely to Chapter 8. In Chapter 8 the implications of the results with respect to the model proposed in Chapter 4 will also be discussed.

The data presented fall into two main categories, hydrological data and sediment response data. The hydrological data were obtained from the H.R.U. The sediment response data are the results of the field data collection programme undertaken over a two-year period. In order to avoid presenting a large number of readings and measurements within the main text, the raw data are given in tables in Appendix A. For the purpose of simplifying the presentation of data, each sample day is recorded as a reference number and not as a date. Table 7.1 lists the specific sampling dates corresponding to the reference numbers.

Table 7.1 Sampling dates and their corresponding reference numbers.

Date	R. No.	Date	R. No.	Date	R. No.	Date	R. No.
4. 4.83	0	24. 9.83	5	6. 4.84	10	6.10.84	15
30. 4.83	1	22.10.83	6	19. 5.84	11	24.11.84	16
30. 5.83	2	26.11.83	7	29. 6.84	12	19. 1.85	17
28. 6.83	3	14. 1.84	8	28. 7.84	13	23. 2.85	18
6. 8.83	4	3. 3.84	9	25. 8.84	14	2. 4.85	19

The majority of field sampling sites were established on 4 April 1983. Prior to this date the catchment was visited on two occasions in order to visually identify and plan the specific data collection sites, as well as the design of the sediment movement sampling points. Figure 6.1 illustrates the channel reach designated as the study area and the various sampling techniques conducted at each site. Figures 7.1 to 7.3 are diagramatic representations of the individual study reaches and specifically illustrate further details about the type of sediment movement sampling techniques employed at each site.

Figure 7.4 illustrates the cumulative amount of rainfall recorded from one sample day to the next. Figure 7.5 is an example of the method used in presenting the bulk of the results where each block (A-E) represents one type of data collected at the various data collection points (sites). The results are illustrated in figure 7.6 to 7.24 on the basis of one sample day per figure, and reflect any movement, removal or accumulation of sediments since the previous sample day. The extent of activity from one sample day to the next in response to any variation of hydrological variables can be readily compared.

7.2 Format of data presentation

The erratic nature of sediment behavoir in semi-arid areas in terms of amount and extent often makes it difficult to represent data from all sample sites on one set of axes. In order to accommodate most of the measurements, which on a linear scale would require excessively long axes, logarithmic scales have been used.

Figure 7.5 is intended to serve as a key to the interpretation of figures 7.6 to 7.24. However, further clarification of specific data recorded in each of the blocks A to F is necessary. Blocks A to E record all the sediment response data. Each specific data collection site, of which there were five, is allotted an equal space on the horizontal axis, sites 1 to 5

numbered from left to right. Each block records a different type of data as follows :

Block A : Amount of sediment trapped in slope base pans, (kg);
Block B : Measurements of deposition on the slopes by means of pins, (cm);
Block C : Measurements of deposition/erosion in the channel by means of pins or channel surface profile studies, (cm);

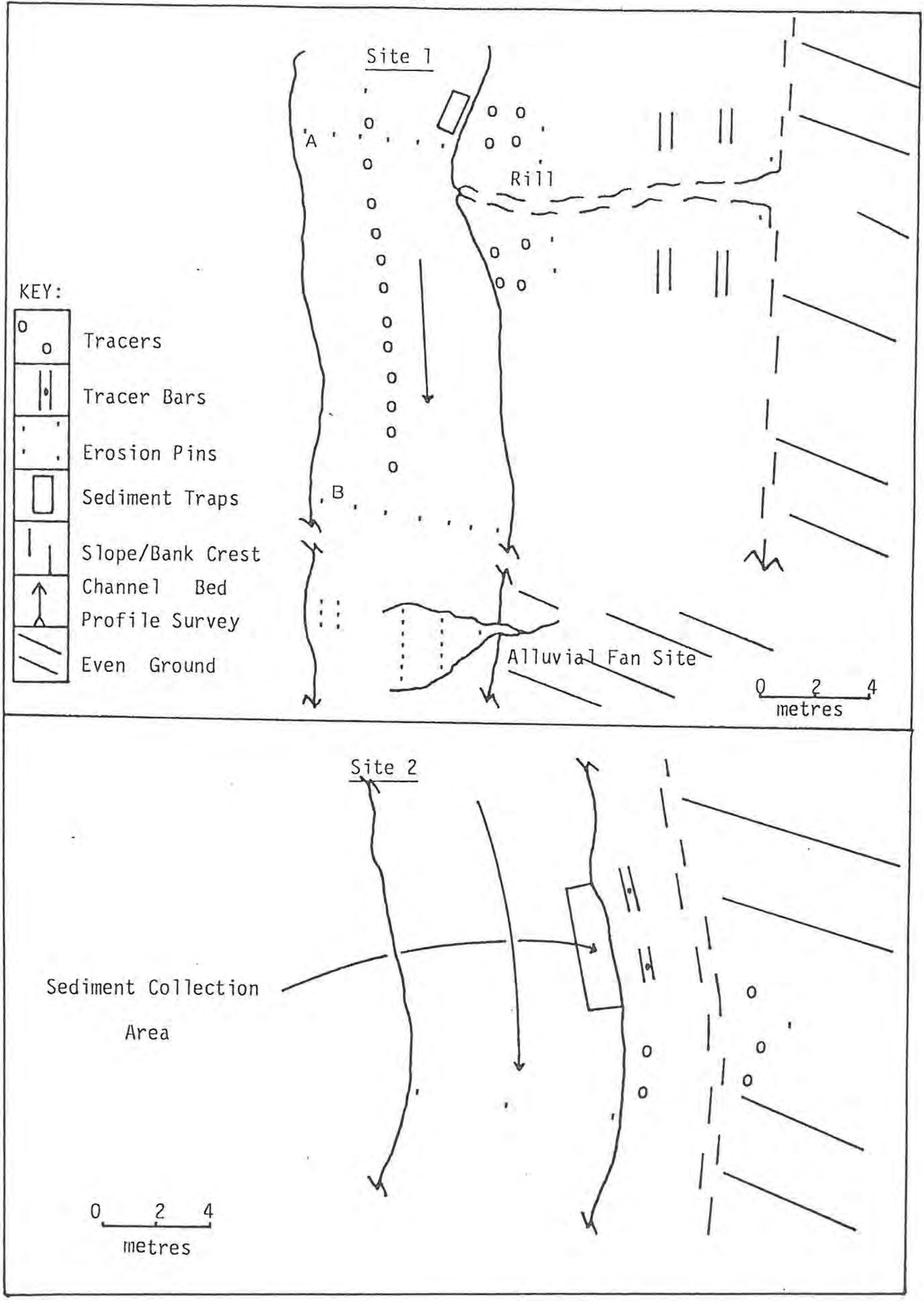

Figure 7.1. The site 1 and 2 data collection points showing data collection methods.

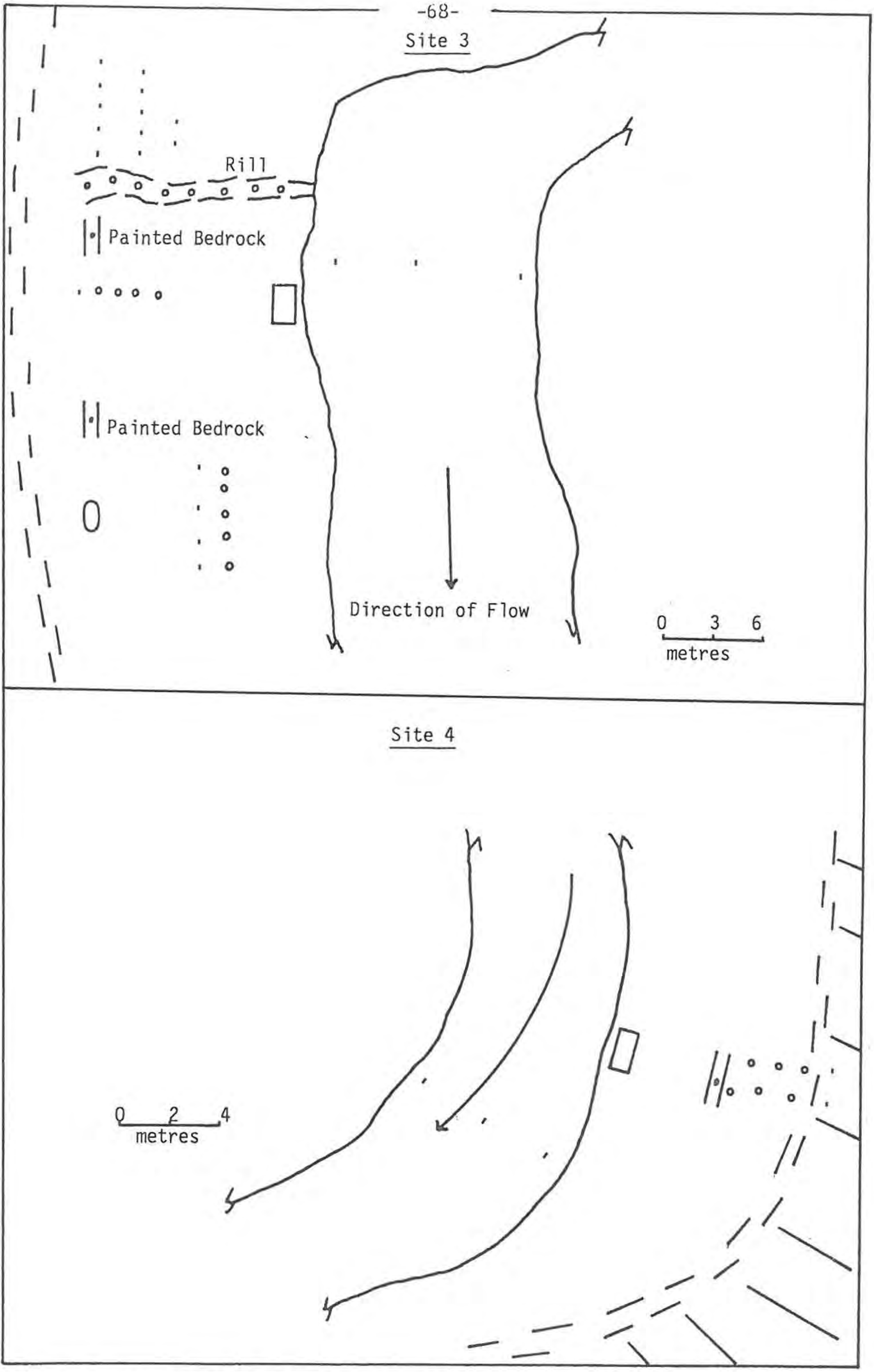

Figure 7.2. The site 3 and 4 data collection points showing data collection methods. (Symbols used as in figure 7.1.)

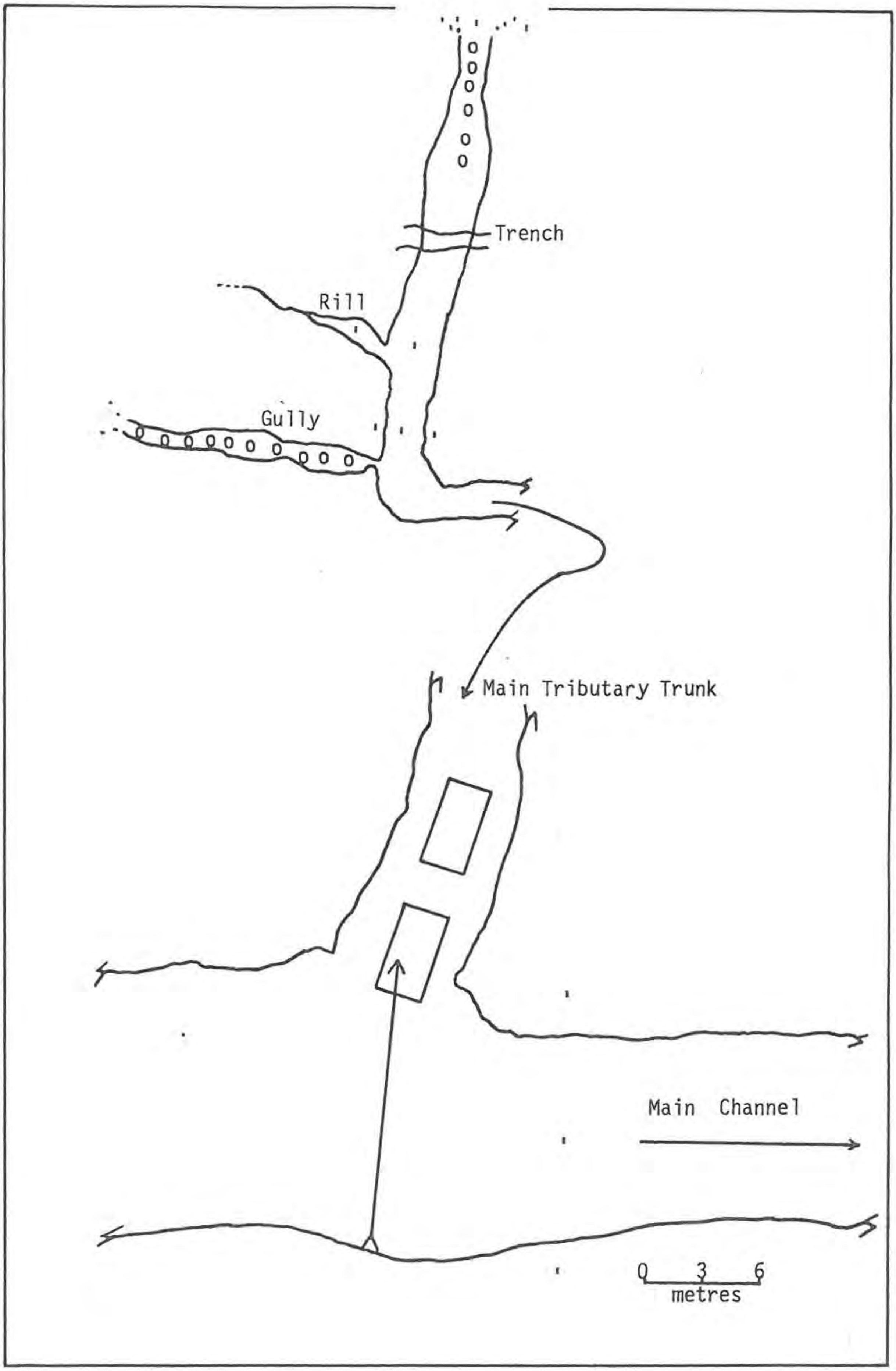

Figure 7.3. The site 5 data collection point showing data collection methods. (Symbols used as in figure 7.1.)

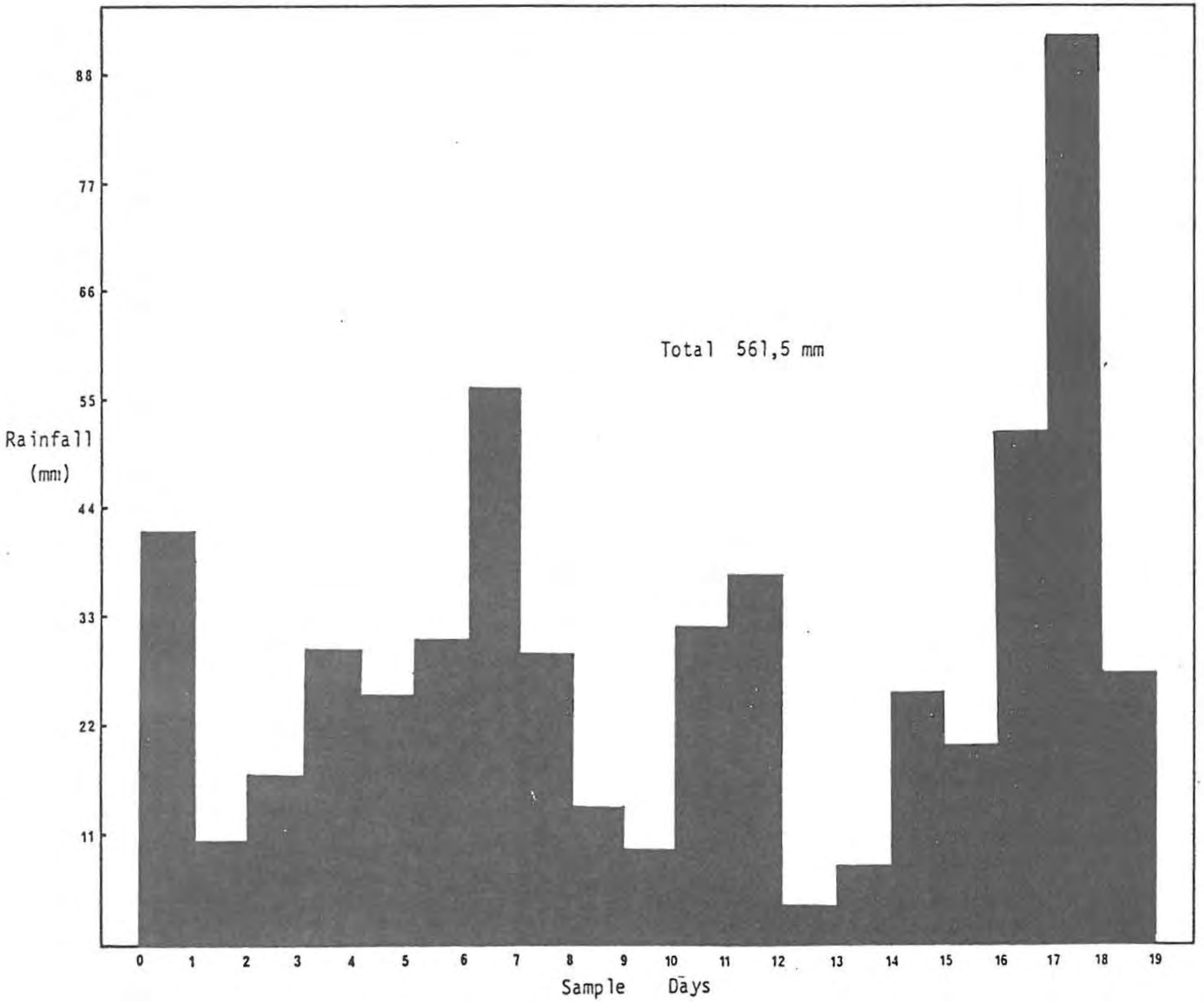

Figure 7.4. The amount of rainfall recorded from one sample day to the next showing the distribution of rainfall amounts through the entire study period.

Block D : Measurements of the movements of all tracer particles in the channel or in rills on the slopes, (cm) and

Block E : The variation of the mean grain size (mm) and sorting (mm) parameters for samples from each of the pan collected sediments.

The various data collection techniques were not conducted at all of the five sites. Thus Block B (slope erosion pins) records the measurements of the pins at site 3 only, as this is the only site where slope erosion pins were deployed. The spaces allocated to sites 1, 2, 4 and 5 do not record any measurements of this nature and are marked with an X. The same is true for sites 2, 3 and 4 in Block C (channel erosion pins), and sites 2 and 4 in Block D (tracer particles). Where the same data collection technique is conducted at any given site but data is obtained from 2 or more data sources, the space allocated for that site is shared between the separate data sources. There were two sources of channel pin data (Block C) collected at site 1, thus site 1's space is divided into two bars, one for each data source. This is also the case for site 5 (Block C), site 3 and 5 in Block D (tracer particles) and all the sites in Block E (mean and sorting parameters). All the sediment response data in Blocks A to E are recorded in a vertical plane.

The hydrological data are recorded in horizontal planes in Block F. The data recorded here are rainfall amount (mm), total erosivity index of rainfall events (EI_{30}), and peak discharge ($m^3.s^{-1}$) measured in the main channel at the weir (Q9M21) during the preceding sample period. Linear axis scaling has been used in the representation of these data. Where no data were measured (e.g. no flow in the channel) the relevant space remains blank. When no bar graph is present in blocks A to E, a distinction is made between no activity (0), missing data (M), no data collection (T) or technique not used at the relevant site (X).

7.3 Climatic and channel flow data

Rainfall was recorded on a continuous basis by the H.R.U. The cumulative total amount of rainfall between sample days could be extracted from the records by totalling the daily rainfall for the period concerned. The accumulated amount is then recorded for the sample day terminating the period (figure 7.4). The amount of 41,5mm recorded on day 1, is the amount

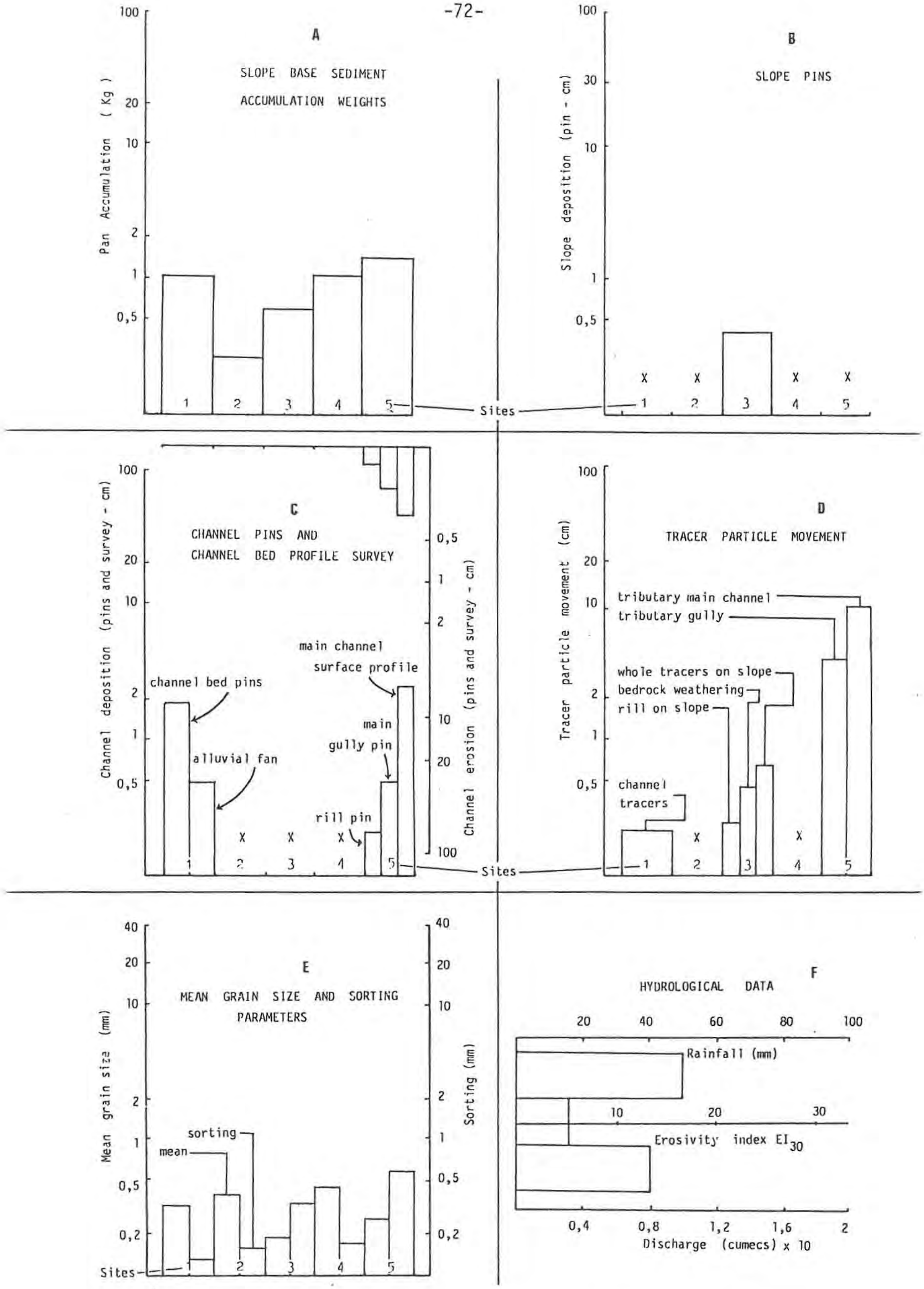

Figure 7.5. Diagram illustrating the data presentation format for figures 7.6 to 7.24.

of rainfall for the period 4.4.83 up to 30.4.83 (Table A.1).

The erosivity index values were readily extracted from the H.R.U. data bank of continuous rainfall records using a program written by Hughes (pers. comm.), (see Chapter 6). The purpose of including the erosivity index values in the data is to indicate the variation of the energy of the rainfall input. Not all rainfall events of similar amounts have similar erosivity values. Sediment responses can be expected to vary according to a variation in the energy expended by a rainfall event. Because of the low intensity nature of some of the rainfall events in the study area, not all sample days recorded a value for this variable (Table A.1).

The third hydrological variable, flow in the channel, is also readily available from the H.R.U. data bank. Flow is measured at the outlet from sub-catchment B using a sharp crested compound V-notch weir. There are only 7 sample days for which flow is recorded during the entire study period. The channel flow data is included to assess the relationship (if any) between this variable and sediment transport, removal or deposition within the channel confines. Much of the theory pertaining to channel processes has been discussed in Chapter 3, and needs to be qualified in terms of the model proposed in Chapter 4 of the present study.

7.4 Gully and slope base sediment traps.

The amount of coarse sediment trapped in pans is illustrated in Block A of figures 7.6 to 7.24, the values being extracted from Table A.2 in the appendix. Sediment traps were located in two areas within the channel confines; at the base of active slopes and at the mouth of a tributary gully system. Slope base traps were deployed at the bases of slopes at sites 1,3 and 4. The traps were placed in such a way as to trap a representative sample of sediment supplied by that slope. It should be noted that the ground surface remote from the immediate channel bank environment is flat to gently sloping. These areas represent a low energy environment where coarse sediment transport is unlikely to occur, and were therefore not monitored. The amounts of sediment collected in the tributary mouth traps (site 5) represent sediment transported in a channel. The amounts however, do not always relate to flow in the main stream channel.

7.5 Erosion pin studies to record erosion or deposition.

In the present study pins were deployed in two main areas with respect to the channel; on channel banks and in the channel bed.

7.5.1 Erosion pins on channel banks

All the data pertaining to bank erosion pins is recorded in Block B of figures 7,6 to 7,24. It was only the sloping bank of the channel at site 3 that appeared suitable, having sufficient depth of sediment to bed rock to enable pins to be installed. A section deemed representative of the entire slope was chosen and 7 pins were deployed. The amount of sediment accumulation occurring on the bank at each pin was measured on every sample day (Table A.3).

7.5.2 Channel bed pins and channel bed profile studies

Although two methods (pins and profile repeat surveys) were used to monitor erosion and deposition of sediments on the channel bed, the nature of the data yielded by both methods are identical and recorded in Block C. There are two data sources at site 1. The first source was provided by two rows of pins in and transverse to the channel (Table A.4). The second source was provided by pins deployed in a cross-section arrangement across an alluvial fan. The fan had formed in the channel bed, the sediment being derived from a minor rill leading into the channel (Table A.5).

Further pin data were obtained at site 5 from three data sources. The first source was provided by a pin driven into the bed of a minor rill within the gully system (figure 7.3; Table A.6). The second source was provided by a pin recording fluctuations in the bed of the main tributary channel (Table A.6). Channel bed cross-section surveys provided the third data source. These repeat surveys were conducted in the main channel at the tributary mouth (figure 7.3). Surveys were done only on sample days when it was obvious, by visual inspection, that flow had occurred in the main channel. Together with the fact that the method was only initiated half way through the fieldwork period, the few flow events resulted in only four sample days on which surveys were carried out (Table A.7).

7.6 The movement of slope and channel tracers

All data pertaining to tracer movements have been recorded in Block D. The amounts recorded represent the average of all tracers at a site which registered movement during the sample period. The tracer method of observing sediment movement was used at sites 1, 3 and 5. Data were provided by one source at site 1, where numbered tracers were placed in the main channel (figure 7.1; Table A.8).

Data were provided by three sources at site 3. Firstly, numbered tracers were placed in a rill on the slope (figure 7.3; Table A.9). The second data source was provided by particles of shale weathered from an initially painted bedrock outcrop (figure 7.3). As particles broke away from the outcrop, their movement downslope was recorded (Table A.10). The third source of data was provided by whole painted tracers on the slope. The average movement of all tracers per sample day was calculated and is illustrated in figures 7.6 to 7.24.

Data was obtained from two sources at site 5. Numbered tracers were placed in a minor gully leading into the main tributary gully (figure 7.3; Table A.11). Average movement per sample day of these tracers is illustrated in figures 7.6 to 7.24. A second set of numbered tracers were placed in the main tributary channel close to its source (figure 7.3; Table A.12), and constitute the second data source at site 5.

At all the above sites there would have been times when certain tracers moved more than any others on certain days, and the averages used in the presentation of these data can be misleading. But as the present study seeks to investigate the general trends of sediment supply, averages are considered to be adequate and facilitate graphical representation of data. Certain sections of the talus on banks were painted (tracer bars at site 1), but recording of movement would have been unavoidably inaccurate. This was done for observational purposes only. The degree to which individual sediment particles re-organize themselves in relation to one another (mixing) as they move downslope can be observed by this method.

In respect of the type of rock particles chosen for use as tracers, they consisted in all cases of the same material as the environment in which they were deployed. The size of the particles usually reflected the average size of the material of the immediate environment. The lengths of the long axis' of the individual channel tracers are recorded in the tables (Appendix A).

7.7 Sequential photographic surveys

The sequential photographic survey method of data collection did not prove successful due to inferior commercial development of negatives in some cases, and poor lighting in others. These two factors rendered certain sequential photographs unsuitable so that even the worthwhile photographs in the sequence serve little purpose.

It is perhaps not a very suitable method of monitoring particle movement. It is often difficult to identify the same particle from one photograph to the next. The exercise is probably better suited to gross channel morphology changes where such processes as bank collapse and gravel bar migration are involved.

During the period of field work for the present study, one episode of bank collapse did occur. In anticipation of collapse occurring a photograph (plate 7.1a) was taken of a loose section of a vertical bank (indicated by the lens cap) in November 1983. Collapse occurred during August 1984 (plate 7.1b). A second process recorded on film was that of rill erosion (plates 7.2 (a) and (b). The first photograph 7.2 (a) was taken of the rill and position of the erosion pin on sample day 1, the second (7.2 (b)) on sample day 2.

7.8 Sediment characteristics : Particle size analysis.

The variations in the mean grain size and sorting parameters of all the sediment collected in the slope base and gully traps are illustrated in Block E. The mean grain size is illustrated in the first column for the five sites, while the sorting is illustrated in the second column. The data is recorded in Table A.13.

When mean grain size is plotted against sorting (figures 7.25 and 7.26) the sediment from each site tends to cluster in a grouping indicated by the closed circles. Characterisation of sediments in this manner can serve as an indication of the energy conditions of the environment at each of the sediment sources (Blatt, Middleton and Murray, 1972).

Plate 7.1a. A section of the channel bank at the tributary gully site before an episode of bank collapse.

Plate 7.1b. Channel bank collapse at the tributary gully of a section of the bank shown above.

Plate 7.2a. An erosion pin in a minor rill at the tributary gully at site 5.

Plate 7.2b. The erosion pin registers erosion in the rill.

Key to symbols used in figures 7.6 to 7.24

0 - No sediment activity measured.

M - Missing data.

T - Data collection not yet initiated at site or collection terminated.

X - Technique not used at site.

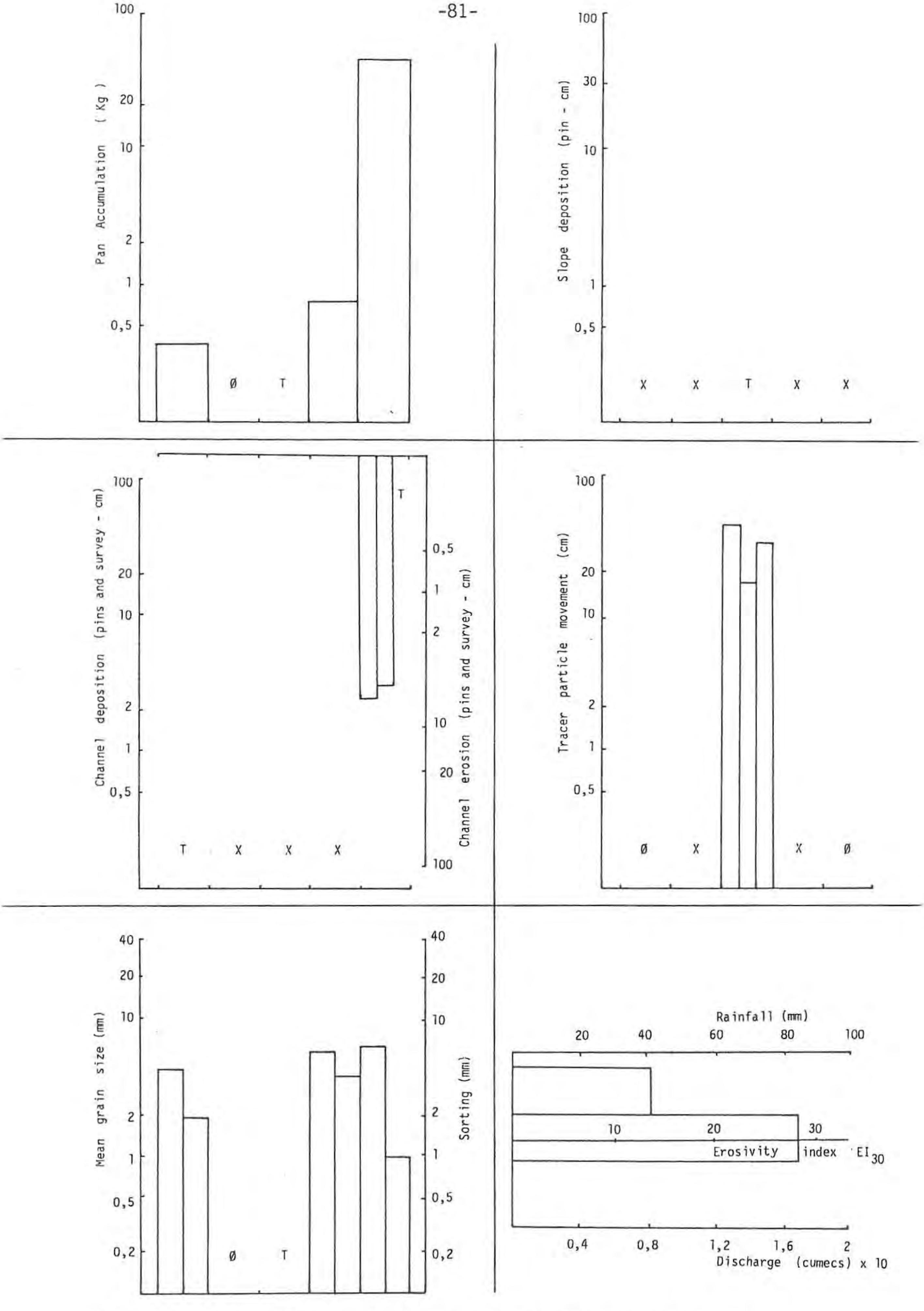

Figure 7.6. Data collected at the various sites on sample day 1.

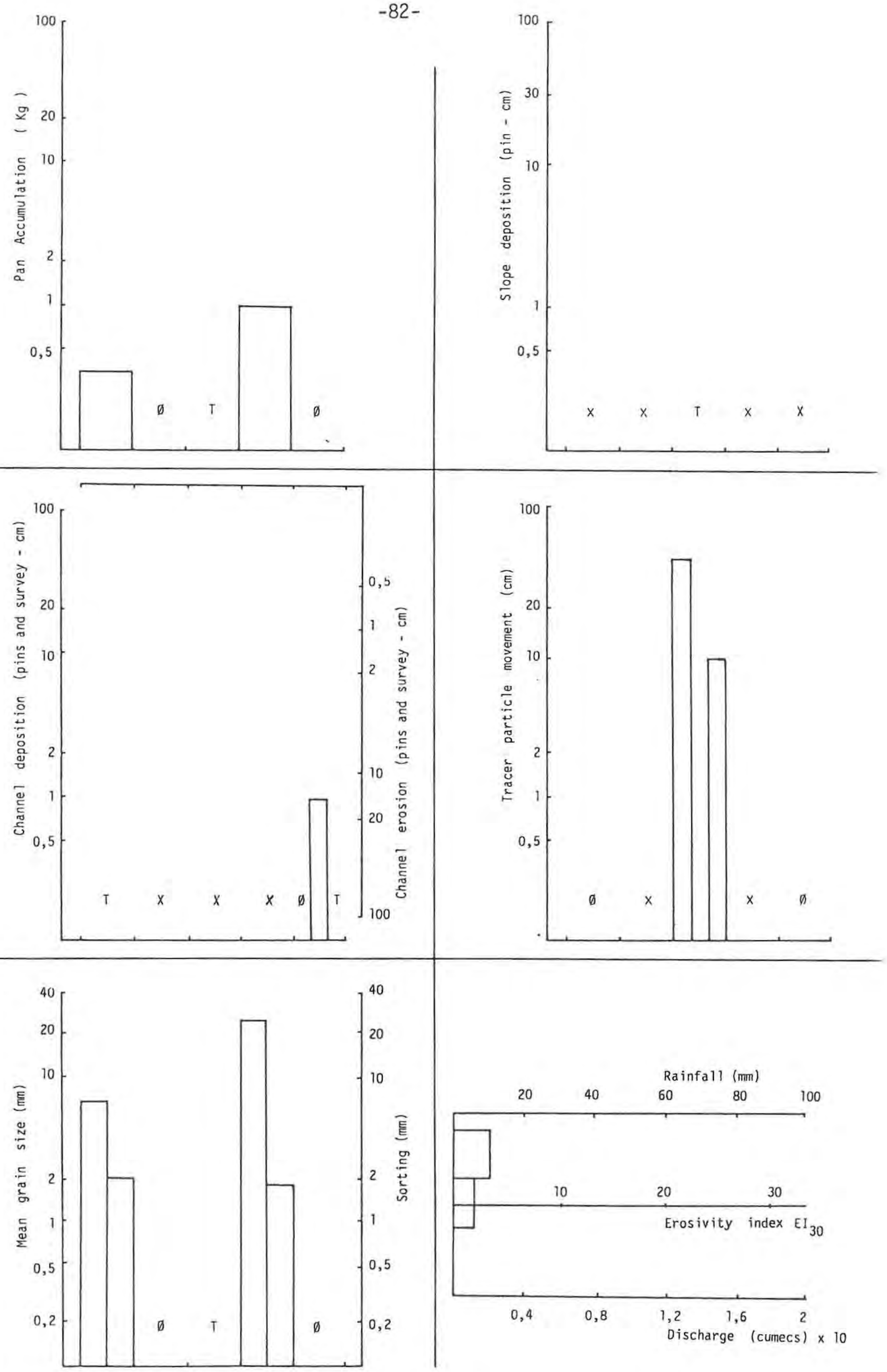

Figure 7.7. Data collected at the various sites on sample day 2.

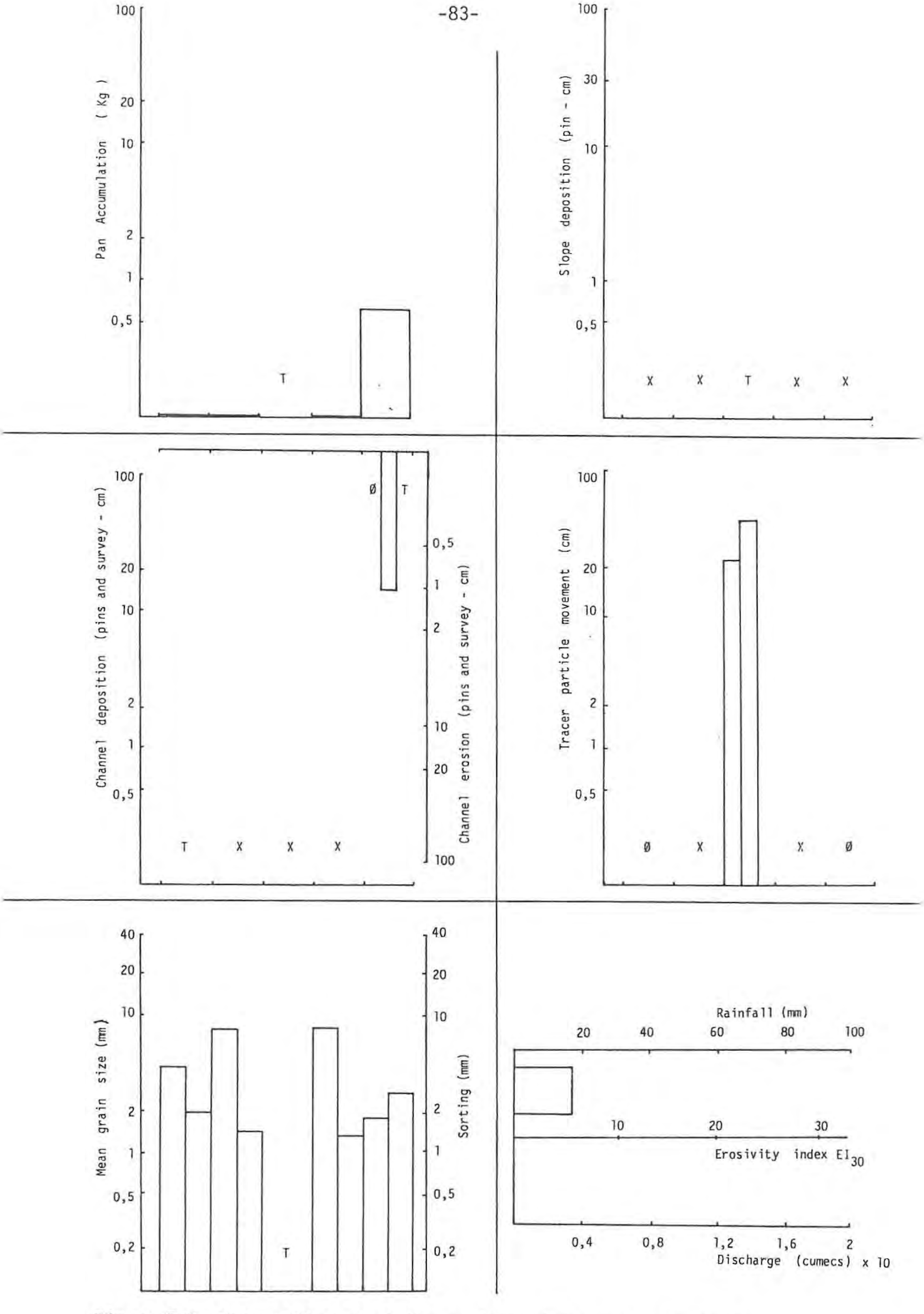

Figure 7.8. Data collected at the various sites on sample day 3.

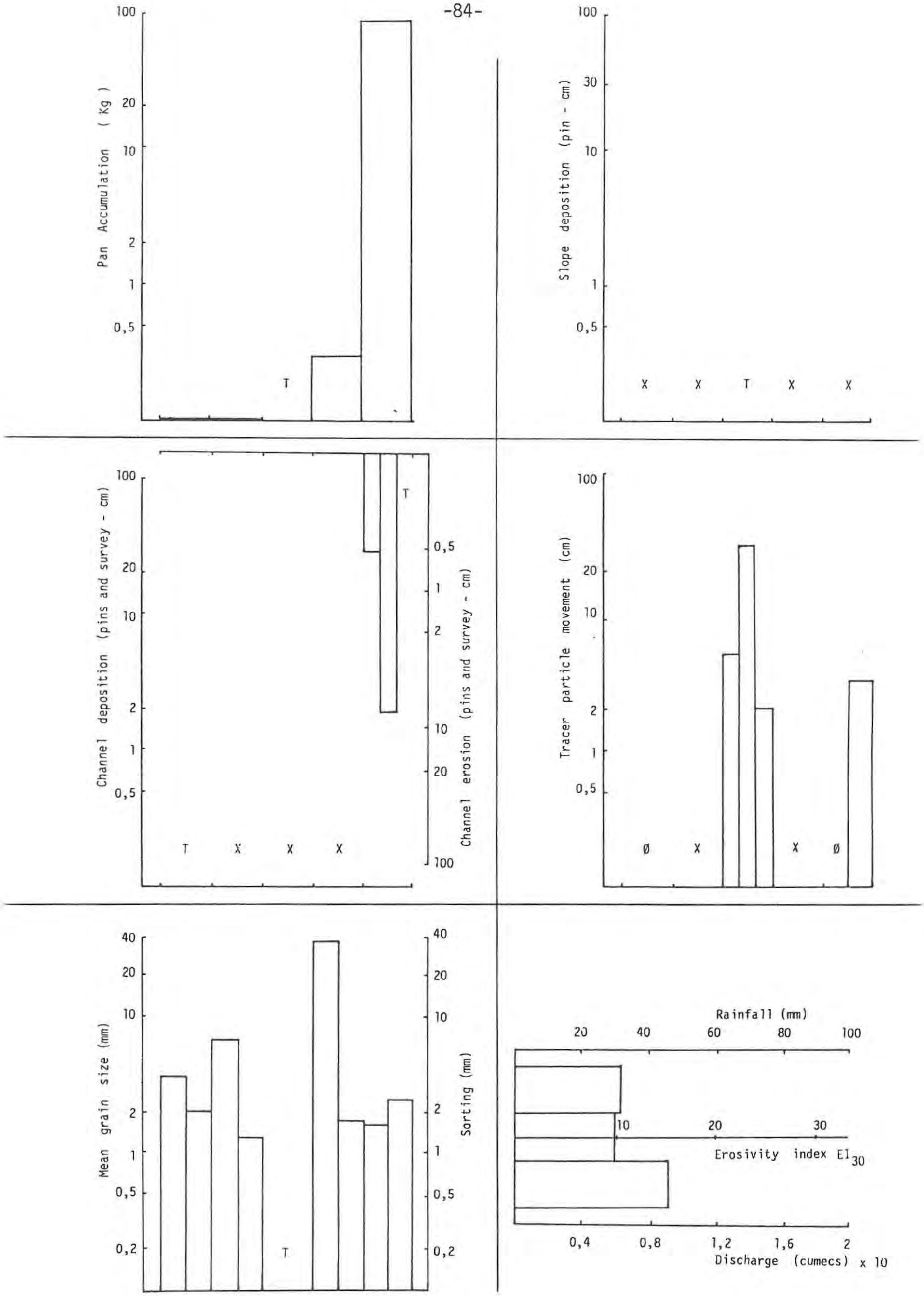

Figure 7.9. Data collected at the various sites on sample day 4.

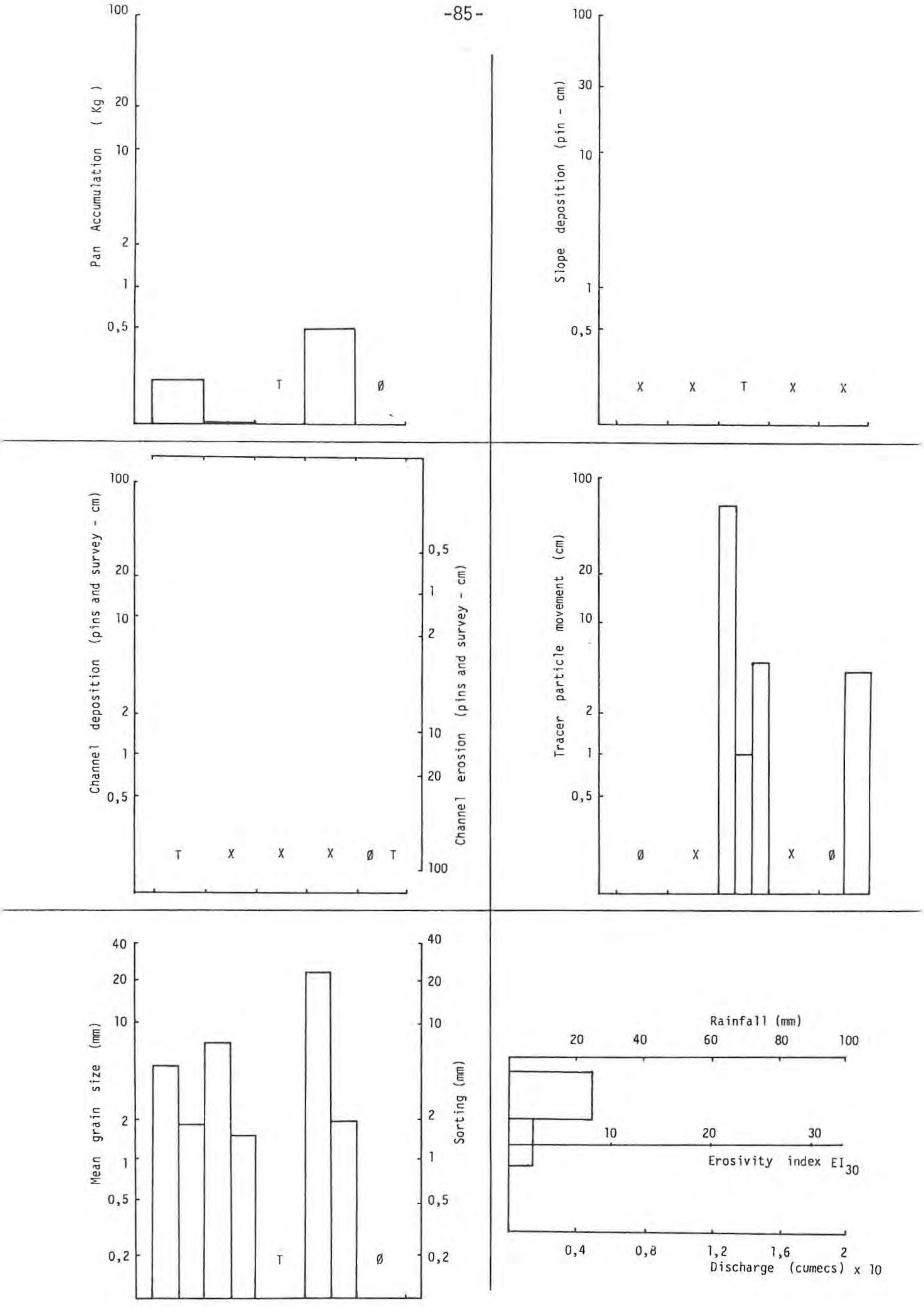

Figure 7.10. Data collected at the various sites on sample day 5.

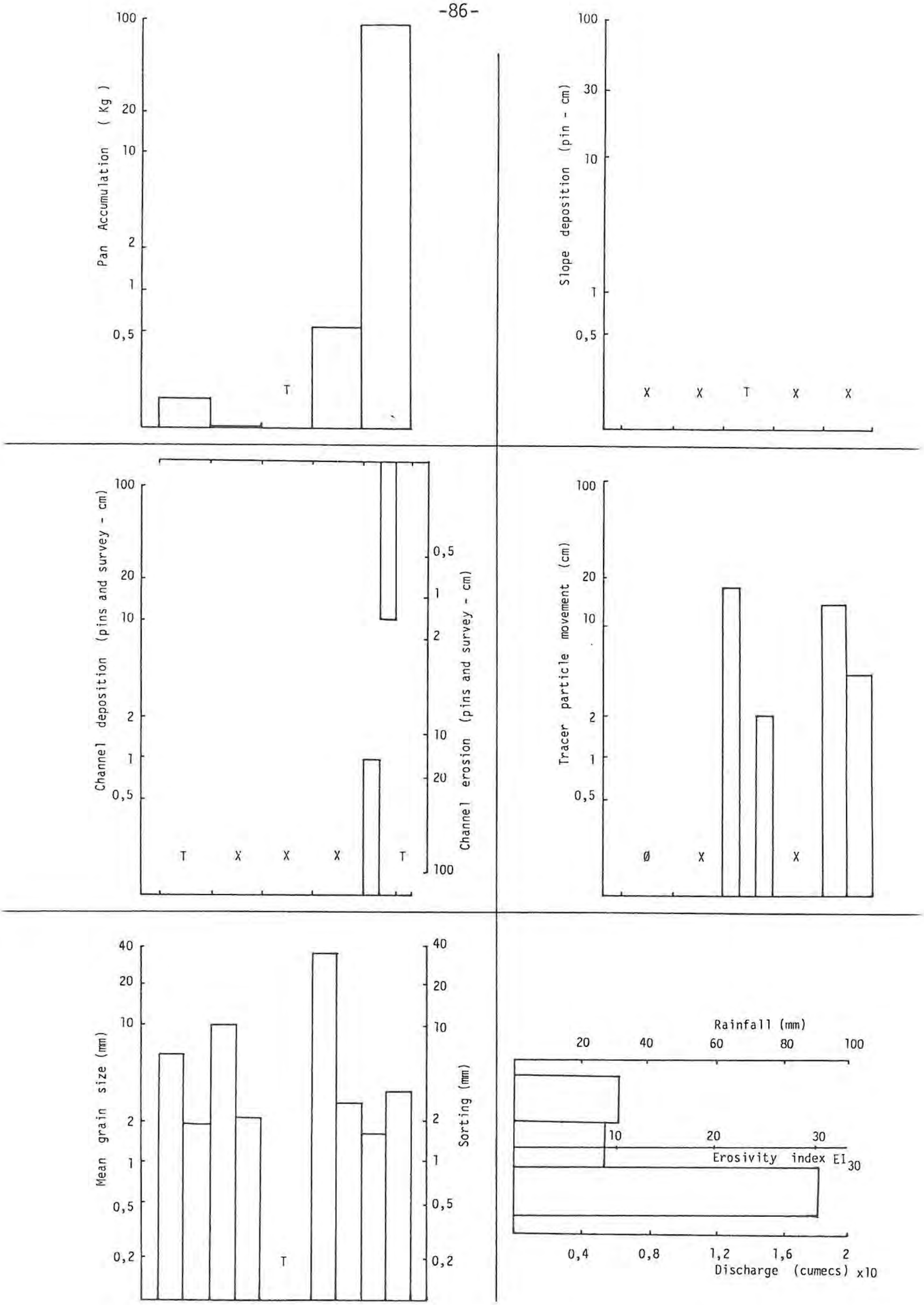

Figure 7.11. Data collected at the various sites on sample day 6.

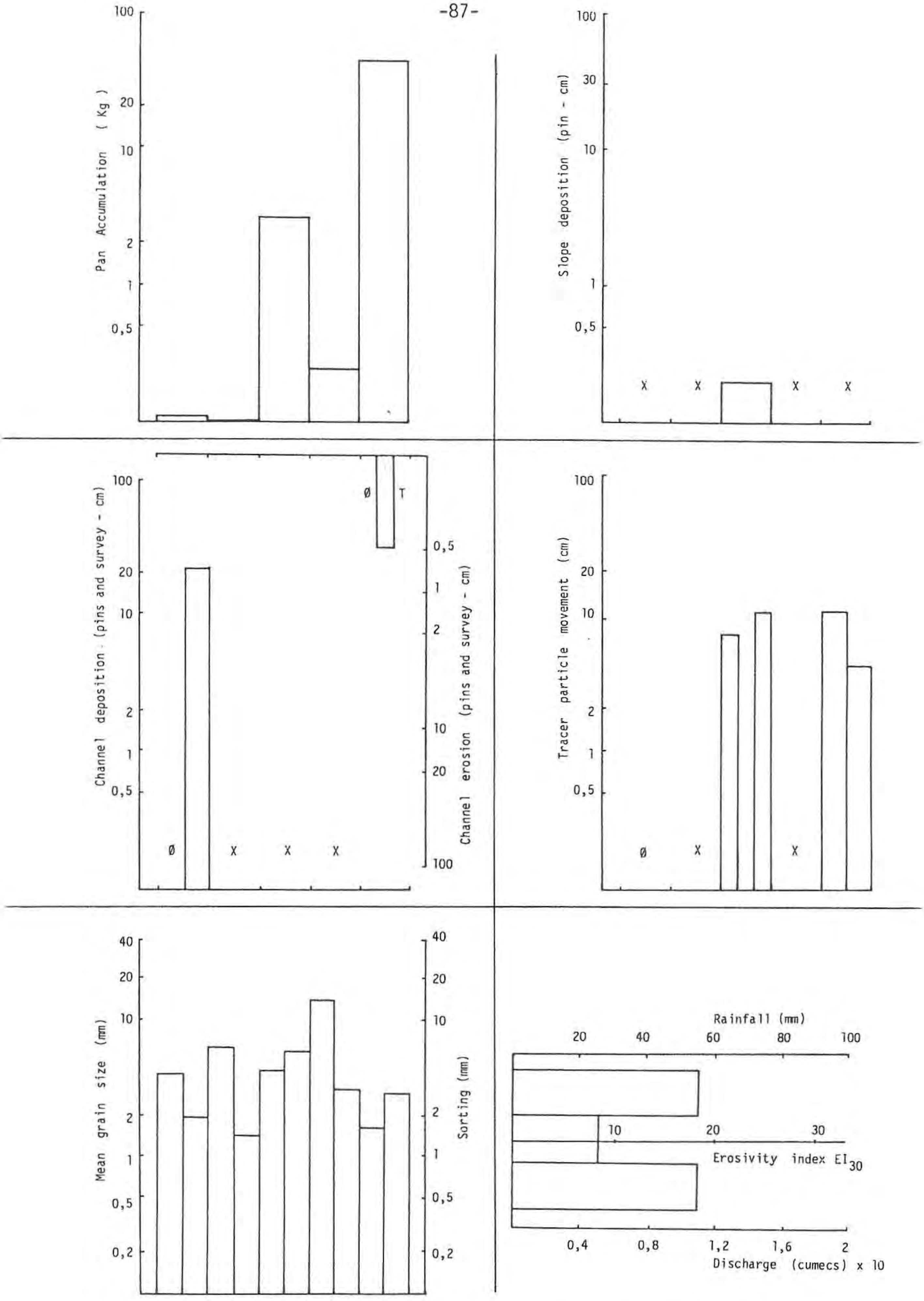

Figure 7.12. Data collected at the various sites on sample day 7.

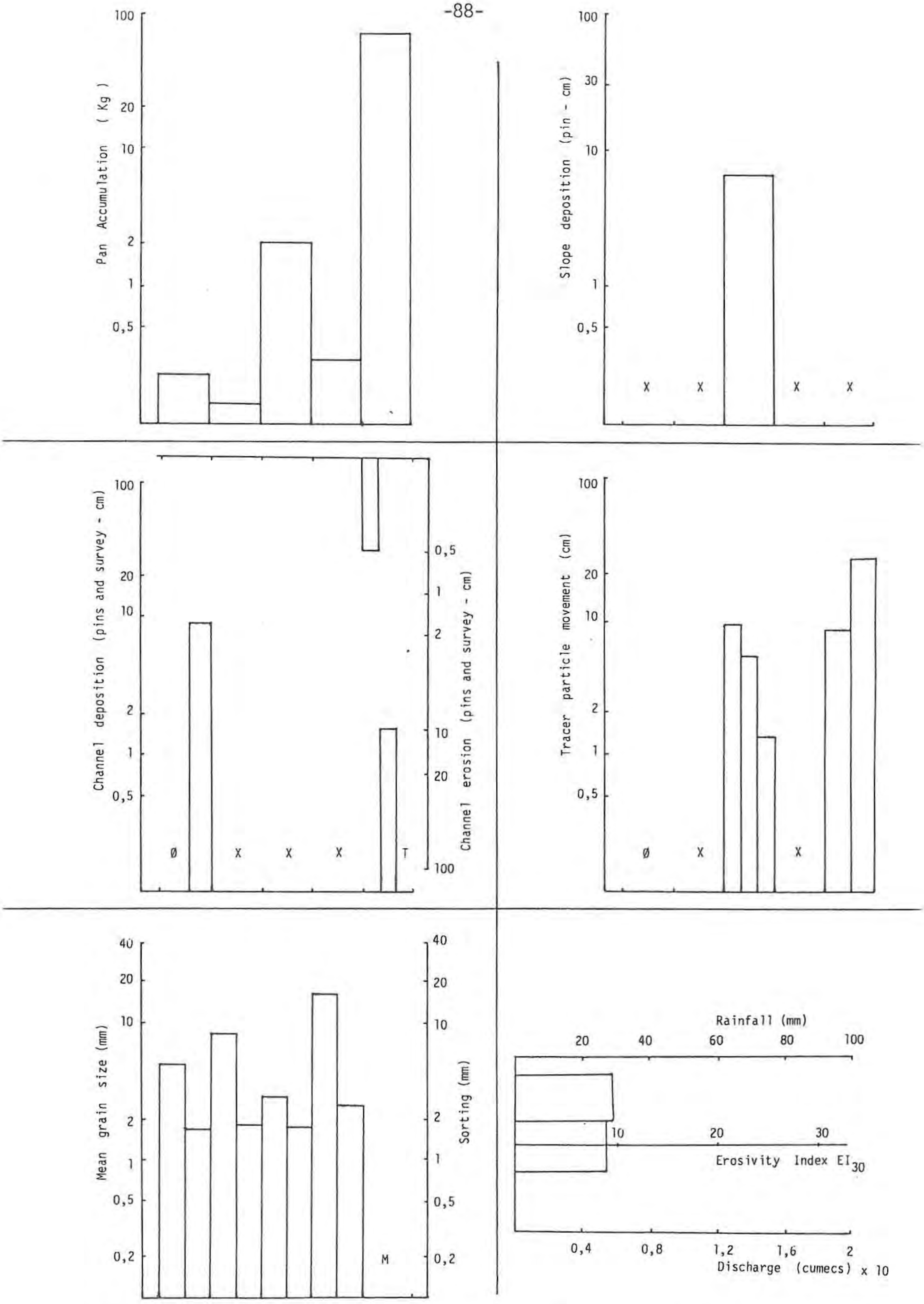

Figure 7.13. Data collected at the various sites on sample day 8.

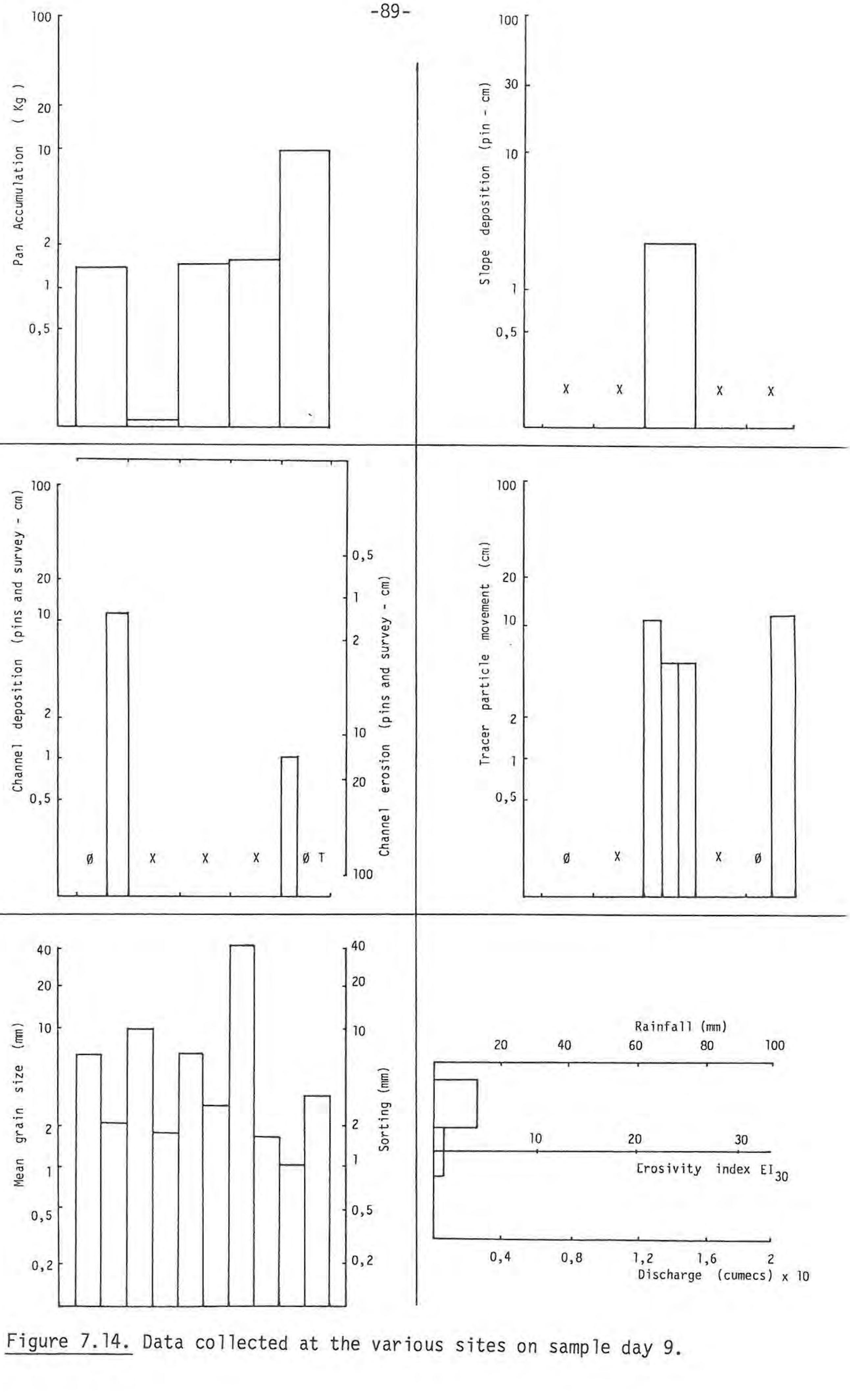

Figure 7.14. Data collected at the various sites on sample day 9.

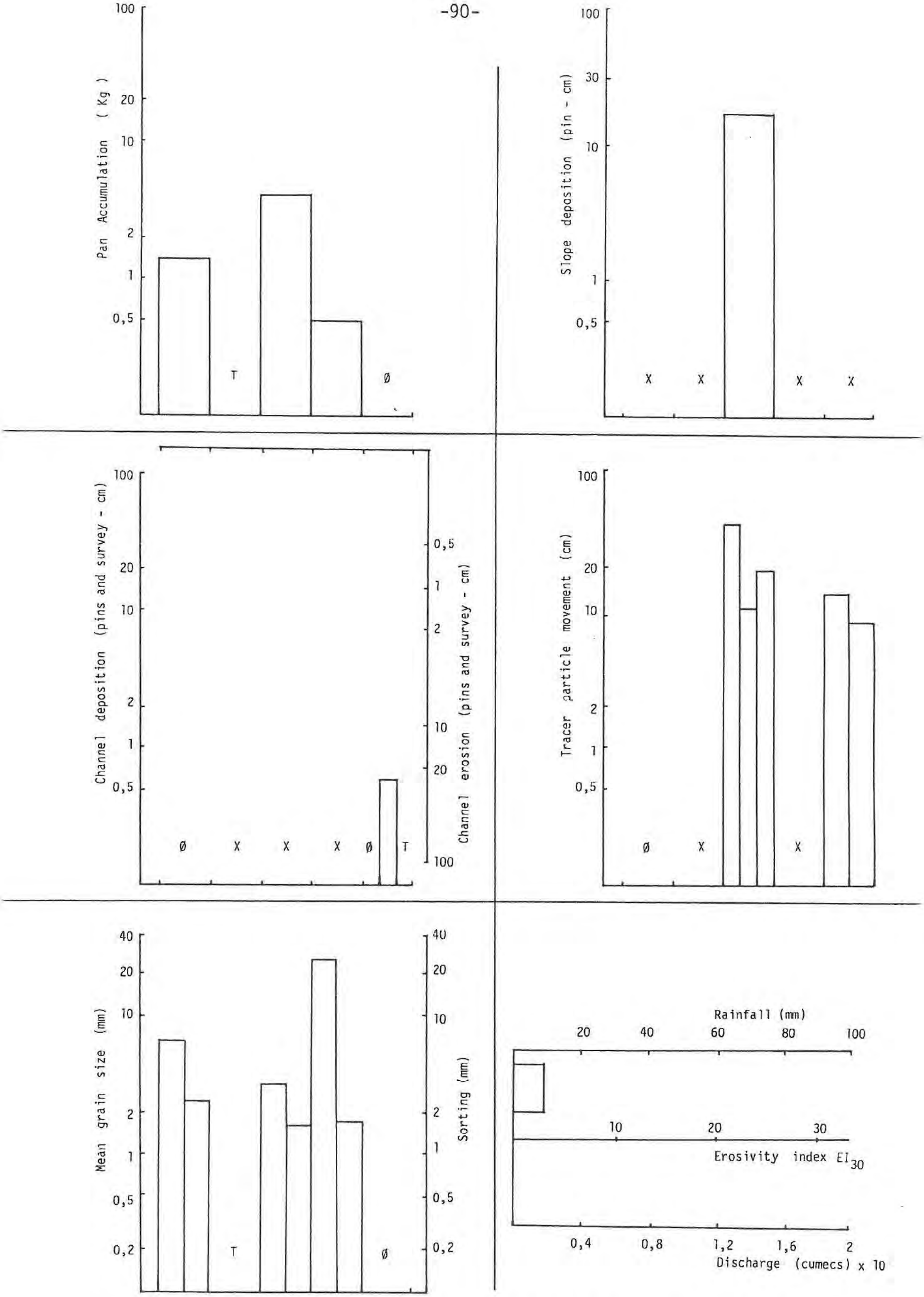

Figure 7.15. Data collected at the various sites on sample day 10.

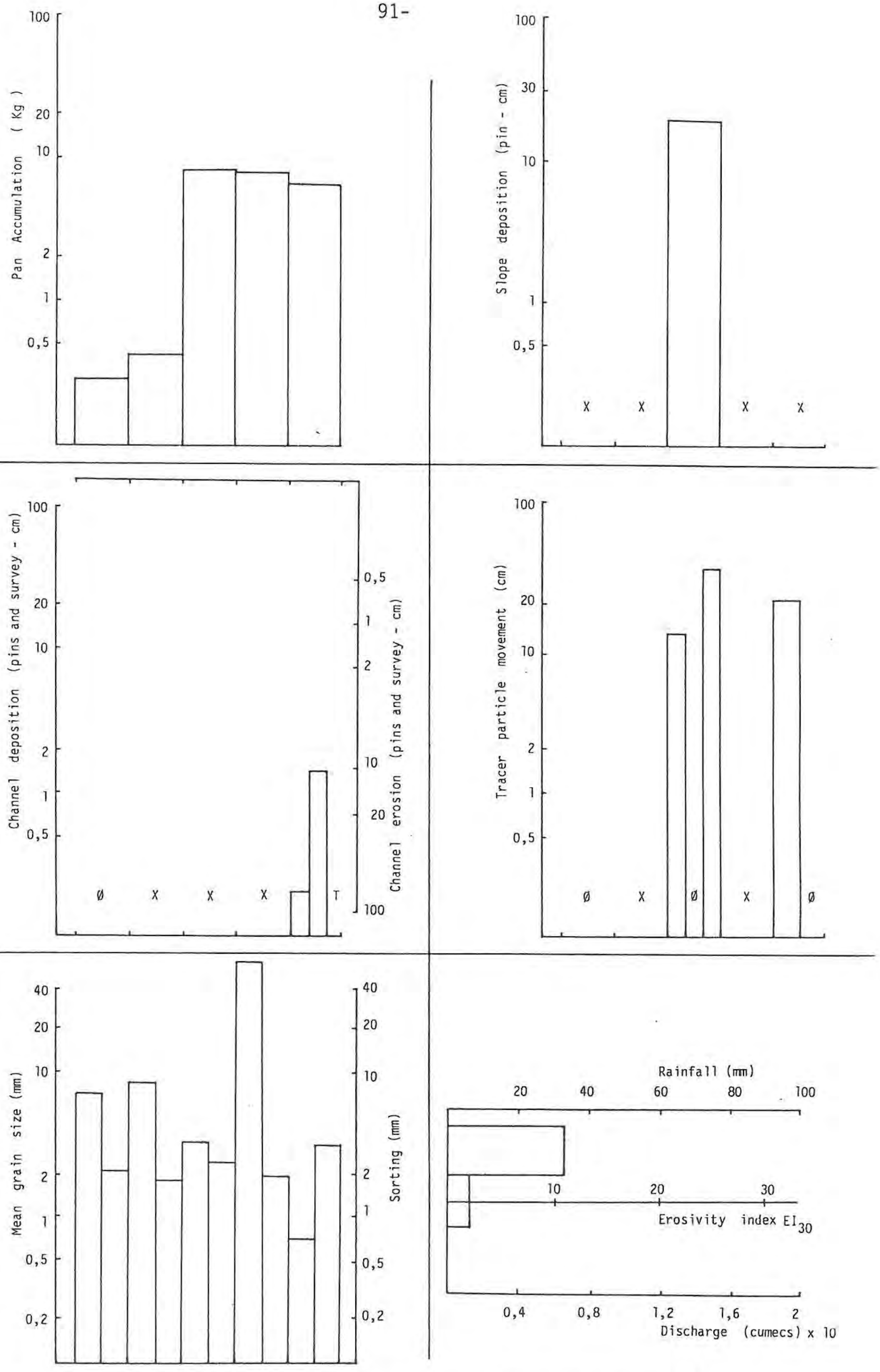

Figure 7.16. Data collected at the various sites on sample day 11.

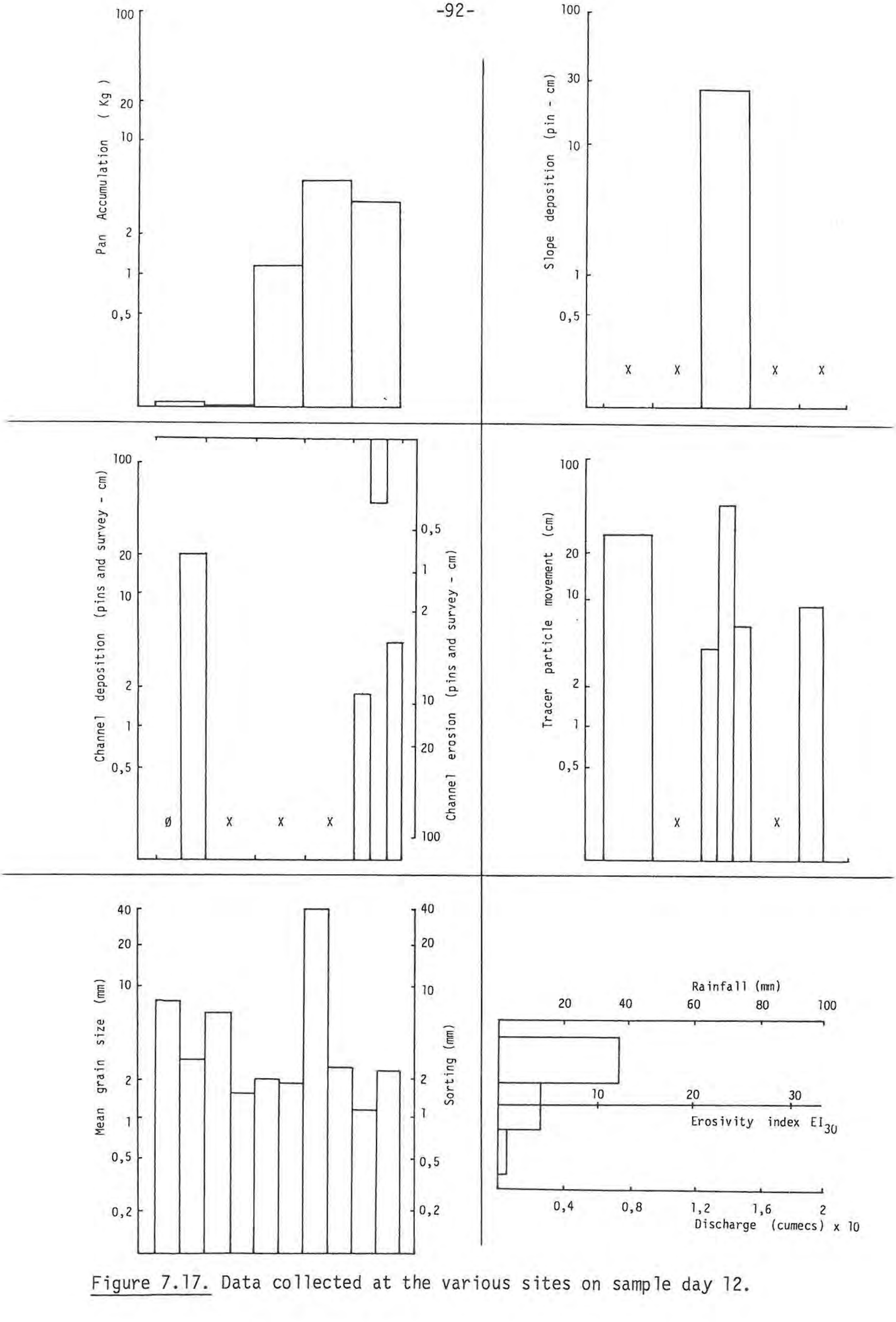

Figure 7.17. Data collected at the various sites on sample day 12.

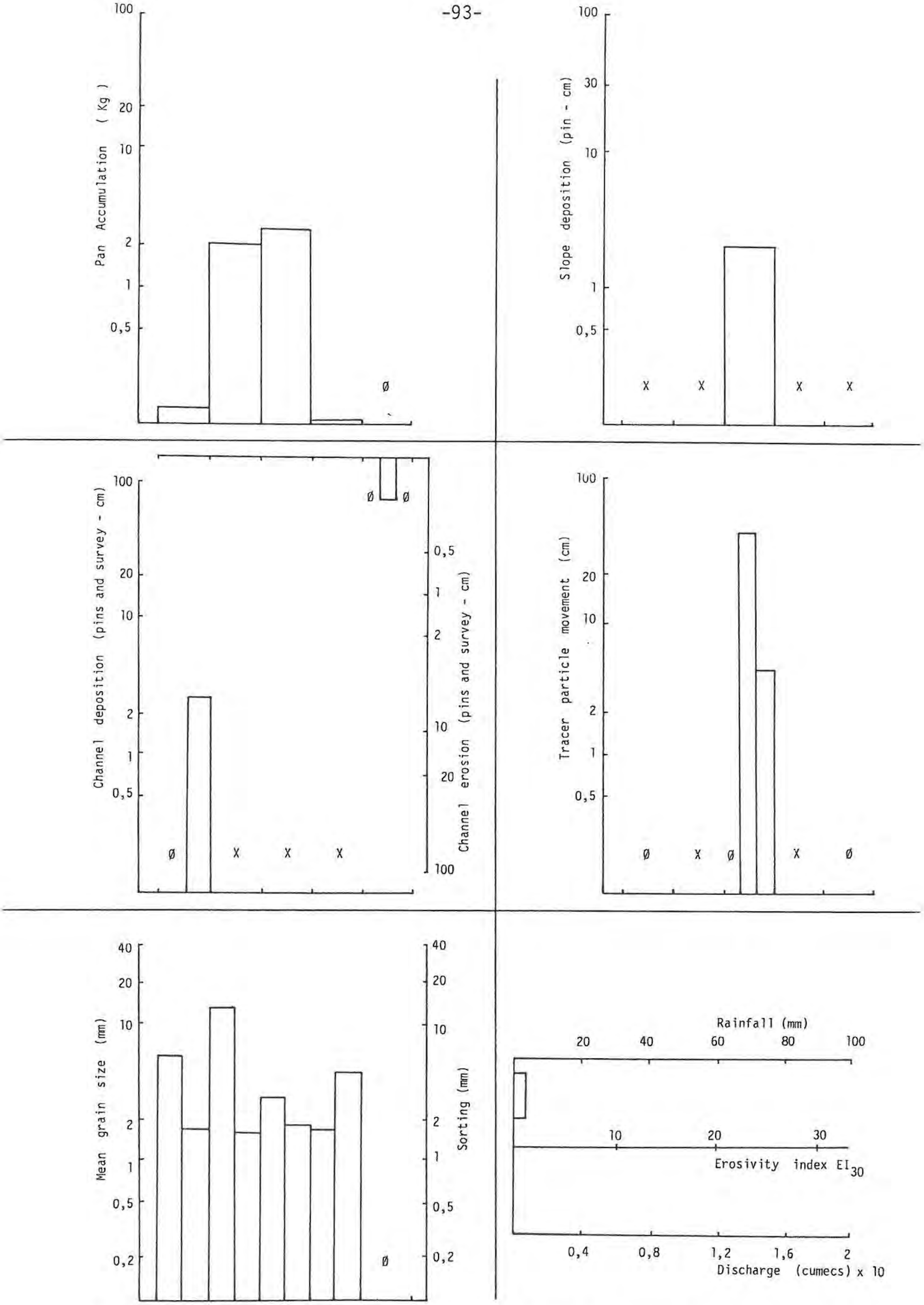

Figure 7.18. Data collected at the various sites on sample day 13.

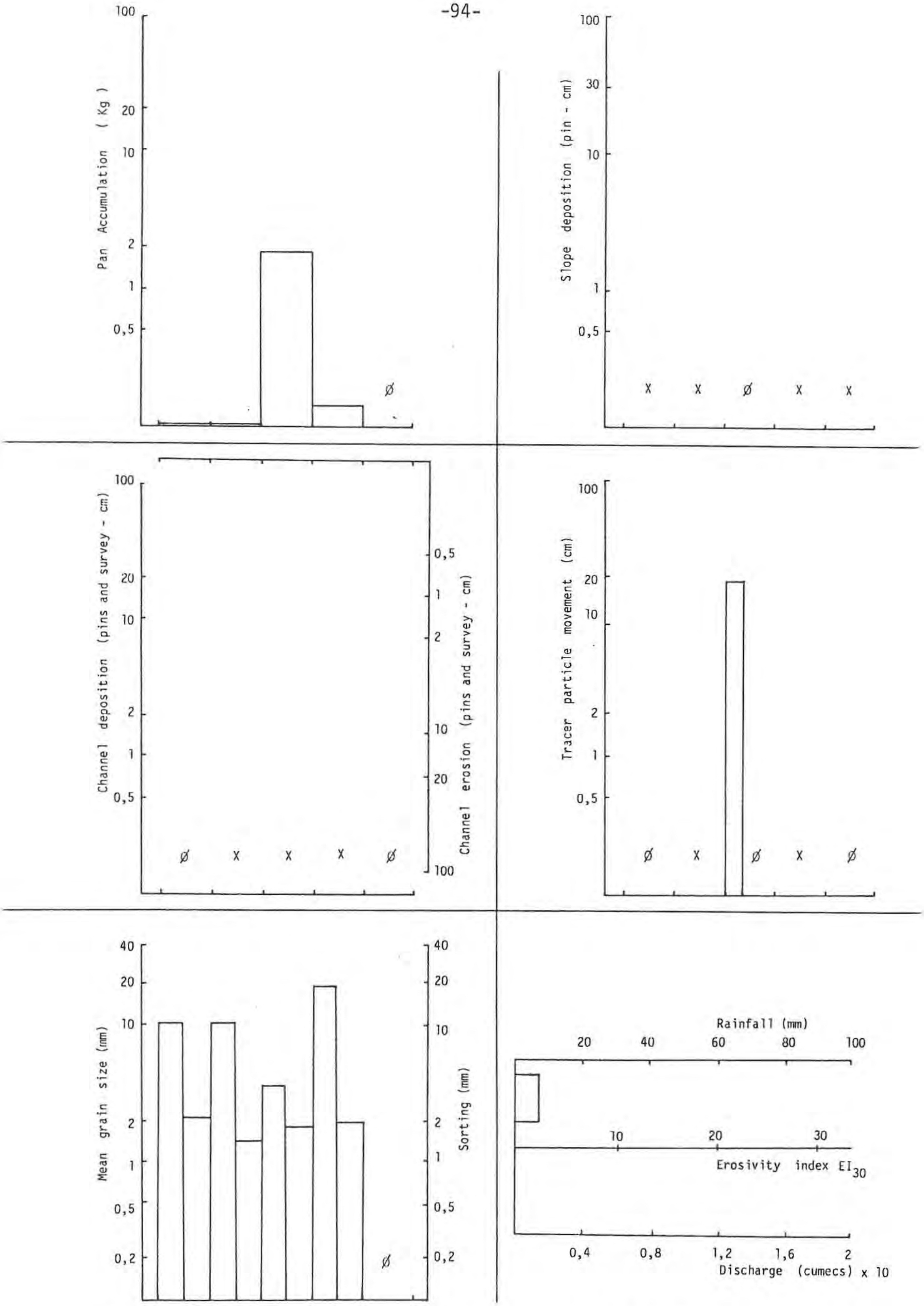

Figure 7.19. Data collected at the various sites on sample day 14.

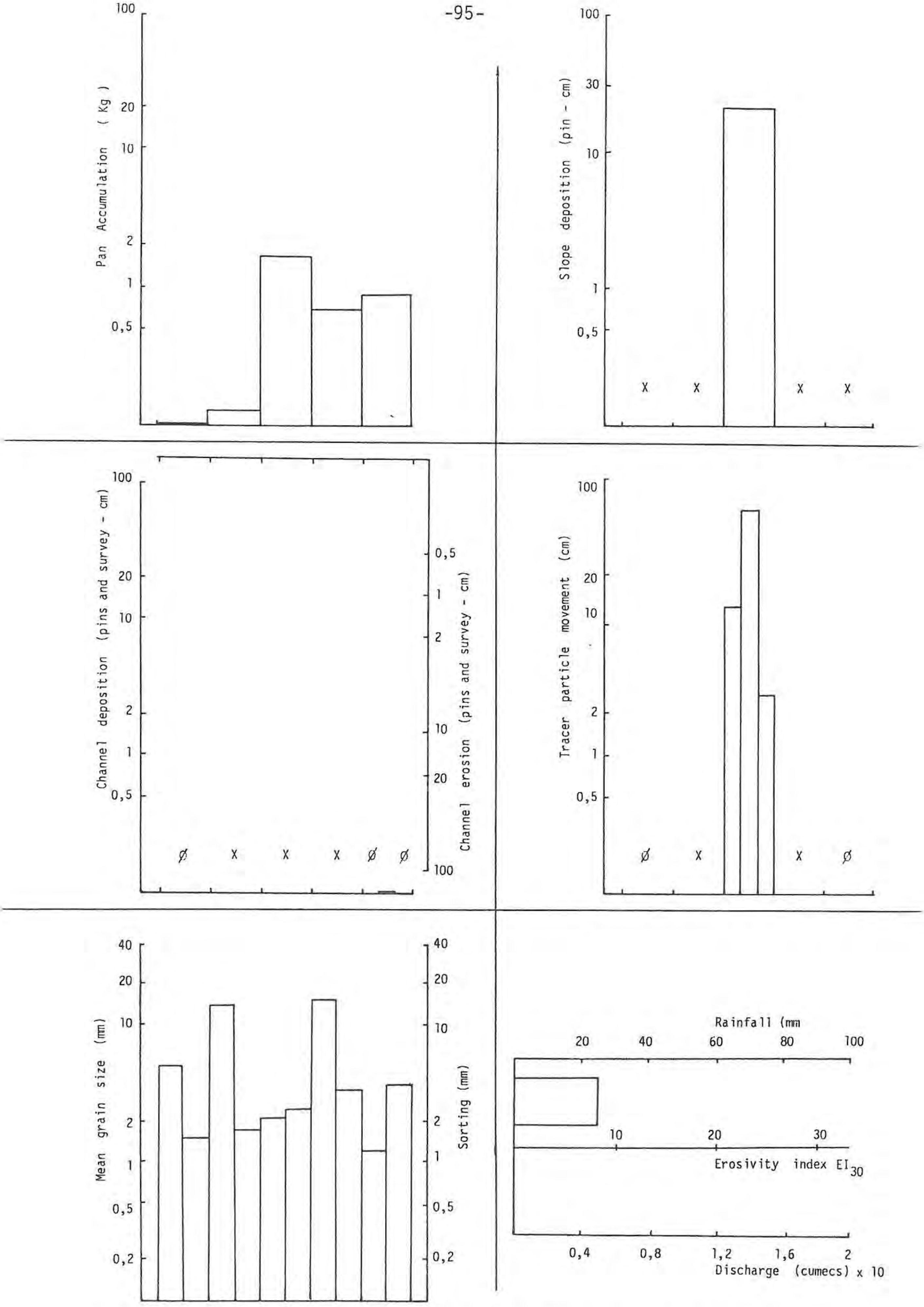

Figure 7.20. Data collected at the various sites on sample day 15.

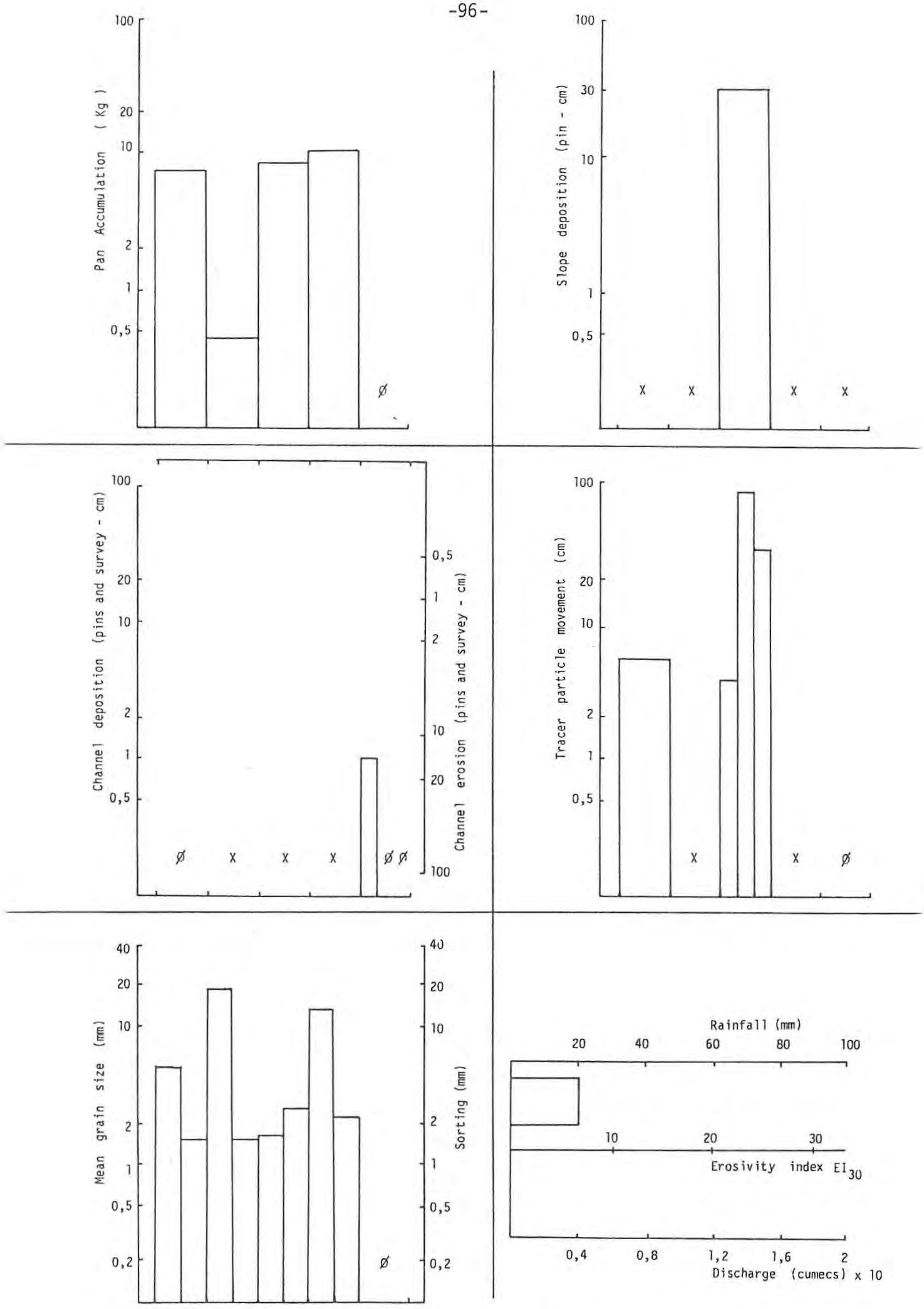

Figure 7.21. Data collected at the various sites on sample day 16.

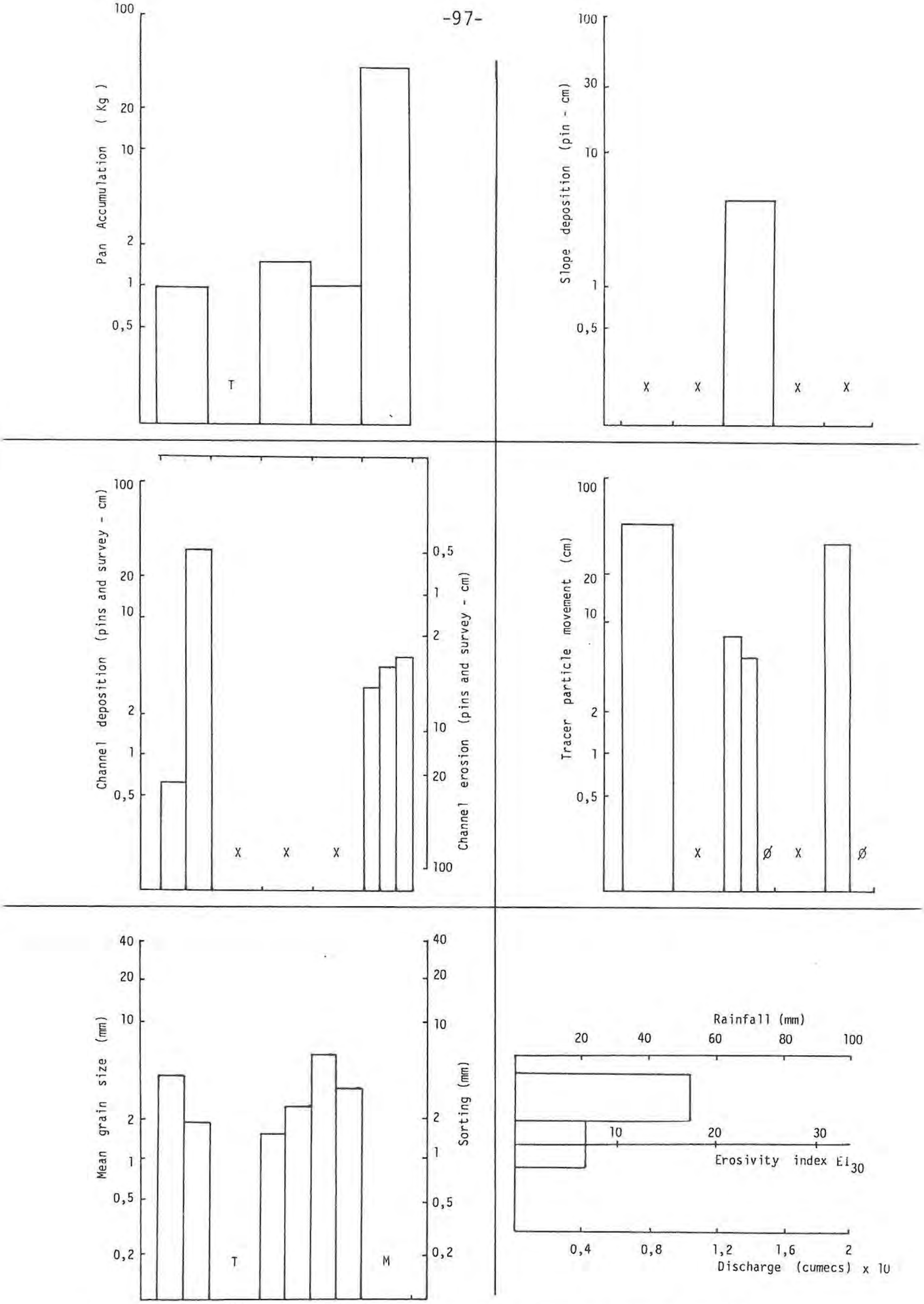

Figure 7.22. Data collected at the various sites on sample day 17.

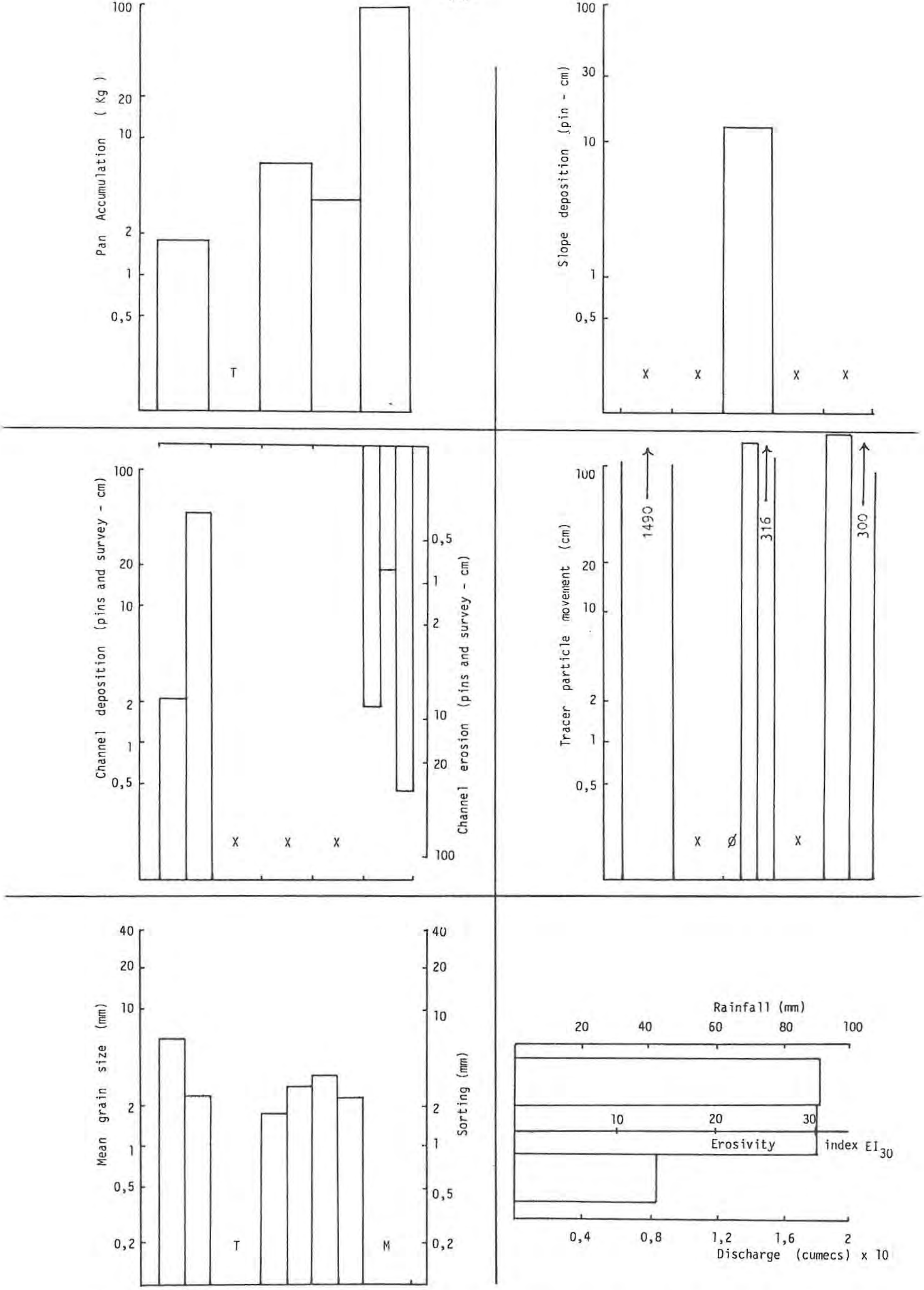

Figure 7.23. Data collected at the various sites on sample day 18.

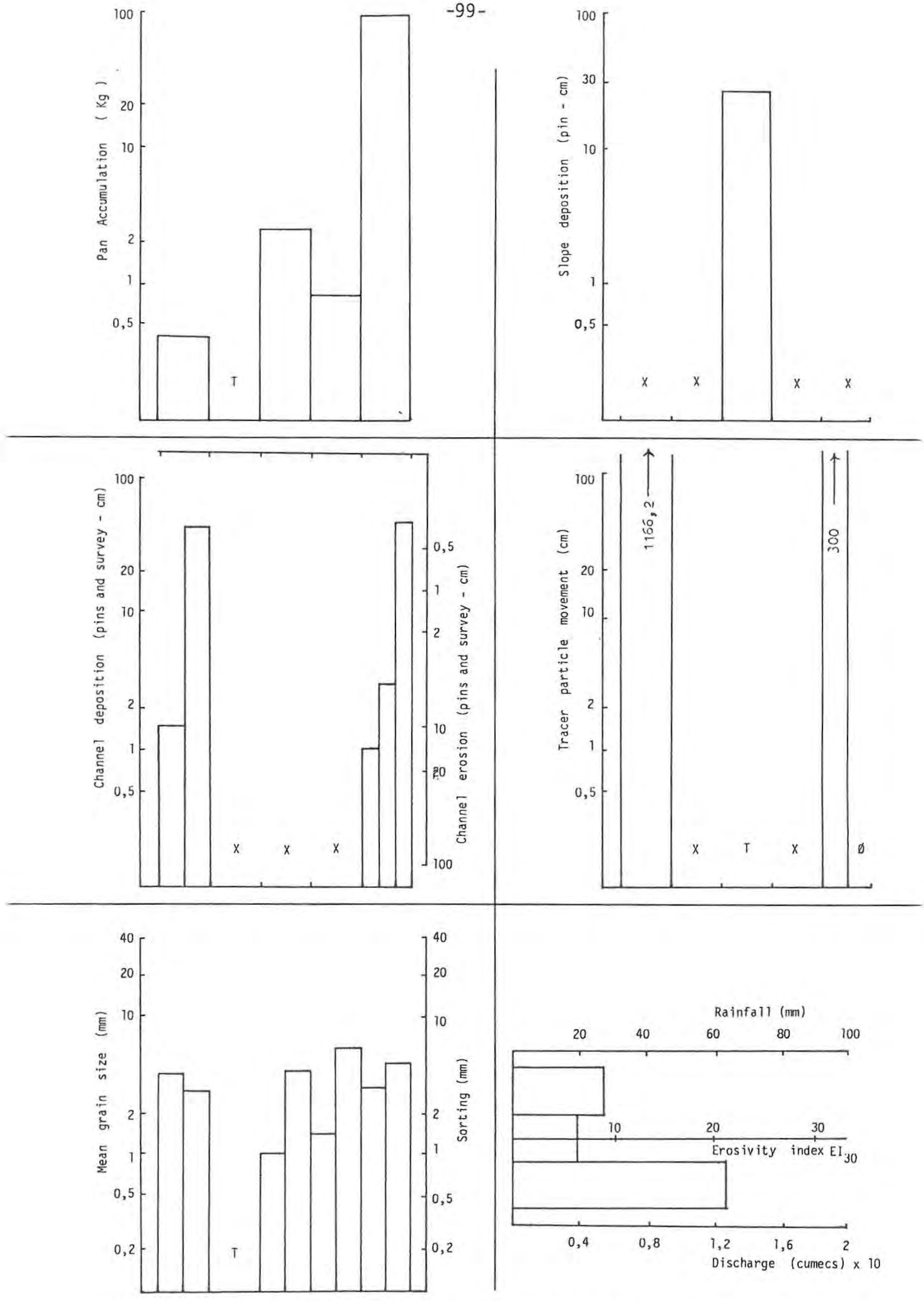

Figure 7.24. Data collected at the various sites on sample day 19.

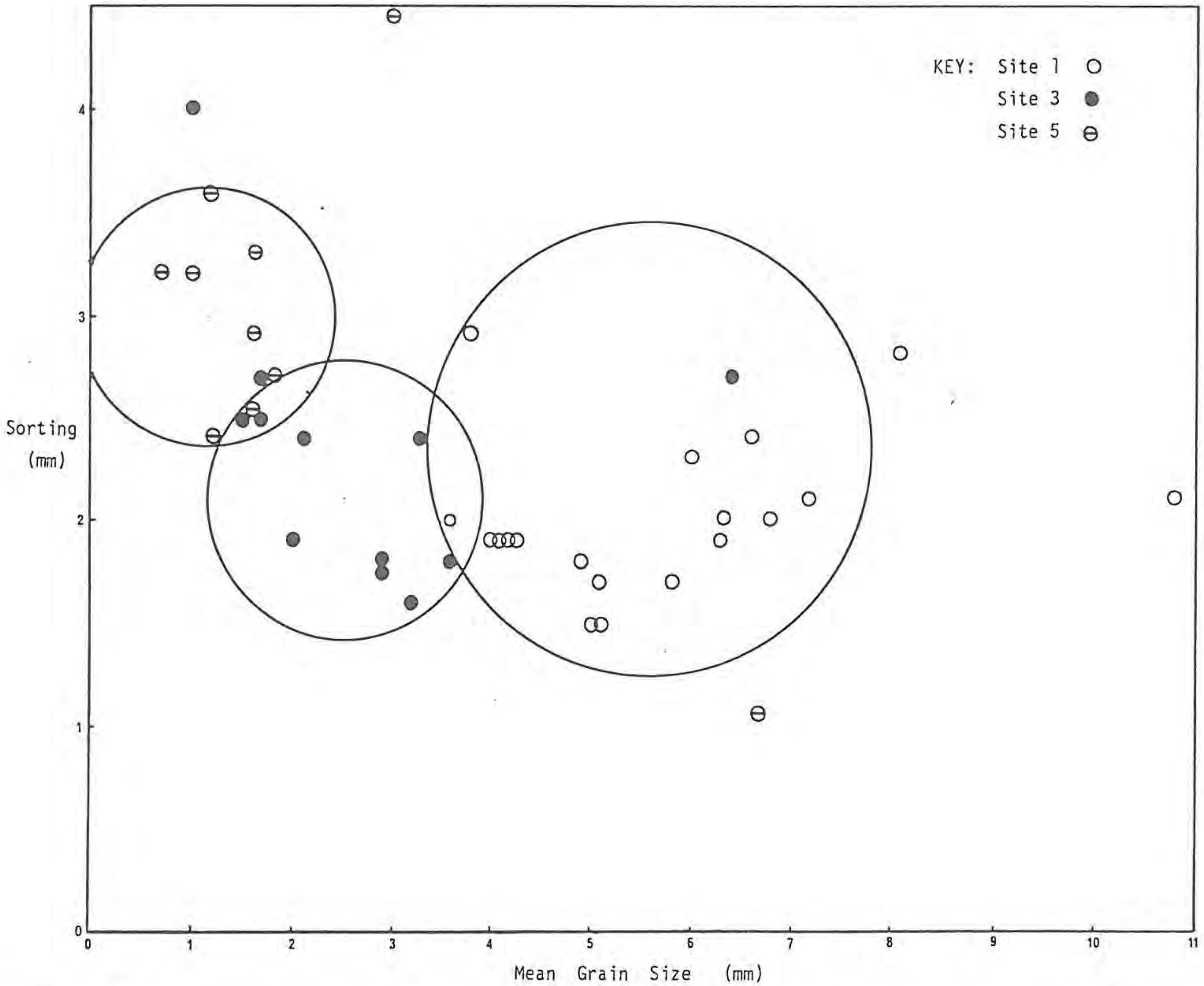

Figure 7.25. Scattergram showing the relationship between mean grain size and sorting of sediments from sites 1, 3 and 5.

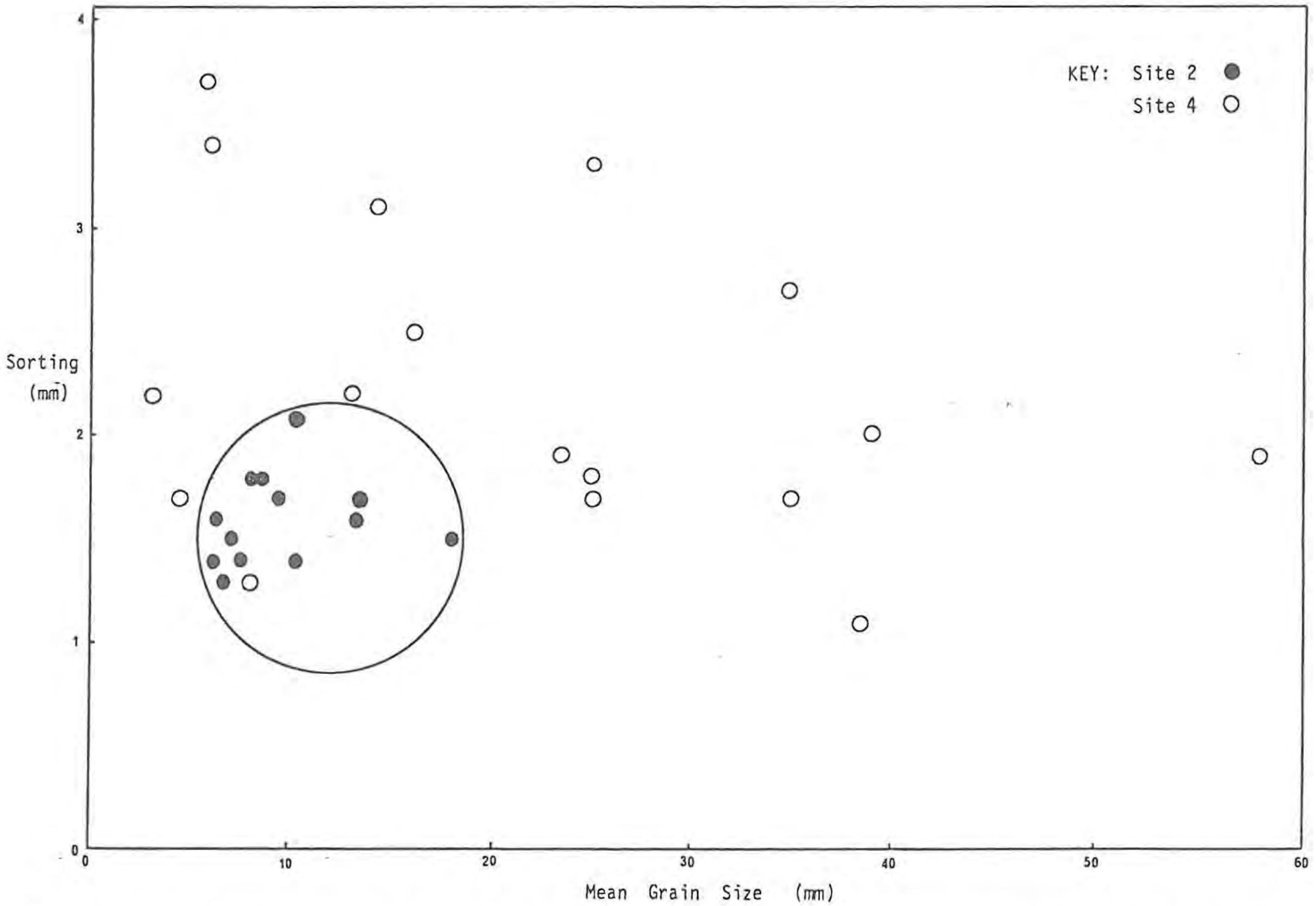

Figure 7.26. Scattergram showing the relationship between mean grain size and sorting of sediments from sites 2 and 4.

8. INTERPRETATION AND DISCUSSION OF RESULTS

8.1 Introduction

The results presented in chapter 7 require interpretation in terms of the aims of the study, as well as the conceptual model proposed in chapter 4. The results have limitations in that research was confined firstly to a 1-kilometre reach of channel assumed to be representative of the entire channel, and secondly to a period of two years, which fell during a period of drought (1983-1984). The results probably reflect reduced scales of sediment activity and are specific to the Ecca catchment, although wider application might be possible. The content of each section in the present chapter is based on one of the aims set out in chapter 1.

8.2 Processes active in the supply and transport of sediment in the Ecca catchment.

Processes which play a role in the eventual supply of sediment to a channel can be divided into two groups :

- Weathering of bedrock, making material available for
- Transport processes.

8.2.1 Weathering processes

The movement of particles, once attached to the section of exposed and painted bedrock, down the slope at site 3 represent qualitative evidence of the existence and rate of weathering in the study area. By the end of the fieldwork period, the entire section of the two painted shale outcrops (site 3) had been incorporated into the talus veneer on the slope. Shale, a dark fine-grained rock composed predominantly of clay, is highly susceptible to insolation weathering as well as hydration. The dark colour gives rise to low albedo values and allows heat absorption, while the clay particles absorb water causing volumetric changes which exert pressure (Clark and Small, 1982). Hydration is enhanced by the pronounced wet-dry cycles in semi-arid areas. Further weathering of the shale shards on the slope serves to reduce particle size as they move to the channel. This is indicated by grain size analysis on the slope at site 3. The mean grain size of sediment from the upper section of the slope was found to be 8,0 mm. Sediment from the middle section displayed a value of 6,42 mm. The mean grain size of sediment arriving in the pan at the base of the slope is 2,8 mm. A sample of sediment taken from the channel at site 3 displayed a mean grain size of 1,9 mm, indicating further size reduction in the channel by either in-channel weathering or mechanical breakdown by channel processes.

The model proposed in chapter 4 accommodates weathering in all event types A to D (see figures 4.4 a - d), and allows for an increase in weathering during rainfall episodes. Higher moisture levels serve to accelerate weathering processes (Clark and Small, 1982).

8.2.2 Transport processes.

A knowledge of the physical characteristics of a specific source area from which sediment is derived, as well as of the amount and frequency of supply from that source area, can give an indication of the specific sediment transporting process. The physical characteristics of each site monitored have been described and illustrated in previous chapters. The amount and frequency of sediment movement has been recorded in the data in chapter 7, and reproduced together with hydro-meteorological data as a time series in figure 8.1. Rainfall and discharge are recorded on a daily basis. It is possible to infer from the above, the transporting processes presently operating in the study area.

Transport processes are divided into three categories :

a) Channel processes
b) Slope processes, and
c) Animal activity related processes.

a) Channel processes: Two forms of channel flow, each representing a different scale of hydro-meteorological event, are evident in the study area:

i) Main channel flow : Thornes (1977) refers to main channel events as "fully-integrated" flow events, at which time flowing water occupies all

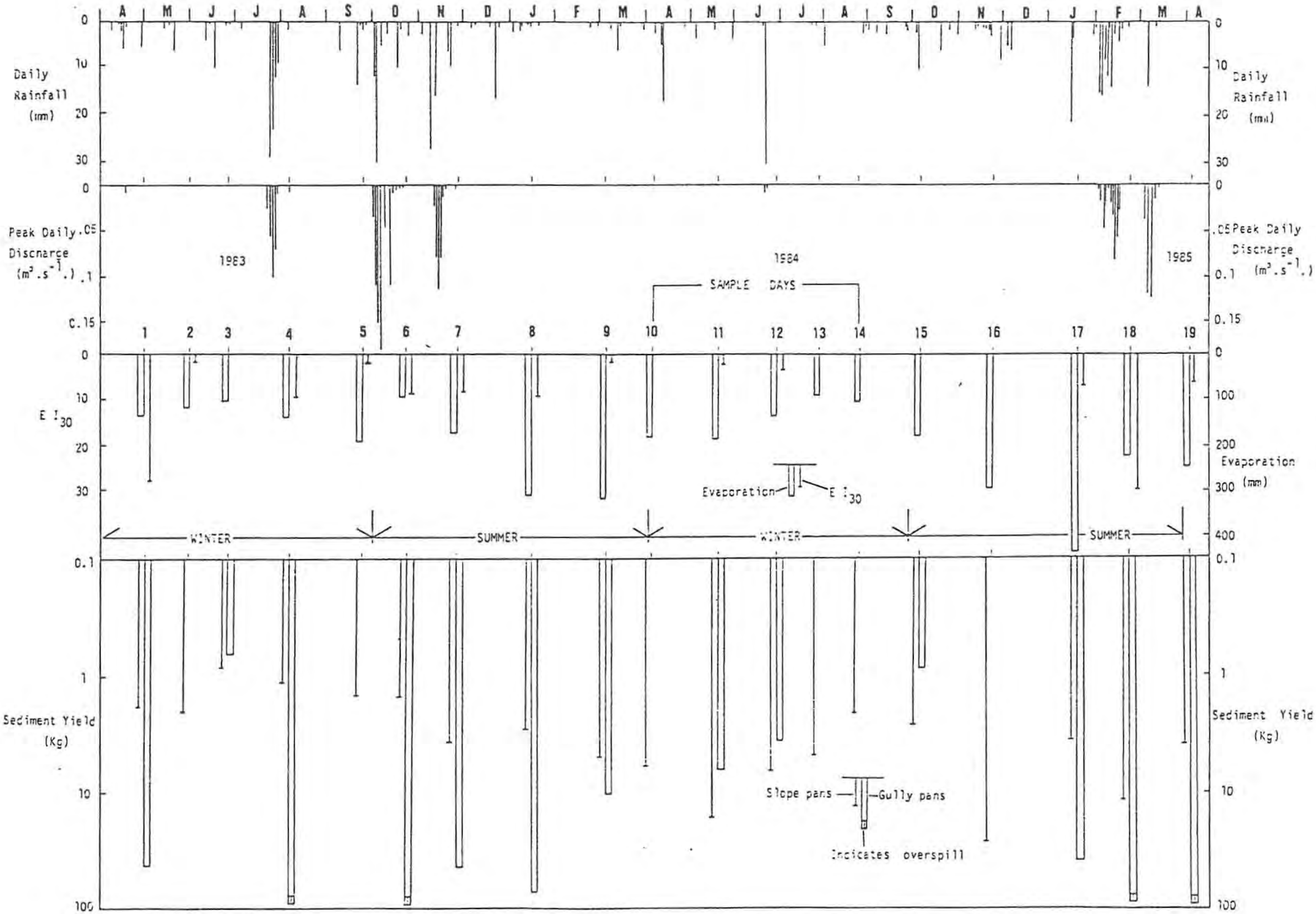

Figure 8.1. A representation of hydro-meteorological data and pan trapped data for the entire study period. Slope and gully pan data are illustrated seperately.

channels in the drainage basin. These events have a low frequency of occurrence in semi-arid areas. Several flow events of varying magnitude are recorded in the present study (figure 8.1). During these events the tributary gully pans trap excessive amounts of sediment (figure 8.1, periods 4, 6, 18 and 19) indicating tributary inflow. Movement of channel tracers at site 1 (table A.8) indicate channel transport. The channel survey at site 5 indicates erosion in the channel (table A.7) during the flow event recorded during period 18. Deposition of sediment occurred in the channel at site 5 during period 19 (table A.7). Bank undercutting is accelerated which promotes subsequent bank collapse (plate 7.1b).

After cessation of the formal data collection program, an event generating relatively high flows in comparison to the events observed during the study period was recorded. A discharge of 1,7 $m^3.s^{-1}$ was measured at the weir, whilst the highest discharge during the study period was 0,183 $m^3.s^{-1}$. The catchment was visited to assess the sediment response to a large scale event event. Observations made are based on tracers and erosion pins not removed from the study area. Channel erosion, as indicated by erosion pins, occurred to depths of 30 cm. Pins originally driven to this depth were completely missing, while others were barely left standing, particularly at site 1. The channel pins at site 1 had recorded net accumulation throughout the entire study period. Tracer particles long missing (table A.8; A.11 and A.12), presumed buried by previous events, were recovered far from their original location (up to 200 m). The largest tracer (long axis - 16 cm) had been transported approximately 60 m. The long established sediment accumulations at the base of slopes at site 1, 2 and 3 were entirely depleted. Bank erosion at the site 5 location (gully) had initiated numerous small scale bank collapse episodes. Where bank collapse had previously occurred in the tributary gully, the collapsed material had been removed. Deposition of sediment in certain channel environments was evident, especially upstream of the weir at the catchment outlet.

ii) Tributary inflow events: Termed "asynchronous tributary flow" by Thornes (1977) these events are characterised by tributary inflow to a dry main channel (chapter 3). Sediment trapped in the pans at the mouth of the gully system indicate periods during which these events occur (figure 8.1). Their occurrence is not necessarily related to flow in the main channel.

During these events sediment accumulated in the main channel. This accumulation then awaits a larger scale channel flow event to either remove the sediment, or re-distribute it in a downstream direction. The processes operative in the gully system during such episodes are transport of sediment derived from bank collapse episodes and minor rills (plates 7.2a and b) leading into the gully and bank undercutting in the erodible alluvial material.

Tributary inflow events are generally associated with increased EI_{30} values which may not necessarily generate main channel flow (figure 8.1). The gully system therefore represents an environment reponsive to smaller scale rainfall episodes than those required to generate main channel flow.

b) Slope processes: The total amount of slope-derived, pan trapped, sediment for each sample period demonstrates the lack of a clear relationship to rainfall amount or EI_{30} (figure 8.2 and 8.3). The supply of material from slopes continues on an uninterrupted basis, varying only in amounts (figure 8.1). The period from April 1983 to January 1984 (periods 1 to 8) does, however, indicate reduced sediment activity on the slopes (figure 8.2 and 8.3). The processes which are responsible for sediment transport on the slopes must be interpreted against this background. For convenience they are divided into three classes :

i) Wash related processes,
ii) Gravity, and
iii) Combination of gravity and fluvial.

i) Wash related processes : The cumulative plot of tracer movement on the slope at site 3 (in a rill and on the open slope) against rainfall (figure 8.4) indicate a general increase in movement in relation to rainfall increases. The movement of tracers on the slope is evidence of the ability of water on the slopes to transport sediment. The two processes illustrated in figure 8.4, rilling and slope wash, appear to operate in alternating cycles. Up to period 10, a large amount of movement is recorded for tracers in the rill, but comparatively very little on the open slope. After period 10, slope sediments begin to move larger distances, while rill tracers show a decline in movement. Carson and Kirkby (1972) have described how rills

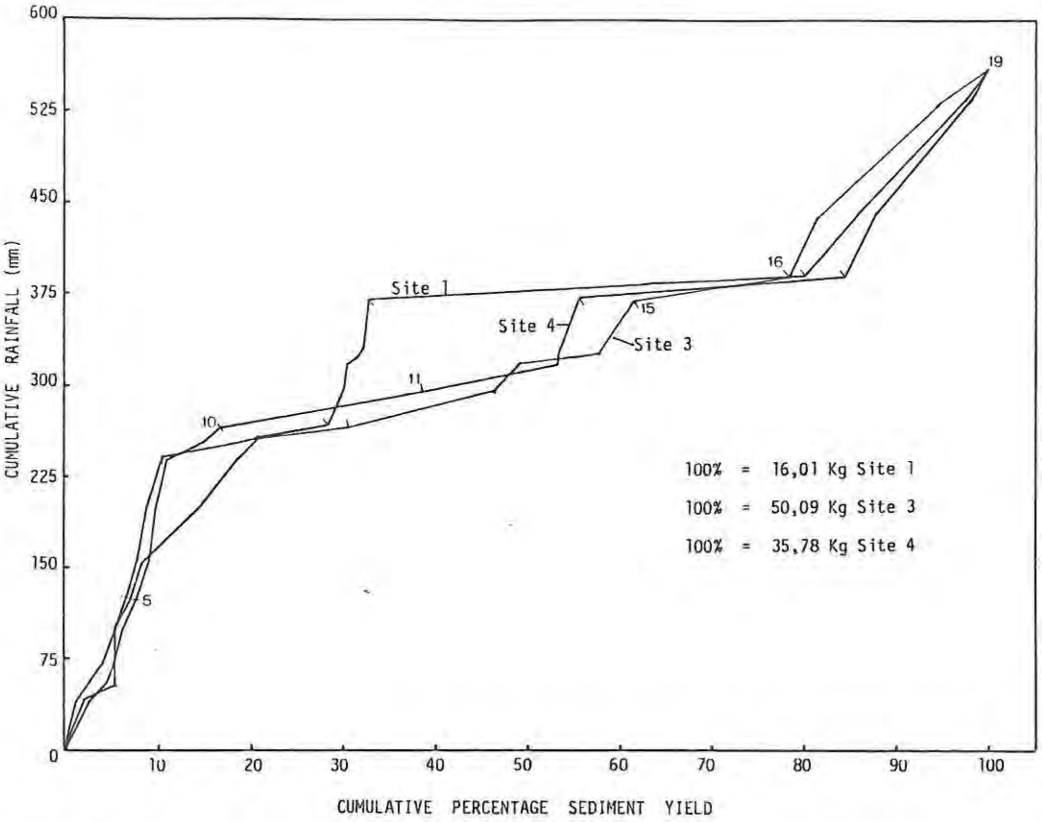

Figure 8.2. Cumulative rainfall and cumulative percentage sediment yield for three slope pans at sites 1, 3 and 4.

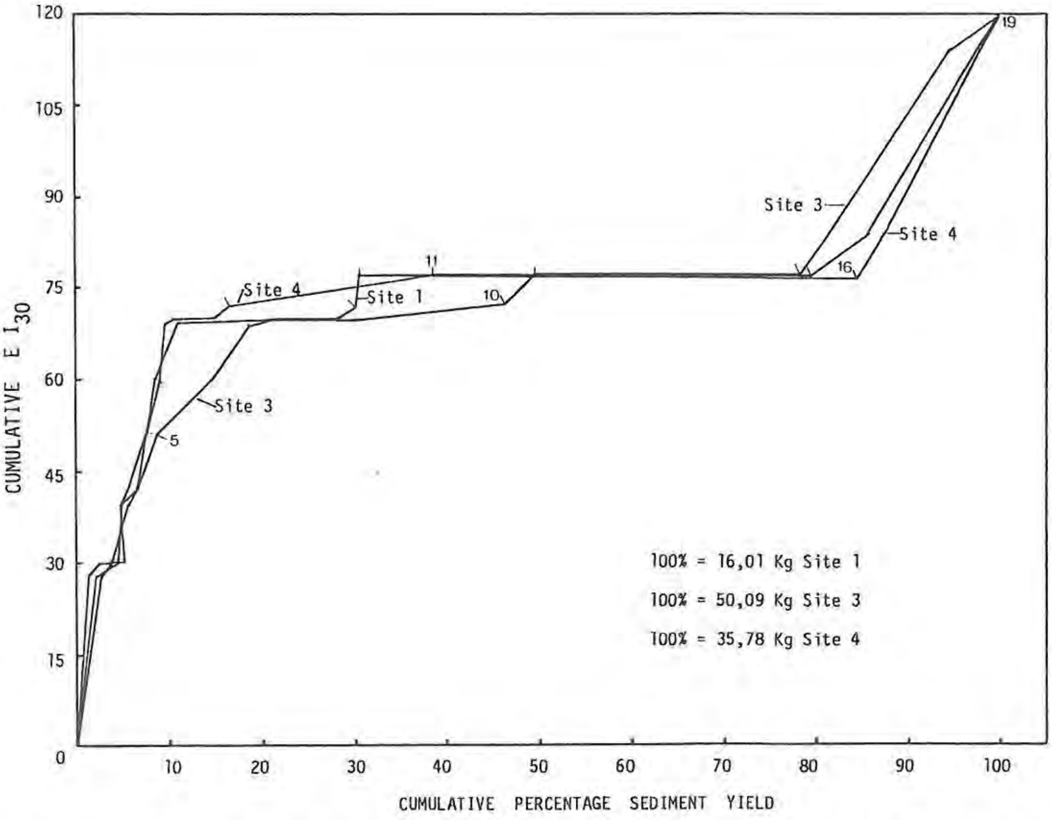

Figure 8.3. Cumulative EI_{30} and cumulative percentage sediment yield for the slope pans at sites 1,3 and 4.

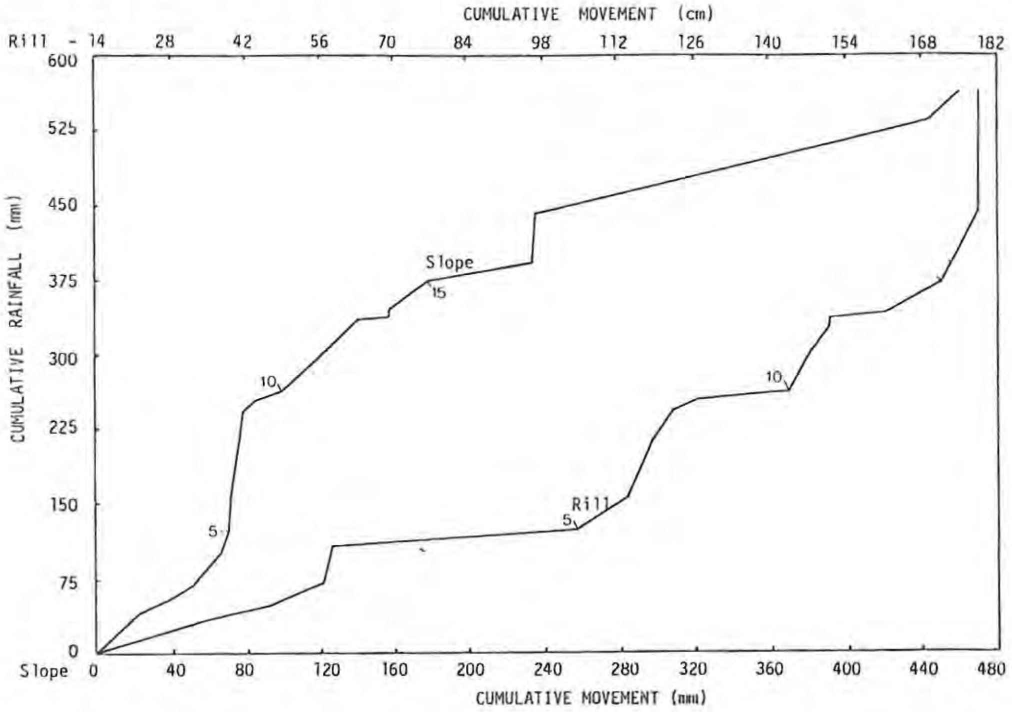

Figure 8.4. Cumulative rainfall and cumulative tracer movement on the slope and in the rill at site 3.

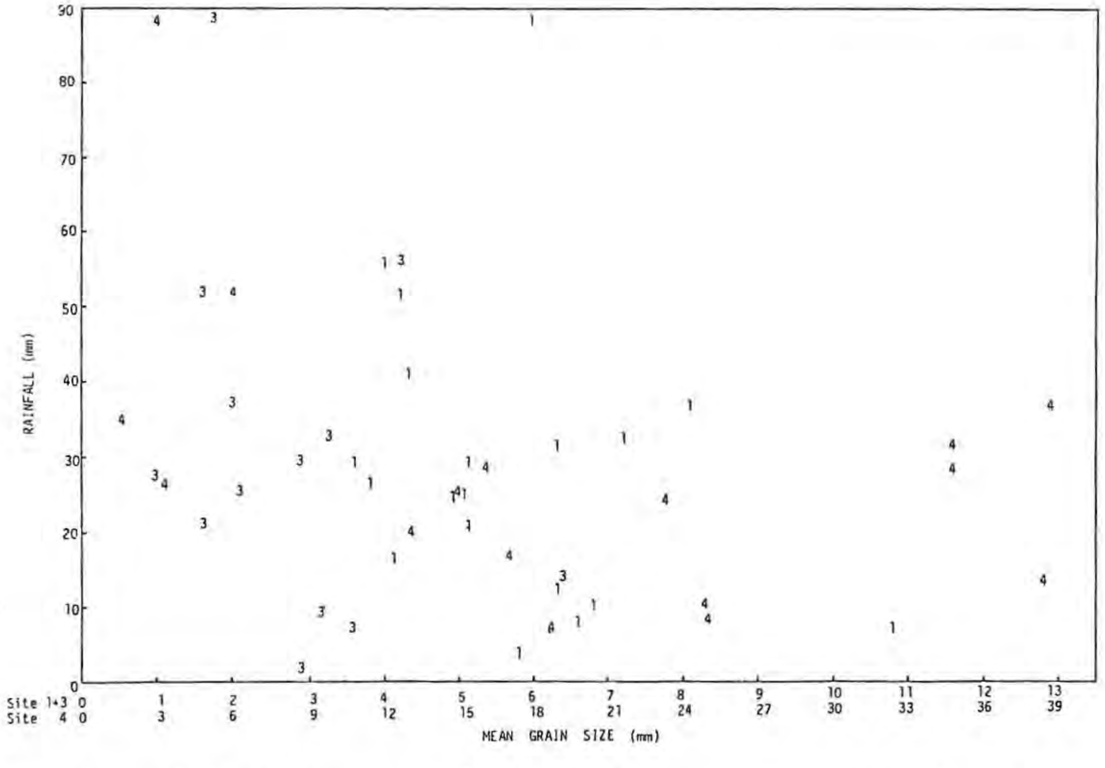

Figure 8.5. Scattergram of rainfall versus mean grain size of sediments from sites 1, 3 and 4. The numbers represent points for that site.

tend to become blocked in time and alter course as a result. This appears to be the case in the present study where after period 17, the rill altered course. The rill tracers abandoned in the old channel record no movement in response to the highest rainfall period recorded in the study (period 18).

ii) Gravitational processes : As no sample period was without rain, the present study recognises the difficulty in isolating any purely gravitational transport episodes on the slopes. The rainfall and EI_{30} amounts recorded for periods 13 and 14 cannot explain the amount of sediment activity on the slopes (figure 8.1). It is suggested that during these periods. gravity plays a more important role in sediment transport in the form of talus creep. Certain authors (Kirkby, 1969; Gardner, 1979) have described how minimal amounts of rainfall serve to remove fine material from the base of coarser particles (chapter 2) rendering them unstable. The coarser particles then move downslope under the influence of gravity. It would be reasonable to expect an increased mean grain size value for this gravity supplied sediment. The scattergram of rainfall versus mean grain size (figure 8.5) illustrates the tendency for mean grain size to increase with decreasing rainfall, especially at site 4. The suggestion is that during low rainfall periods, sediment supply is dominated by gravity processes. which are effective in transporting the larger particles of the sediment fraction, leading to an increase in mean grain size. Raindrop impact, where the drops are able to move individual particles residing in a condition of instability, is likely to be an important process during such periods (Palmer, 1965). Periods when gravitational supply processes (talus creep) became important can therefore be identified from the grain size characteristics of the sediment yield (Harvey, 1974).

A second gravity induced process observed in the study area is that of bank collapse (plates 7.1a and b). Bank collapse is an important process in the erodible alluvial material of the gully environment, where bank undercutting by fluvial processes leads to instability in sections of the bank. The depth to which the bank is undercut at specific sections is estimated at about 70 cm.

iii) Combined gravity and fluvial processes : The nature of the material at site 4 (consolidated colluvium) is such that gravity would find greatest expression when sections of the slope become saturated. The resultant decrease in shear strength renders the material vulnerable to mass movements such as slumps (Selby, 1982). One such slump is recorded in the present study at site 4 during period 11 (figure 8.2 and 8.3). The large mean grain size of the sediment (table A.13) trapped in the pan is typical of this type of process (Kelsey, 1980).

c) Animal activity related processes : Although animal activity would normally be integrated into a discussion of slope processes, the scale and significance of the process in the present study warrants a separate discussion. Period 16 records the largest amount of sediment yielded by the slopes at all sites (figure 8.2 and 8.3). The same period also records less than average rainfall (standard score, -0,44), no EI_{30} value and no gully pan sediment (figure 8.1). The influence of animal activity on sediment transport on slopes has been documented by authors such as Thomas (1965), Schumm (1967) and Harvey (1974). At the end of sample period 16, significant amounts of goat droppings were observed in the pans, suggesting a period of grazing. In negotiating steep channel bank environs, goats are capable of disturbing loose sediment accumulations and triggering slides on banks veneered with talus. Carson and Kirkby (1972) have indicated that trampling by animals can cause filling of rills. It is therefore possible that animal activity contributed to the eventual blocking of the rill on the slope at site 3 (see discussion in b) above). The scale and frequency of animal activity will depend entirely on the grazing rotation plan practised by the farmer. In semi-arid areas the sum effect of animal activity would be to increase the channel storage component of the sediment supply model in between major flow events.

Attention has been drawn to the effects of the major flow producing event on channel processes. The effects of this event on slope material should be summarized in order to provide a broader base on which to evaluate the conceptual model in a later chapter. The scale of sediment activity on slopes far exceeded that for any event during formal fieldwork, and indications of mass removal of available sediment were in evidence. In certain locations (e.g. site 1) sections of slope buried under talus for the entire study period were washed clear. Although difficult to confirm without instrumentation, certain sections of slopes appeared to have undergone minimal lowering. All tracers not previously transported to the channel were in the channel some distance (±5 m) from the source area. The shale particles in the channel were much reduced in size compared to those remaining on the slopes. Certain slope sections having a veneer of debris surviving the wash processes, were highly dissected by numerous rills. Isolated cases of former ephemeral rills were now established as more dominant features. Alternatively, other rills abandoned old courses for new ones, while yet others were entirely obliterated by sediment infill. As the pans had been removed, no sediment had been trapped. The positions which they had occupied were completely buried, indicating that amounts which might have been trapped would have exceeded those for any period during the formal data collection program.

8.2.3 Conclusions

The following conclusions can be drawn from the above discussion on processes active in the study ares :

a) The process identified above can operate independently (e.g. weathering) but mostly they are inter-dependent (e.g. bank collapse and bank undercutting).

b) A major rainfall event will cause all of the above process to operate (channel and slope).

c) To a certain extent, the type of process dominating at any time is reflected by the size characteristics of the sediment yield (Harvey, 1974).

d) Weathering processes serve to detach particles from the bedrock but subsequent removal may have to await instability failures or a period of extreme surface erosion.

e) It is difficult to distinguish between purely gravity and purely fluvial transport as transport is not related to measurable hydro-meteorological variables. Gravitational and fluvial transport processes are therefore highly interrelated.

8.3 Factors affecting supply of coarse sediment

8.3.1. Introduction

The third aim of the study was to determine the extent to which certain variables might affect sediment supply. The variables are divided into two groups, extrinsic and intrinsic. The extrinsic variables include a) rainfall amount, b) rainfall intensity, and c) channel flow. The intrinsic variables include a) geology/lithology, b) dip of strata, c) aspect of channel banks, and d) size of material. To facilitate the discussion in the present section, a summary of the conditions at each site is given in Table 8.1.

Table 8.1 A comparison of intrinsic conditions at sites 1 to 5

Site	Geology/lithology	Dip of strata	Angle of Bank	Aspect
1	Shale	Away from channel	65°	South
2	Shale	Away from channel	80°	South
3	Shale	Into channel	40°	North
4	Consolidated Colluvium	-	85°	South
5	Consolidated Alluvium	-	-	-

8.3.2 Extrinsic factors

a) Rainfall amount : A comparison of the distribution of rainfall amount with sediment yield for the entire study period does not reveal a clear relationship between these two variables. This is particularly true of slope derived sediment (figure 8.1). Some of the highest slope yields are recorded during periods of lowest rainfall. The cumulative plot of rainfall against percentage sediment yield from all the slope pans illustrates three phases of sediment activity (figure 8.6). In the first phase (periods 1 to 8) a relatively large increase in rainfall does not lead to correspondingly high sediment yields. In the second phase (periods 9 to 16), smaller increases in rainfall result in an almost threefold increase in sediment

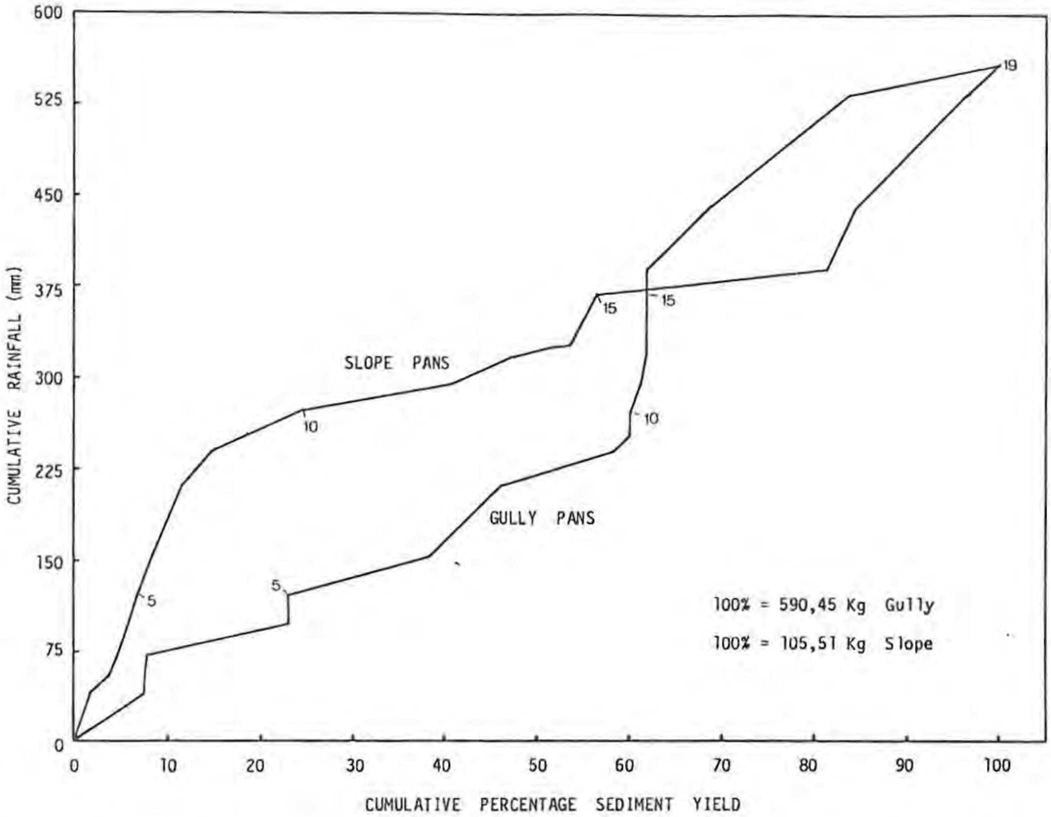

Figure 8.6. Cumulative rainfall and cumulative percentage sediment yield for all slope pans and the gully pans.

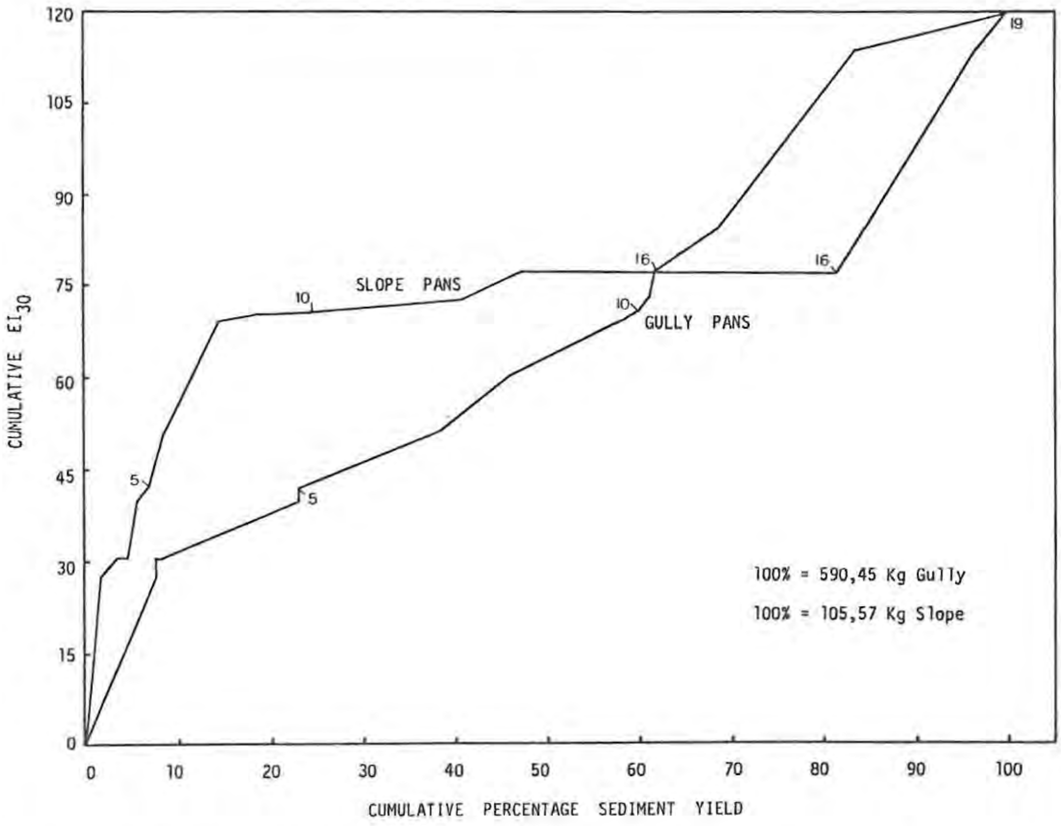

Figure 8.7. Cumulative EI_{30} and cumulative percentage sediment yield for all slope pans and the gully pans.

response. The third phase (periods 17 yo 19) reverts back to the first phase pattern of reduced sediment response. It must be concluded that sediment yield from the slopes is also affected by other variables apart from rainfall amount. This aspect will be discussed in section 8.3.3a)

Sediment yield at the gully pans is less influenced by gravity processes or animal activity. As a result higher rainfall periods generally record larger sediment yields at the gully mouth (figure 8.1). Largely because the relationship between rainfall and surface runoff is a poor one, the relationship between sediment yield at the gully mouth and rainfall amount is nevertheless a poor one.

The cumulative plot of rainfall against sediment yield from the gully reveals a tendency for sediment supply to increase in summer and decrease in winter (figure 8.6). From April 1983 to September 1983 (winter) the sediment yield is much less than for the summer of 1983/4 (periods 5 to 9). The flattening of the curve indicates increased yield during these periods. From March through to October (winter 1984, periods 9 to 16) the steepening of the curve to almost vertical indicates a sharp decline in sediment yield from the gully. The flattening of the curve from November onwards (summer 1984/5) indicates substantial increases in sediment yield similar to the 1983/4 summer pattern. The actual sediment amounts yielded during the winter and summer seasons (extracted from table A.2) reveal that summer yields are more than double (2.8) than those for winter (table 8.2).

Table 8.2 Winter and summer sediment yield (kg) at the gully mouth

Season	1983	1984	1985	Total
Winter	136,15	21,08		157,23 kg
Summer		218,23	225,00	443,23 kg

However, because the distribution of rainfall amounts are not as seasonally pronounced as sediment yield, the cause of this seasonality of yields must be sought in some other climate-related variable.

b) Rainfall intensity : The variable used to give an indication of rainfall intensity is EI_{30} (see chapter 6). EI_{30} values are generally higher in summer (figure 8.1), with the exception of periods 1 and 4. The cumulative plot of EI_{30} against slope sediment yield shows a similar pattern to the rainfall plot (figure 8.7). The same three phases are apparent, indicating the lack of a relationship between EI_{30} and sediment yield from the slopes. The cumulative plot of EI_{30} against sediment yield from the gully again reveals a seasonal pattern as described in the discussion above. It has been noted in chapter 5 of the present study that most of the summer rainfall resulted from short duration, high intensity convectional thunderstorms. This would explain higher EI_{30} values in summer. All periods recording EI_{30} values, except 2 and 5, also record sediment yield at the gully. Periods not recording EI_{30} values do not record sediment yield at the gully (except 3 and 15). It appears that EI_{30} is a useful indicating variable for tributary inflow events, and the seasonality of this variable is reflected in the seasonality of sediment yield at the gully mouth.

Thornes (1977) indicates that high intensity rainfall episodes are able to overcome infiltration rates sooner than low intensity episodes, giving rise to high energy turbulent flows. These type of flow events, although limited in space and time due to transmission losses, are capable of transporting significant amounts of sediment. The cumulative plot of rainfall and EI_{30} against tracer movement in the upper gully system (figure 8.8) indicates that EI_{30} gives a more accurate account of sediment movement. This is shown by the shorter vertical section of the EI_{30} curve from periods 10 to 17. Increasing amounts of rainfall through these periods reflect no movement. During this period of no movement, EI_{30} does not increase to the extent that rainfall does. Periods 12 to 16 record neither tracer movement nor EI_{30} values.

Variation in EI_{30} amounts also appears to be important for channel erosion. The channel bed survey at site 5 (figure 8.9) indicates net erosion during the flow event recorded during period 18 and net deposition during period 19. Period 18 records a higher EI_{30} value than period 19 (figure 8.1). The sequence of erosion and deposition at site 5 from period 18 to period 19 is more complicated, however, and will be discussed in a later section.

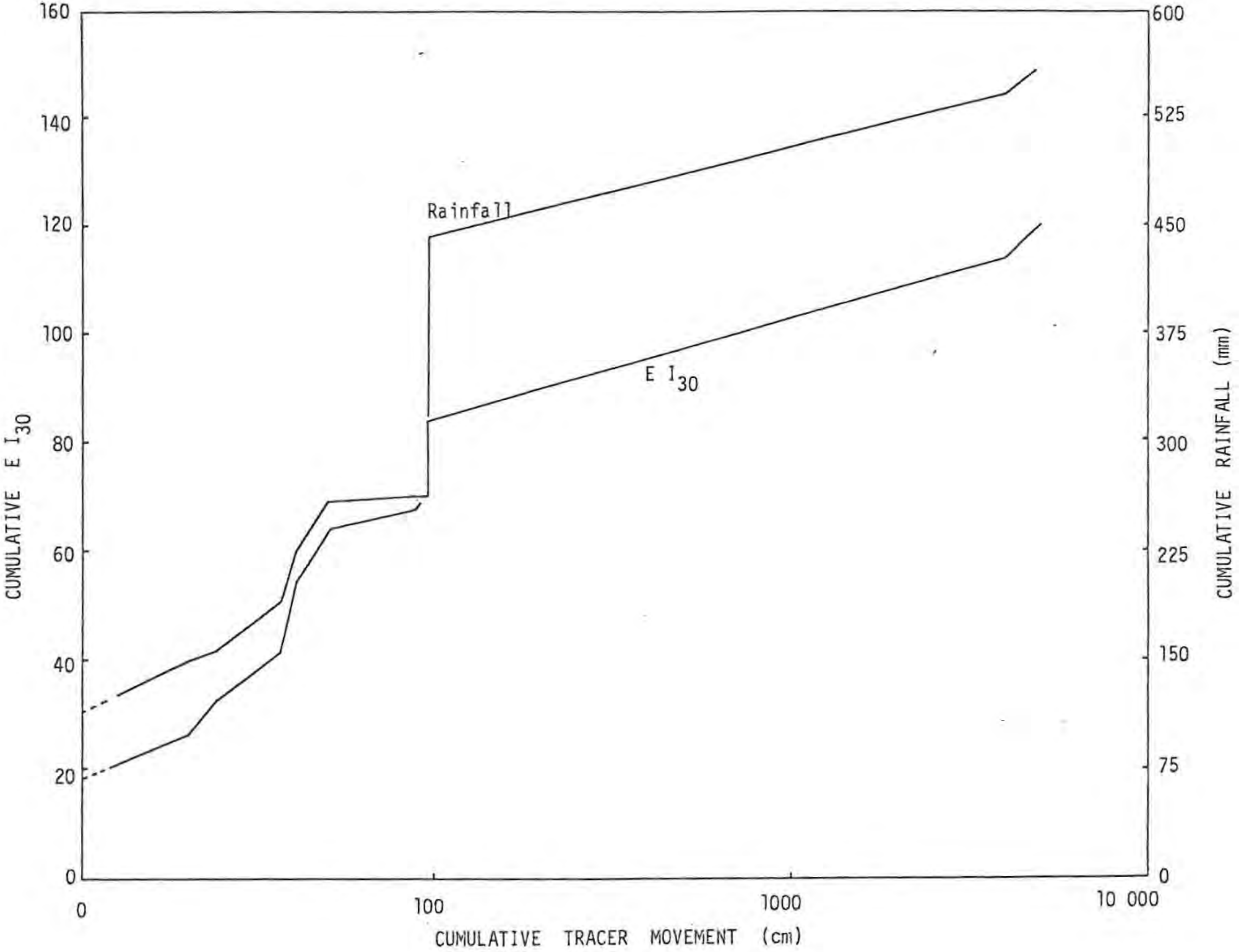

Figure 8.8. Cumulative rainfall / EI$_{30}$ and cumulative tracer movement of tracers in the main gully head at site 5.

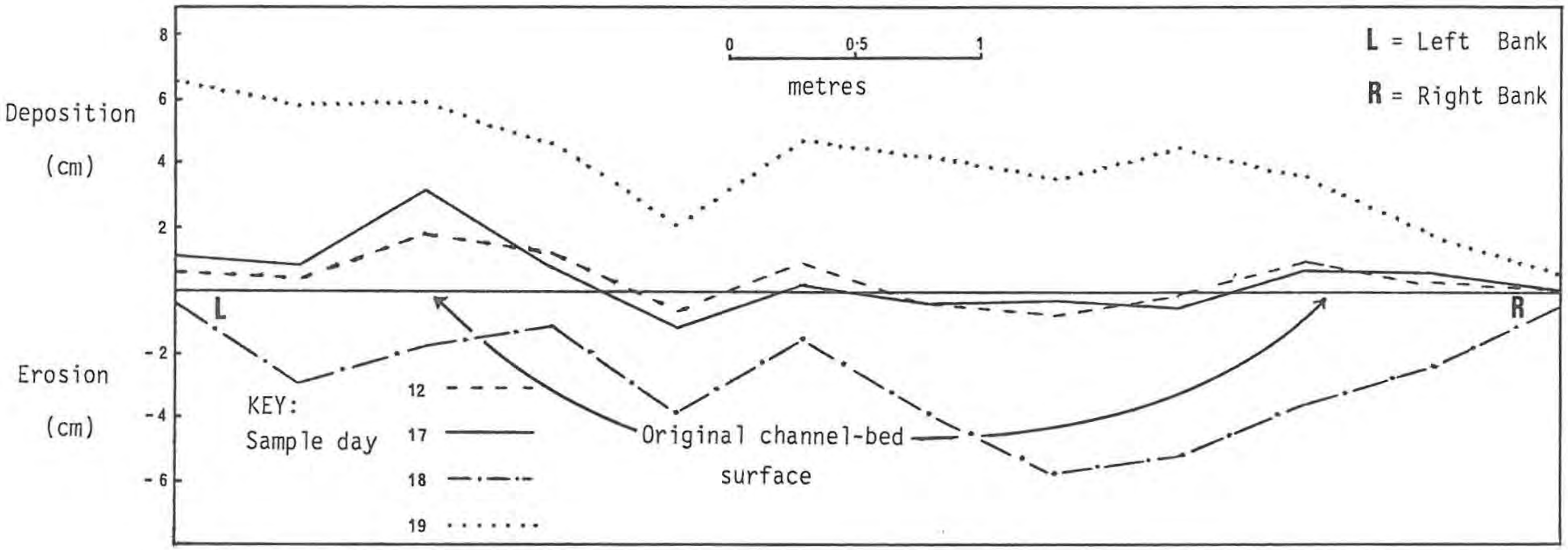

Figure 8.9. Channel bed surface profile variations at the tributary inlet.

c) Channel flow : Two scales of channel flow have been identified. Tributary inflow events are responsible for the accumulation of sediments in the main channel as channel storage (chapter 3). Major flow events are also responsible for deposition of allocthonous up-channel sediments in the reach, which increase sediment availability for future major flow events. The process of bank undercutting during flow events prepares the banks for future collapse episodes which ensure future supply.

8.3.3 Intrinsic factors

a) Geology/Lithology : The manner in which geology influences sediment supply is through its control of material type, spacing of joints, susceptibility to and rate of weathering, particle size of weathered fragments and hardness of material. The rate of weathering determines the weathering period which in turn influences the sediment availability factor. In the present study, three source materials have been identified and monitored : exposed sections of shale bedrock, alluvium and colluvium.

The exposed sections of shale bedrock are capable of supplying significant amounts of shale particles. The amounts supplied have been shown to vary (section 8.2.2b), the variation being unrelated to rainfall amount or EI_{30} (section 8.3.2a and b). Slope sediment transport also bears little relationship to rainfall amount or EI_{30}. It is suggested that sediment availability as determined by the rate of bedrock weathering (similar to the "weather period" referred to by Harvey, 1974 p. 47) on the slopes is a factor which, along with the influence of gravity movement, could be partly responsible for the poor rainfall - sediment supply relationship from the slopes.

The conceptual model (chapter 4) recognises the importance of the availability factor in that it incorporates three storage components, in situ and secondary slope storage as well as channel storage. These components can vary with the scale of the event, and equally importantly, with the sequence of events, as large scale events can reduce sediment availability for a subsequent event.

The alluvial material at the tributary gully location, while being consolidated, appears to be highly susceptible to erosion by running water. Flow events never fail to transport sediment from this source. The type of material at the tributary location is illustrated in plates 7.2a and b, and morphology changes in the channel of the rill were clearly visible after a 25 minute 16 mm rainfall event during period 1. The colluvial material at site 4 was trapped in smaller amounts than the alluvial material at site 5, but more regularly and unrelated to flow events. The lithological structure of the material at site 4 in terms of the presence of larger cobbles providing effective armouring protecting the surface, exercises rigorous control on the transport of sediment from this source.

b) Dip of strata : The angle of the channel bank is determined by the angle of dip of the strata where a channel is cut into dipping sedimentary rock. Where strata dip into the channel, the slope angle is reduced (table 8.1). For two slopes of the same height, the length of the slope is increased for that slope having a less steep gradient. The bank at site 3 is an example of an environment where the above conditions exist. The data presented in chapter 7 (figures 7.6 to 7.24) indicate that the slope at site 3 consistently produces larger volumes of sediment than the slope at site 1, where the opposite conditions exist. The length of slope at site 3 exposes a larger area of bedrock on which weathering processes may act. Processes such as slide and creep of weathered material are enhanced on the sloping bedding planes dipping into the channel. The bedding planes present themselves as surfaces across which sediment transport by wash-related processes is facilitated (Carson and Kirkby, 1972). On slopes which have gradients approaching the angle of repose of the particulate matter mantling the slope, relatively small hydraulic forces are required to move it (Carson and Kirkby, 1972).

At site 1, the weathered debris tends to remain in position on the slope. Gravity acts in such a way as to move the particles down the bedding plane, which in this case means into the bank. Material thus becomes trapped on the slope by reversed bedding planes until entire sections become undermined and failure occurs. Sediment supply from this type of environment is on a decreased scale for long periods until failure occurs. Failures can be triggered by animal activity. The period when increased animal activity has been assumed (period 16) shows a significant increase in yield at site 1 (figure 8.2).

c) Aspect of channel bank : The amount of insolation received at any slope or channel bank is governed by latitude and aspect (Guy, 1970). Insolation in turn affects weathering rates, including those active in the study area, namely hydration and insolation weathering (Clark and Small, 1982; see table 2.1). Therefore when channel banks are exposed to greater amounts of solar radiation, more sediment is made available for transport by increased weathering. The channel bank at site 3 having a north aspect (table 8.1) receives greater amounts of insolation. Accelerated weathering processes in the exposed shale produce more sediment, which in turn is transported to the channel over the dipping bedding planes previously described. The sediment yield at site 3 is therefore larger than at site 1, which has a south aspect.

In the case of sediment yield at site 3, it is probably better to attribute the higher yields to a combination of aspect and dip. The study did not monitor a south aspect bank having strata dipping into the channel. Comparative statements are therefore not really possible, and it must be accepted that both dip and aspect do influence sediment yield in mechanically weaker rocks such as shale.

d) Size of material : Samples of sediments collected in pans for each sample day were analysed for mean grain size and sorting. The averages for all collected samples from all the sites are recorded in table 8.3.

Table 8.3. Mean grain size and sorting for all source area sediments. (Averages for all collected samples)

Site	Mean (mm)	Sorting (mm)	Total weight collected (kg)	Slope gradient
1	5,6	2,0	16,01	65°
2	9,8	1,6	3,61	80°
3	2,8	2,6	45,97	40°
4	19,9	2,6	35,78	85°

The size characteristics of sediment indicate to a certain extent the processes active in supplying that sediment (section 8.2.2b). Sediment derived from predominantly fluvial environments display smaller mean grain sizes. Table 8.3 indicates that site 5 (gully) where fluvial activity is entirely responsible for supply, has the smallest mean grain size. Gravitational processes become increasingly important with increases in slope gradients. Carson and Kirkby (1972) have indicated that where gravitational processes are more likely to play a role, for example on steeper talus mantled slopes, the mean grain size of sediment arriving at the base of the slope tends to increase. A comparison of mean grain size of the sediments from the four slope sites with slope angle (table 8.3) tends to support this idea. The steepest slope (site 4) supplied sediments displaying the largest mean grain size, whilst the low angled slope at site 3 recorded smaller mean grain sizes. Sediment yield at site 3 consequently has a more consistent relationship with rainfall amount than sites 1 and 4 (figure 8.2). The discussion on increased mean grain size with decreasing rainfall (section 8.2.2b) is referred to here (figure 8.5).

The influence of size of material appears to be complicated. Size of material per se does not appear to influence sediment yield. Processes (gravitational and fluvial) appear to be selective in terms of the size of material they mobilize. The frequency of operation of each of the set of processes (or a combination) will determine how much sediment of a given size class is supplied. In semi-arid areas, the infrequency of fluvial supply episodes elevates the role of gravity processes. Together with the relatively lower rates of weathering this ensures the characteristic coarse nature of sediment yields in semi-arid areas (Campbell, 1977a; Graf, 1983).

The fourth aim of the present study focuses attention on the comparative ability of gravitational and fluvial processes to supply sediment. Much of the results interpretation that needs to be done in fulfillment of the fourth aim are discussed in the above section as well as in the process section (section 8.2). The next few paragraphs address the fourth aim more specifically.

When large rainfall events occur, the scale of sediment transport on the slopes and in the channel increases (figures 8.1, 8.2, 8.3, 8.4, 8.6 and 8.7

- period 18). However, this type of rainfall episode occurs infrequently. During low rainfall periods, sediment transport continues under the influence of gravity (figure 8.1, 8.2, 8.6, 8.7 - periods 2, 9, 10, 13, and 14). The significant increase in sediment activity during period 16 has been attributed to animal activity. At times gravity movements are triggered by lesser rainfall episodes (figure 8.2 - period 11 at site 4).

Based on the conclusion, suggested by the results and supported by the authors referred to, that periods during which gravity processes dominate can be identified on the basis of grain size characteristics, an attempt is made to compare the transporting ability of fluvial and gravitational processes (table 8.4). The following criteria were used to identify periods during which gravitational processes and fluvial processes seem to dominate:
Gravity - high grain size, low rainfall, no. EI_{30}, no channel flow.
Fluvial - lower grain size, high rainfall, high EI_{30}, runoff in channel.
Periods 10 and 14 can be identified as predominantly gravitational supply periods on the basis of the above criteria.

One of the periods during which sediment activity can be described as predominantly fluvial (gravity playing a lesser role) is period 18. Table 8.4 records a comparison of the amounts of sediment supplied under the above conditions.

Table 8.4 A comparison of the amounts of sediment supplied under predominantly gravity or fluvial conditions.

Site	Total Yield	Gravity	Percentage of Total	Fluvial	Percentage of Total
1	16,01 kg	1,56 kg	9,7	1,83 kg	11,4
3	45,97 kg	6,03 kg	13,1	6,62 kg	14,4
4	35,78 kg	0,65 kg	1,8	3,58 kg	10,0

The amount of material supplied during 'predominantly gravity' periods is very similar to the amount supplied during a single larger-scale fluvial event (sites 1 and 3). The amount of gravity supplied material at site 4

(0,65 kg) is considerably less than the fluvially derived amount (3,58 kg). Site 4 has previously been described as an environment particularly susceptible to a combination of gravitational and fluvial process, e.g. slump.

The above calculations are very approximate but do give an indication of the relative ability of the two sets of processes. The assumption that gravity supply during low rainfall periods is similar in amount to that supplied during a shorter period of significant fluvial activity appears to be justified. It can therefore be concluded that the difference between fluvially and gravity related transport processes in terms of sediment supply, lies not in the volumes each are capable of yielding, but in the time period taken to produce that yield.

The sorting parameter provides an indication of the consistency of the energy conditions at any source environment (Blatt, Middleton and Murray, 1972). All sediments collected in the present study can be described as "very poorly sorted" (Blatt, Middleton and Murray, 1972; p.60), except for site 2 which are "poorly sorted". The least sorted sediments are those from the tributary gully. Poor sorting indicates a highly mixed sediment fraction, and is evidence of the intermittent nature of sediment transport episodes (Thornes, 1977). Sediment transport episodes mobilize a large range of grain sizes in the gully, which constitutes a high energy environment. When the sediment reaches the main channel, a low energy environment, it is deposited 'en masse', resulting in poor sorting. The sediments derived from the slopes display slightly better sorting. The reasons are that either the energy conditions responsible for sediment supply from the slopes are more consistent than the conditions prevailing in a channel environment, or that the material on the slopes is more homogenous in terms of size of particles. Channel sediments comprise an admixture of fluvially derived sediments and slope derived gravity sediments. also contributing to the poor sorting nature of the sediment.

The scattergram of mean grain size against sorting for all sediment samples indicates that each source-area-sediment falls into a distinct class (figure 7.25 and 7.26). The scattergrams support the claim that each source environment is governed by its own distinctive set of energy conditions, transport processes or available material.

8.3.4 Conclusions

The following conclusions can be drawn from the above discussions:

a) no one factor affecting sediment supply should be seen in isolation, certain factors may be more important at specific stages;
b) sediment supply at any given point in time and space must be seen in relation to a variety of factors;
c) gravity and fluvial processes, although differing in transport rates appear to demonstrate similar sediment yields over long time periods.
d) A lack of data excluded the possibility of commenting on the role of antecedent moisture conditions in the study area.

8.4 Sources of coarse sediment in the Ecca

Burns (1979) has suggested that each sediment source should be viewed as possessing a unique delivery potential and that the probability of sediment being exported from a particular source should be related to its relative position with respect to the channel and the basin divide. Any discussion on sources should also take into account the processes operating at each source area, as well as the factors influencing sediment production. The latter two considerations have been discussed in the two previous sections. The type of material constituting a source area has also been referred to by certain authors (see chapter 2) as a sediment source. In this regard, the predominant bedrock source material in the channel reach studied is shale (figure 5.2 and 5.6). There are also deposits of alluvium serving as source material at the tributary gully location (site 5), while the bank material at site 4 is comprised of colluvium. Also present in the channel reach are particles of sandstone and quartz derived from up-channel locations.

8.4.1 Identification of source areas

In terms of source areas, four environments which serve as coarse sediment producing areas with respect to the channel reach studied are identified :

a) the channel bed, including allocthonous up-channel deposits remobilized during major flow events;
b) major tributary gullies leading into the main channel, of which there was only one in the reach studied;
c) the immediate channel banks; and
d) areas remote from the immediate channel environment.

The latter areas (d), because of their low gradients, represent low energy environments and are unlikely to be areas of coarse sediment mobilization. They may be important for the suspended sediment fraction of the total load during major rainfall events. For the purposes of this study they cannot be considered as sediment sources. The minor rill at the alluvial fan site and the gully system at site 5, which extend across these remote areas were monitored, but these sources are considered an extension of the drainage system, distinctly separate from the remote areas.

8.4.2 Spatial and temporal variations of source area

The source areas identified in the present study constitute a small percentage of the total valley area and consist almost entirely of the channel bed and banks. Temporal variations in the absolute area serving as source environments are evident in the study area (figure 8.1). During no rainfall periods, steep banks where gravitational processes operate, will serve as source areas. This constitutes an even smaller percentage of the valley area. During tributary inflow events, source area extends to the limits of the gully system, as well as the channel banks. During major rainfall events, sediment is derived from areas further afield than the immediate channel environment. Up-channel sediments are remobilized and transported into the reach together with sediments from the local tributary. The source area is thus effectively extended. The percentage of the total valley area serving as source areas therefore fluctuates with the scale of the hydro-meteorological input, but nevertheless still appears to remain a small percentage of the total area.

8.4.3 Sediment yield variations from source areas

a) The channel bed : The channel bed can only act as a sediment source during flow events. The magnitude of the flow event will determine the extent of sediment mobilization on the channel bed. In the specific reach studied, the surveys conducted at site 5 (figure 8.9) suggest a removal-accumulation cycle (compare periods 18 and 19). Removal or accumulation at a specific site depends on the condition of the channel at that site, the proportion of channel floor occupied by flowing water and hence the scale of the hydrological input. The major flow event observed subsequent to formal data collection was responsible for net removal of sediment through the entire reach.

b) The tributary gully : The tributary inflow events identified earlier represent smaller scale events during which flow in the tributary can contribute sediment to a dry main channel. These events, indicated by sediment accumulation in the tributary gully pans (figure 8.1) occur more frequently than major main channel flow episodes. Two characteristics of sediment supply which give rise to yield variations from the gully are evident. The first is the apparent seasonality of sediment supply from this source. This aspect has been discussed (section 8.3.2b) and is merely referred to here. The second characteristic is the suggestion that the gully acts as a conduit for sediment. Sediment moves 'through' the gully and not 'out' of the gully. The gully pin data illustrated in figure 8.10 indicates a similar removal-accumulation cycle but on a smaller scale to that evident in the main channel. Fluctuations in the depth of the gully occur throughout the entire study period. If sediment was being removed from the gully bed during sediment transport episodes, the pin should record net erosion (figure 8.10). At the end of the study period, the pin records net accumulation (3 cm).

The sediment moving 'through' the gully system is derived from two sources : firstly, from the erosion of minor rills leading into the gully. Plates 7.2a and b record the amount of erosion from one such rill leading into the gully system. Secondly, episodes of bank collapse (plates 7.1a and b) as well as bank undercutting contribute substantial amounts of sediment. Both the above sources are confined to the immediate banks of the gully system. Tracer movement at the head of the gully system (figure 8.8) indicates sustained periods of no movement (periods 10 to 17) implying that only minimal amounts of sediment are being imported at the head of the gully.

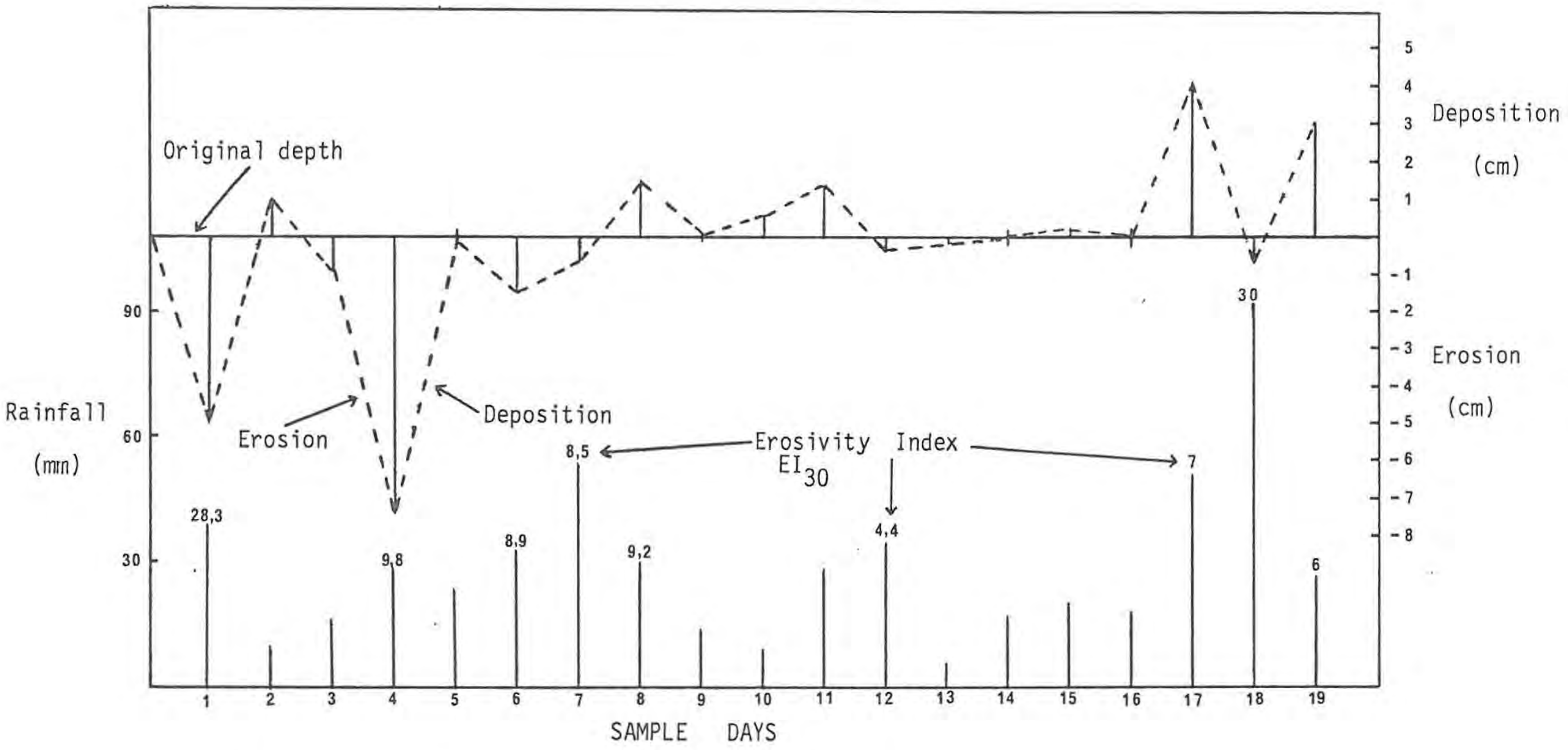

Figure 8.10. Variation of the depth of the tributary gully as measured by an erosion pin. The change of depth from the original is recorded for each sample day.

Only period 18 records significant tracer movement.

c) Channel banks : The slopes/channel banks, unlike the tributary gully or the main channel bed, are not as dependent on rainfall amount or EI_{30} for sediment mobilization. The cumulative plots of rainfall against slope sediment yield (figure 8.2 and 8.6) indicate periods during which large sediment accumulations are recorded with minimal increases in rainfall amount. The cumulative plot of EI_{30} against slope sediment yield (figure 8.3 and 8.7) indicate an even poorer relationship with sediment yield. Sediment transport and ultimate supply from the channel banks appears to be a time-continuous phenomenon. Variations in the amounts of sediment yielded from the slopes is attributed to a number of factors, all of which have been discussed in previous sections and are merely referred to here :

- the effects of an apparent 'weathering period' during which weathering processes seem to be more important than transport processes (section 8.3.3a).
- a variation in the scale of operation of transport processes with the hydro-meteorological input (8.3.2a and b)
- exhaustion effects (Walling and Webb, 1982) leading to reduced sediment availability after a major removal episode (8.3.3a).

8.4.4 Relative importance of source areas

Sediment has been collected from a variety of source environments. Each collection point represents a sample of the whole source area in that environment. The present section attempts to extrapolate, from these sample measurements, a rough estimate of the total amount supplied from each source, thereby giving an indication of the relative importance of each source environment. The total amounts are extrapolated by taking the length of slope as well as the amount of overspill at the gully (table 8.5) into account. It is pointed out that the alluvial fan and gully environments represent concentrated sources, while the slope environments are diffuse sources. Real gully data is underestimated due to overspill. The amount of sediment delivered at the alluvial fan site (site 1) is calculated from erosion pin data, assuming a bulk density of 1,6 g. cm^{-3} (MacVicar et al, 1977).

Table 8.5 Estimates of sediment delivery from each source environment based on absolute amounts collected per unit area.

Site	Absolute amt. (Kg)	Length of of slope (m)	Overspill (kg)	Total Yield (kg)
1	16,01	237	-	3794,37/14,0%
2	3,61	273	-	* 985,53/ 3,6%
3	45,97	311	-	14296,67/52,9%
4	35,78	176	-	6297,28/23,3%
5	590,45	-	± 360 kg	950,45/ 3,5%
Alluvial fan	716	-		716,00/ 2,7%
Total				27040,30/100%

* Total of slope pans 25 373,85 kg/93,83%

The estimated yield from all the slopes in the reach represent 93,83 percent of the total estimated yield, emphasizing the importance of these environments as coarse sediment sources. By implication, the importance of each process active in supplying sediment from the slopes is elevated. That sediment is not derived from purely fluvial sources to the same extent as from 'gravity and fluvial' sources indicates that a consideration of gravity is important in semi-arid areas.

The tributary gully and rill systems constitute purely fluvial sources, and in an environment where fluvial transport events are relatively infrequent, the role of these sources appears to be secondary to the slope sources. Unfortunately the contribution from these sources is unknown during events such as the one observed after formal field data collection. It is anticipated that during such 'transport unlimited' events the yield from these concentrated high energy sources will outweigh slope yields.

The intermittent nature of sediment removal, transport and deposition exclude the possibility of even estimating the sediment yield from the channel bed. The channel bed represents a 'throughput' system and it would be necessary to know both input at the head and output at the outlet of the reach before any accurate amount can be arrived at.

As indicated in chapter 6, surveys of sediment accumulations behind the weir at the catchment outlet (Q9M21) are carried out by the H.R.U. Two of these surveys spanned the study period for the present study. The latter survey indicated sediment accumulations amounting to 18m^3 of sediment infill (28,8 tons). Although a portion of this amount could be in the suspended fraction, the amount is comparable to the yield (27,04 tons) recorded in the present study. The remaining amount of 1,76 tons could represent the sediment transported 'through' the reach, substantiating the claim that the reach acts as a 'throughput' system. The above discussion on source areas, their identification and importance has covered the second aim set for the study.

8.5 Time sequence of supply and removal : An evaluation of the sediment supply model

The nature of sediment transport in semi-arid areas is described in chapter 3. Based on the supporting literature and theory outlined in chapter 3, a sediment supply model for semi-arid areas is proposed in chapter 4. This conceptual model has both a static (figure 4.3) and a dynamic component (figures 4.4a-d). The dynamic component (A- to D- type events) allows for a variation in the scale of operation of processes with increased climatic inputs, which in turn determine the extent of removal or accumulation in storage compartments. The conceptual model was to be tested by fieldwork in a specific semi-arid catchment. The discussion in the previous sections of the present chapter have elucidated the characteristics of sediment response in the study area, and comments were made in terms of the static model. The present section attempts to define sediment response in terms of the dynamic component of the model. As the dynamic component of the model relates to a sequence of removal and accumulation episodes, this aspect is dealt with initially.

8.5.1 Time sequence of supply and removal of sediment

The fifth aim of the study is to establish the relationship between supply/accumulation of sediment in the channel and the subsequent transport/removal of that sediment. It has been pointed out in previous sections that while supply of sediment to a channel is a continuous process due to either gravity or the action of water, removal of stored sediment is

a less frequent occurrence. The infrequent removal of channel stores is attributed to the infrequent episodes of channel flow (thus climatic input) capable of transporting sediment in the channel (Campbell, 1977b). The removal of channel stored sediment is not only infrequent but also varies in space (figure 8.9). Graf (1983) has indicated that "...one of the important implications of the spatial variation of sediment removal is that it imposes a particular spatial control on subsequent fluvial processes. The channel morphology left after the erosion episode dictates the likely foci of erosion and deposition" (p 650). Removal or accumulation thus appears to vary in space and time. The variation is due largely to a variation in the scale of the climatic input, and is modified by channel morphology.
As the scale of the climate input largely controls the possibility and variability of removal or accumulation episodes, three categories of climatic input have been identified in the present study.

a) low or no rainfall periods,
b) rainfall able to generate tributary inflow, but not in the main channel, and
c) large or major rainfall episodes producing flow in the main channel.

a) Low rainfall periods : Representing the lowest scale of transport episode, these periods are encountered frequently in semi-arid areas (figure 8.1). They are characterised by removal of sediment from slope stores and addition to channel stores (periods 2, 5, 10, 13, 14 and 16, figure 8.1). Some addition to slope storage also occurs through weathering processes.

b) Tributary inflow : In the present study, tributary inflow occurred during 6 periods when no flow was recorded in the main channel. A further 7 tributary inflow events occurred at times when flow was recorded in the main channel, bringing the total of these events to 13 (figure 8.1). This number represents a fairly high frequency of occurrence in terms of the present study, and the suggestion is that these type of events are dominant in semi-arid areas. The tributary inflow soon dissipates in the main channel in a downstream direction, depositing sediment in the process. This phenomenon leads to a lack of accordance in the drainage system (Schumm and Hadley, 1957). At times (figure 8,1, periods 1, 4, 6, 7, 12) flow in the main channel occurs on a limited scale. Flow is confined to a set of inset channels within the main channel, and serves to re-distribute channel stored sediment (Thornes, 1977). During these events sediment removal occurs on slopes and in tributary environments, while net accumulation occurs in the main channel.

The nature of flow and sediment movement within the tributary itself is demonstrated by the erosion pin data from the tributary channel bed (figure 8.10). Clearly discernible are periods of removal alternating with periods of accumulation. The apparent removal-accumulation cycle (r-a cycle) appears to be unrelated to rainfall and EI_{30} amounts. This fact supports the statement above where it was indicated that fluvial processes are largely controlled by former removal episodes, which through modification of channel morphology, dictate the likely foci of future erosion and deposition (Graf, 1983). The r-a cycles illustrated in figure 8.10 are evidence of the 'pulse-like' movement of sediment through the drainage system (Campbell 1977b).

c) Major rainfall periods : The term 'flow in the main channel' can apply to a wide range of actual flow events. The flow events recorded in the present study (periods 1, 4, 6, 7, 12, 18 and 19) were not of the same magnitude (discharge 0,005 to 0,183 $m^3.s^{-1}$) as the event described which occurred after cessation of formal field data collection (discharge $1,7m^3.s^{-1}$). The results of the surveys at the tributary inlet (site 5) demonstrate the cyclic nature of removal and accumulation in the main channel (figure 8.9) under the influence of these smaller scale flow events. The data illustrated (figure 8.9) represents a set of minor r-a cycles.

The larger scale fully-integrated flow event occurring after the formal field data collection program signified a period of removal of accumulated storage throughout the entire channel reach. The event represents a removal episode of a longer term major r-a cycle. The event was the first event of such magnitude to occur after a period of 6 years (see table A.14; 21.7.1979). An estimation of the time scale involved in a major r-a cycle would be dependent on the return period of events of the above magnitude. As this return period spans a number of years, a sequence of minor r-a cycles such as those recorded in the present study, occur during this period. During the accumulation stage of the major cycle, minor episodes of removal in preferred sections of the channel will occur. The removals are seldom 'out of reach' and sediment is usually deposited further down the channel. Site 1 channel pins record net accumulation for all flow events. The minor episodes can be seen as short term micro r-a cycles, superimposed upon longer term major r-a cycles. After a period dependent on the return period of major rainfall events generating relatively high flows, a major removal episode occurs. The resultant sediment yield would to a small degree, be governed by the history of micro r-a cycles preceding such a major removal episode. The infrequent occurrence of major removal events implies that sediment movement to channels occurs more frequently than sediment movement in channels in semi-arid areas. However, one large scale event of sufficient magnitude is capable of depleting stores accumulated during the preceding sequence of minor 'in reach' r-a cycles. Table A.14 records the peak discharges of flow events measured at the weir (Q9M21) from 1976, and gives some idea of the sequence and time scale of specific-scale events responsible for micro r-a cycles. Three macro scale removal episodes are recorded - March, 1977; July, 1979; November, 1985. A summary of the aforegoing discussion is provided (table 8.6).

Table 8.6 Time sequence and scales of sediment r-a cycles

Event Type	Channel space occupied by flow	Time scale	Sediment activity
No/low rainfall	nil	Frequent/Quasi-continuous	Increased slope & channel storage
Tributary inflow	Inset channels for short sections	Between 5 & 15 times annually	Increased channel storage; some re-distribution
Large to major events	Inset channels through entire reach/bankfull discharge; fully integrated flow	Less frequent annual or longer	Within reach removal/accumulation Removal of storage through entire reach

8.5.2 Evaluation of the model in terms of the field results

The model proposed in chapter 4 envisages four types of climatic events. The model is not prescriptive in terms of the boundaries between each event regarding rainfall amount, intensity and discharge. The model is descriptive in terms of the sediment response to varying scales of climatic input and channel flow. The results from field data collection have identified three classes of 'events', summarised in table 8.6, against which the models' events can be tested.

A-type event : During ineffective or no rainfall periods weathering and gravity transport are recorded in the data (figure 8.1). The weathering of shale bedrock implies addition to in situ slope storage, and gravity movements (talus creep) implies addition to secondary slope storage (figure 8.2 and 8.4). Where sediment is moved to the channel, a small amount of channel storage occurs (figure 8.6). The addition to channel storage can take the form of bank collapse, thereby implying the operation of bank erosion (plate 7.1a and b). All of the above are described in the model and confirmed by the data. The A-type event proposed by the model is therefore accepted. Typical sample periods recording these type of events are 2, 5, 10, 13, 14 and 16 (figure 8.1).

B-type event : During these events, flow is not generated in the main channel. However, flow in the tributary gully is recorded (figure 8.1). The higher EI_{30} values during these periods suggest that rainfall intensity is an important causative factor for tributary inflow. The higher rainfall amounts together with increased EI_{30} values do lead to increased movement of slope sediment (figures 8.1, 8.2, 8.3 and 8.4) due to increased surface flow and concomitant slope wash processes. Higher moisture levels trigger gravity movements on a larger scale (figure 8.2, period 11, site 4), and accelerates weathering processes. This in turn leads to increased removal from both slope stores and larger amounts added to channel storage, thereby increasing channel sediment availability. As the tributary inflow process is not accounted for during these events, the model will be revised to allow for this. Typical sample days recording these type of events are 1, 3, 4, 6, 7, 8, 9, 11, 12, 15 and 17.

C-type event : Period 18 records a flow event approaching the magnitude envisaged by the study as a c-type event. The data records significant amounts of transport to the channel from the slopes (figures 8.1, 8.2, 8.3, 8.4, 8.6 and 8.7), hence removal from slope storage by fluvial slope processes. Some sediment is moved in from sections higher on the slope indicating addition to slope storage (table A.3). The section of channel at site 5 records removal of sediments at this section (figure 8.9) hence removal from channel storage. The erosion pins at site 1 (table A.4) record accumulation at the second cross-section (pins B1 to B8) and together with slope derived sediment not mobilized by the flow in the channel, indicate some addition to channel storage. Movement of channel tracers indicates operation of the channel transport process (table A.8).

A true C-type event is the one not recorded in the formal data but described in section 8.2.2a), and is merely referred to here. Together with the processes and sediment response documented above, the event fully satisfied the requirements of a C-type event.

D-type event : Period 19 records a main channel flow event which occurred soon after the flow event recorded during period 18. Period 19 does however record lower rainfall and EI_{30} values. The higher discharge measured during period 19 could be related to higher antecedent moisture levels. The slope base pan data record lesser amounts of sediment trapped than during period 18, indicating less removal from the slopes. The decreased amounts of slope removal are likely due to lower rainfall and EI_{30} values, but could also be the result of exhaustion effects. The initial discussion on a D-type event in chapter 4 drew attention to the fact that a D-type event, being 'availability' limited rather than 'transport' limited, might give rise to channel erosion. The channel bed survey at site 5 does not seem to support this claim, as net accumulation is recorded (figure 8.9). However, the accumulation in the channel at site 5 can be attributed to the failure of branch debris in the tributary gully just above the pans. The debris had dammed up a vast reservoir of sediment, and upon failure during period 19, this reservoir was washed into and over the pans at the tributary inlet (table A.2). The flow event in the main channel was not sufficient to transport this increased sediment load, and deposition occurred. The flow event recorded during period 19 is probably not on a scale envisaged by the model for a D-type event, but the general sediment response documented above leads to acceptance of the proposed D-type event.

8.5.3 Revision of the model

The results of the data collection techniques have sufficiently confirmed tha A- and B-type events. The magnitude of the C-type event recorded in the data is less than that envisaged by the model, but successfully accommodated within the general framework of a C-type event. The flow event which occurred after data collection confirms the C-type event.

Revision of the model as suggested by the aforegoing discussion is illustrated in figure 8.11. Included in the revised model is a tributary inflow process feeding into channel storage. This process will operate to some degree during B-type events, and to a larger degree during C-type events.

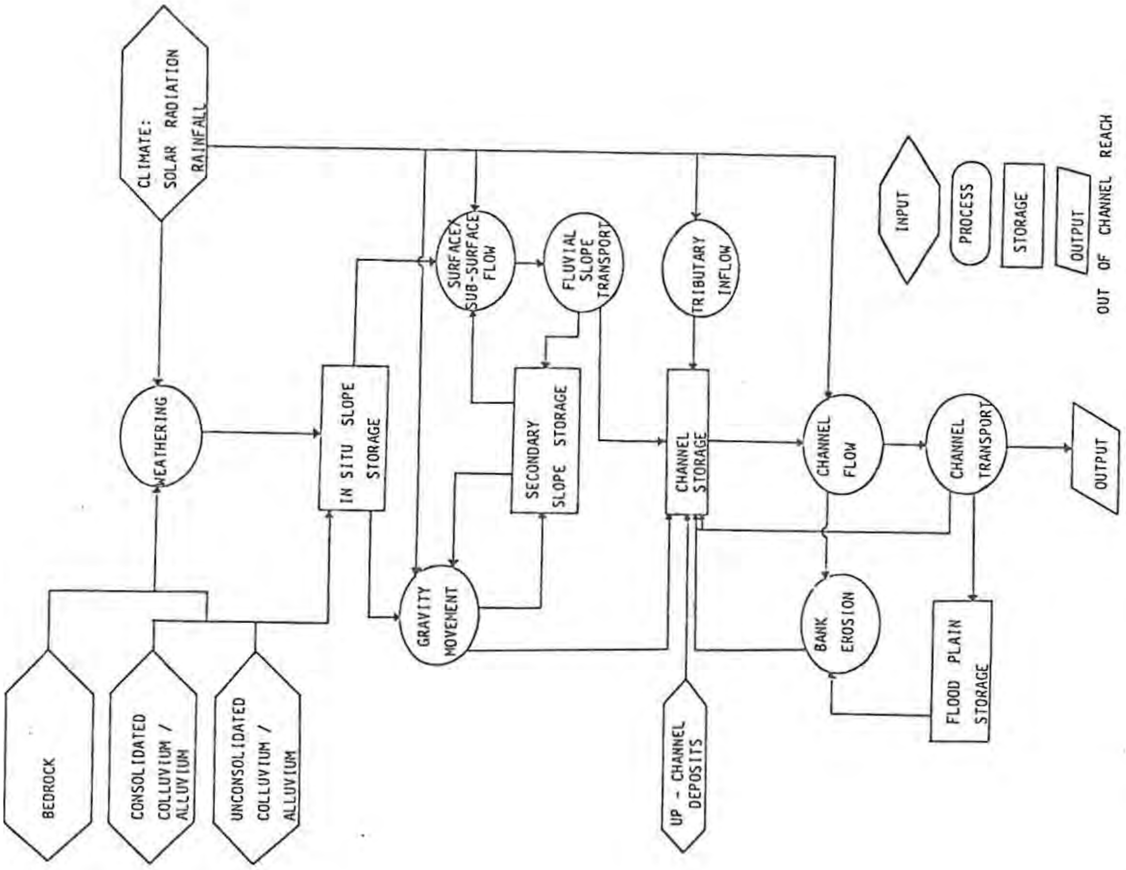

Figure 8.11. The sediment supply model revised to include a tributary inflow process.

9. CONCLUSIONS

9.1 Processes and spatial patterns of coarse sediment supply

In terms of the first aim, several processes have been identified in the study area. It remains a difficult task however to distinguish between gravitational and fluvial transport processes on the slopes or channel banks. The present study, by nature of the data collected, recognises that sediment transport on the slopes is more than likely attributable to a combination of gravitational and fluvial processes.

The study area for the present study was limited to the lower area of a small basin, where it was found that the total area serving as source areas for coarse sediment supply is limited to a small percentage of the total valley area. This situation might be different in first order basins where slopes away from the channels are steeper and could supply sediment directly to the channel, by landslide activity for example. At least, the present study has given an indication of the important role of the immediate channel environment, especially the channel banks, from which sediment supply is quasi-continuous. Furthermore, source areas demonstrate a measure of consistency in terms of the grain size and sorting parameters of the sediment supplied by that source environment.

Identifying the factors affecting sediment supply was found to be difficult in an environment where so many individual factors, as well as any combination of factors, seem to play a role. Determining the role of any one factor would require an environment where the influence of all other possible factors is excluded, and this might be impossible outside the laboratory situation.

The infrequency of fluvial events in semi-arid areas implies that gravitational processes dominate on the banks during no or ineffective rainfall periods. Furthermore, the general lack of a protective vegetal cover which would serve to hamper sediment transport, further elevates the importance of gravitational supply processes. Whilst gravitational processes alone are not usually responsible for excessive amounts of sediment transport to the channel over shorter time scales, the amounts supplied over longer time scales seem to be comparable to that supplied by a single short-lived major fluvial event.

Discussion on the time sequence of supply and removal of sediment in semi-arid channels has drawn attention to the pulse-like movement of sediment 'waves' through the channel. The sequence of supply and removal appears to operate on two scales: a short term micro cycle of removal and accumulation documented in the present study, and a longer term macro cycle, the bounds of which in terms of time, exceed those for the present study.

9.2 Temporal patterns of sediment supply

Sediment has been collected from a variety of slope environments, yet the trends of sediment supply are very similar, as indicated by the pattern of the cumulative plots for the individual slope derived sediments. This tends to suggest that although each source environment is separated in space, the energy conditions over the basin tend to exact the same response in terms of relative amounts of sediment supply at each source. This similarity in trends of sediment supply from a variety of sources might be an important consideration in terms of quantitative modelling.

Sediment supply furthermore appears to be either availability or transport limited in semi-arid areas, depending on the time elapsed since a previous removal episode. The amount of available sediment is related to the scale of a previous climatic input event. During a sustained period of little sediment activity (i.e. no rainfall) the sediment availability factor increases. A series of small scale removal events will bring about a slight reduction in availability. Sediment supply during such a period will be predominantly transport limited. A larger scale removal event will reduce availability further, and a major removal episode may wash the slopes clear so that availability is at its lowest thereafter. During the subsequent period sediment supply might be described as predominantly availability limited. The sequence of removal episodes in time is therefore an important consideration in semi-arid sediment supply systems.

9.3 The coarse sediment supply model

The model proposed and tested in the present study represents a new approach to conceptually representing the system of coarse sediment supply. The study indicates how difficult and time consuming it is to gather sufficient data to quantify a model of this type. Processes active in the system of sediment supply may have been identified, but causative factors in the variation of their scale of operation are not well understood, neither is the complete sediment supply system at a basin scale. Quantification of the model will take many years of data collection over a wider area, including perhaps the entire channel through the whole basin. The model, while basically remaining a sediment supply model, documents the entire sequence of landscape development, in a progression from weathering of bedrock to removal of slope debris and concomitant lowering of slopes to transport of wasted material out of the reach, and eventually out of the basin.

The type of conceptual modelling undertaken in the present study together with the actual model proposed, need not necessarily be limited to semi-arid areas. The model is a basic framework within which research on sediment supply in other climatic regimes could be built up so that it might eventually become a useful tool with which to interpret sediment supply from all climatic regimes, and within which all studies of this nature might be placed in context.

9.4 Suggestions for further study

Quantification of the model will require a wider data base which would have to include an investigation of the role of the factors affecting supply. Smaller scale research of the role of one or more of these factors (for example antecedent moisture, aspect, dip, vegetation, geology, weathering) could be undertaken, within the context of the model, thereby building up and quantifying aspects of the conceptual model, so that finally every aspect/phase of the model has been quantified by a series of these smaller scale research efforts. A wider variety of slope environments could be monitored in order to gain clarity on the spatial and temporal variation of sediment supply from a broader range of lithologies where the effect of the above factors would also vary.

The measurement of sediment output from basins (i.e. collected in dams) in semi-arid areas and quantification of that amount in terms of its source area within the basin remains a little investigated aspect in sedimentology. Investigations of this nature would have to integrate and examine the interaction of processes within the basin area. Although the mechanics of weathering and slope transport processes are very well understood and documented in the literature, there appears to be a singular lack of application of this knowledge on a basin scale. It will also be necessary to incorporate some measurement of suspended sediment and solutes within the framework of an expanded model, so as to estimate the total sediment yield. Obviously such investigations are beyond the scope of any single research effort. However, smaller scale investigations of one aspect of the entire sediment supply system could be undertaken individually. If these investigations are placed within the framework of the model the eventual outcome will be a fully quantified model of total sediment supply. Variations of the model could apply to different climatic regimes so that the same basic model becomes a useful tool with which to interpret sediment supply in any drainage basin.

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APPENDIX A

Table A.1. Hydrological data for the study period. Rainfall is measured from one sample day to the next. Peak discharge for the period between sample days is recorded.

Day		Rain (mm)	Evaporation (mm)	Discharge ($m^3.s^{-1}$)	Erosivity Index EI30
30/4/83	1	41,5	139		28,325
30/5	2	10,5	120		1,864
28/6	3	17,5	103		
6/8	4	29,6	139	0,92	9,821
24/9	5	25,1	192		2,542
22/10	6	31,8	91	0,183	8,956
26/11	7	55,8	174	0,115	8,591
14/1/84	8	29,3	314		9,283
3/3	9	13,8	319		1,326
6/4	10	9,1	177		
19/5	11	32,8	180		2,045
29/6	12	37,2	132	0,005	4,406
28/7	13	3,5	89		
25/8	14	7,7	101		
6/10	15	25,2	178		
24/11	16	20,4	297		
19/1/85	17	52,4	443		7,035
23/2	18	91,4	226	0,085	30,163
2/4	19	27,3	249	0,127	6,569
	Total	561,5			

Table A.2. Amount of sediment collected in pans on each sample day (Kg.).

Day	Site 1	Site 2	Site 3	Site 4	Site 5
1	0,38	0,00	0,69 *	0,77	45,14
2	0,35	0,00	0,69 *	1,02	0,00
3	0,08	0,04	0,69 *	0,01	0,64
4	0,07	0,03	0,69 *	0,32	90,37 +
5	0,21	0,06	0,69 *	0,49	0,00
6	0,18	0,04	0,69 *	0,55	90,37 +
7	0,11	0,04	3,21	0,26	45,14
8	0,24	0,14	2,12	0,30	72,71
9	1,44	0,12	1,54	1,67	10,01
10	1,49	0,00	4,19	0,51	0,00
11	0,29	0,43	8,24	8,04	6,56
12	0,12	0,05	1,22	5,20	3,62
13	0,14	2,03	2,61	0,02	0,00
14	0,07	0,05	1,84	0,14	0,00
15	0,07	0,14	1,74	0,69	0,89
16	7,52	0,44	8,42	10,30	0,00
17	0,99	0,00	1,53	1,08	40,00
18	1,83	0,00	6,62	3,58	90,00 +
19	0,43	0,00	2,64	0,83	95,00 +
Σ	16,01	3,61	50,06 / 45,97 $	35,78	590,45

* Amounts calculated on a percentage basis of the amount recorded at the other slope sites for the same period.

\+ Indicates pans overfull.

$ Excluding periods 1 to 6, which have been calculated.

Table A.3. Addition to and removal from slope storage as measured by erosion pins (cm) at site 3 (see fig. 7.2).

Pin no. Day	1	2	3	4	5	6	7
7	0,0	+ 0,5	- 0,5	0,0	+ 0,2	0,0	0,0
8	+ 2	+ 1,5	- 1	0,0	+ 2	+ 1	+ 1,2
9	- 2	0,0	0,0	0,0	+ 2	+ 1	+ 1,2
10	- 1	+ 5	+ 3	+ 3	+ 2	+ 5	0,0
11	+ 1	+ 4	+ 4	+ 4	+ 3	+ 2	+ 1
12	0,0	+ 13	+ 2,5	+ 1	+ 4	+ 1,5	+ 4
13	- 1	+ 3	0,0	0,0	0,0	0,0	0,0
15	+ 2	+ 4	+ 3	+ 2	+ 3	+ 4	+ 3
16	+ 3	+ 7	+ 6	+ 6	+ 3	+ 3	+ 3,5
17	0,0	+ 4	0,0	+ 0,5	0,0	0,0	0,0
18	+ 4	+ 2	+ 2	+ 3	+ 1	0,0	+ 1
19	+ 4	+ 8	+ 2	+ 3	+ 2	+ 3	+ 5
Total change	+ 12	+ 52	+ 21	+ 22,5	+ 22,2	+ 20,5	+ 19,9

Table A.4. Channel erosion pin measurements at site 1 from 2 cross-sections A and B (see fig. 7.1).

Pin no. Day	A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	B8
14	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
15	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
16	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
17	0,0	0,0	+ 1	+ 2	+ 2	+ 1	0,0	0,0	0,0	0,0	0,0	+ 1	+1,5
18	0,0	- 1	- 2	-0,5	+ 5	+ 5	+ 3	+ 4	+4,5	+5,2	0,0	+ 1	+ 2

Table A.5. Channel erosion pin measurements at the alluvial fan site recording erosion/deposition at the fan. The total volume of sediment yield per sample day is also given (see text).

Day \ Pin no.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	Sediment (Kg) Yield per day
7	- 3	-	- 0,5	+ 8	- 3	-	+ 7	+ 5	-	-	- 4	-	-	+ 7	+ 1	+ 1	74
8	-	+ 0,5	+ 1	-	+ 2	-	-	-	+ 1	-	-	-	+ 1	-	+ 2	+ 1	34
9	- 3	-	+ 1	+ 5	- 1	+ 1	-	-	+ 1	+ 2	- 4	-	-	+ 4	+ 3	+ 2	44
12	- 2,5	- 1	- 1	-	- 1	+ 3	+ 6	+ 5	+ 1,5	- 1	- 2	-	+ 1	+ 3	+ 3,5	+ 3	70
13	- 3	- 1	- 1	+ 1	- 1,5	-	+ 2	+ 5	- 1	- 1	- 2	-	-	-	+ 3,5	+ 1,5	10
17	- 2	- 2,5	-	+ 5	- 1	+ 4	+ 4,5	+ 6	+ 6,5	-	- 6	+ 0,5	-	+ 3	+ 5	+ 6,5	118
18	- 4	-	+ 2	M	+ 1	+ 5	+ 12	+ 9	+ 6	-	+ 3	- 4	+ 6	-	+ 5	+ 3	192
19	- 4	+ 15	-	M	- 0,5	+ 4	+ 11	-	+ 7	-	+ 8	- 5	+ 2	-	+ 5	+ 1	174 / Σ 716

-1 : Removal
+1 : Addition
- : No change
M : Missing

Table A.6. Erosion pin measurements (cm) from a minor rill and the main tributary trunk at site 5. (Same symbols used as in table A.5.). Day 14 - missing data.

Day	Rill South Bank	Rill North Bank	Rill Main Bed	Tributary Main Bed
1	+ 1	-	- 6	- 5
2	-	-	-	+ 1
3	-	-	-	- 1
4	-	+ 1	- 0,5	- 7,5
5	-	+ 1	-	-
6	-	-	+ 1	- 1,5
7	+ 0,5	-	-	- 0,5
8	-	-	- 0,5	+ 1,5
9	- 0,5	-	+ 1	-
10	- 0,5	+ 0,1	-	+ 0,6
11	+ 0,3	- 0,7	+ 0,2	+ 1,4
12	+ 0,6	+ 0,6	+ 1,8	- 0,3
13	- 0,3	-	-	- 0,2
15	-	- 0,5	-	+ 0,1
16	-	-	+ 1	-
17	-	- 0,5	+ 3	+ 4,2
18	- 0,5	-	- 8	- 0,8
19	-	- 0,5	+ 1	+ 3

Table A.7. Variation in the depth (cm) of the main channel at site 5 by channel bed profile surveys. (Same symbols used as in table A.5.).

Point No. / Day	1	2	3	4	5	6	7	8	9	10	11	12
12	+0,6	+0,4	+1,9	+1,2	-0,7	+0,9	-0,4	-0,7	-0,1	+0,9	+0,2	-
17	+1,1	+0,8	+3,2	+0,7	-1,2	+0,1	-0,4	-0,3	-0,5	+0,7	+0,6	-
18	-0,4	-2,9	-1,8	-1,1	-3,9	-1,7	-3,9	-5,8	-5,2	-3,6	-2,4	-0,5
19	+6,6	+5,8	+5,9	+4,6	+2,1	+4,5	+4,2	+3,5	+4,5	+3,6	+1,8	+0,5

Table A.8. Record of movement of numbered channel tracers (m) at site 1, measured from a pin in an upstream location. The number of the pebble has the same value as its original distance from the pin.

Original distance from pin (m)	1	2	3	4	5	6	7	8	9	10	11	12
Size (cm) Long Axis	6	17	11	10	7	12	8	8	8,5	10	10	7
Day \ Pebble No.	1	2	3	4	5	6	7	8	9	10	11	12
6	1	2	3	4	5	6	7	8	9	10	11	12
12	1,1	2	3,5	4,3	5,5	6	7,01	8	9	10,2	11	12
16	1,1	2	3,6	4,3	5,51	6	7,01	8	9	10,2	11,1	12,1
17	1,3	2	3,6	4,3	5,51	6	7,01	8	10,5	10,2	11,2	12,2
18	16,0	30,6	33,2	12,1	17,13	17,7	31,7	10,07	B	15,75	33,4	31,5
19	19,0	30,6	33,4	12,1	17,13	17,7	31,7	10,07	51	19,7	33,4	31,5
$\sum$ Movement	18	28,6	30,4	8,1	12,13	11,7	24,7	3,07	42	9,7	22,4	19,5

B - Indicates Buried.

Note : Days recording movement are underlined.

Table A.9. Net movement (cm) per sample day of seven numbered tracers in a rill on the slope at site 3. Average per sample day is also given.

no. Day	1	2	3	4	5	6	7	Ave.
1	0	0	40	50	0	0	50	20
2	0	0	43	0	46	0	0	12,7
3	0	0	13	0	44	10	0	9,6
4	0	7	3	0	0	0	0	2,1
5	66	183	54	5	0	10	0	45,4
6	0	4	16	1	6	0	0	9,8
7	1	8	2	4	19	0	0	4,9
8	0	14	2	0	10	0	0	3,7
9	26	4	1	0	0	0	0	4,4
10	47	69	8	0	0	0	0	17,7
11	0	20	0	0	5	0	0	3,6
12	0	4	2	2	3	4	8	3,3
13	0	0	0	0	0	0	0	0
14	0	27	5	0	32	10	0	10,6
15	29	7	9	19	5	4	0	10,3
16	1	4	0	0	3	2	8	2,6
17	0	8	0	15	2	0	4	4,1
18	0	0	0	0	0	0	0	0
19	0	0	0	0	0	0	0	0
$\sum$	169	401	198	96	185	40	70	164,8

Table A.10. Net movement (cm) of : tracer particles from two weathered bedrock sites (A and B); and four numbered particles (1 to 4) on the slope at site 3.

Day \ No.	A	B	1	2	3	4	Ave.
1	7	27	44	56	0	0	22,3
2	1	13	0	4	24	40	13,6
3	79	14	0	0	0	0	15,5
4	50	12	6	0	0	17	14,2
5	0	2	4	0	10	10	4,3
6	0	0	0	6	0	0	1,0
7	0	0	0	10	20	0	5,0
8	10	0	0	0	4	0	2,3
9	0	10	7	8	0	11	6,0
10	10	10	18	32	7	9	14,3
11	0	0	5	100	2	22	21,5
12	23	70	0	10	7	10	21,6
13	53	26	0	12	0	1	15,3
14	0	0	0	0	0	0	0,0
15	105	17	0	8	0	0	21,6
16	70	152	12	75	12	21	57,0
17	10	0	0	0	0	6	2,7
18	290	0	35	325	588	0	206,3
19	M	M	M	M	M	M	0,0
$\sum$	708	353	131	646	674	147	444,8

Table A.11. Record of numbered tracer particle movements (m) in a tributary rill of the gully system measured from a pin upchannel. Day 1 records the original distance from the pin.

Size (cm) Long Axis	8	21	8	6	13	7	4,5	5	9,5	10,5	4,3	6
Day \ No.	1	2	3	4	5	6	7	8	9	10	11	12
1	0,5	1	1,5	2	2,5	3	3,5	4	4,5	5	5,5	6
2	0,5	1	1,5	2	2,5	3	3,5	4	4,5	5	5,5	6
3	0,5	1	1,5	2	2,5	3	3,5	4	4,5	5	5,5	6
4	0,5	1	1,5	2	2,5	3	3,5	4	4,5	5	5,5	6
5	0,5	1	1,5	2	2,5	3	3,5	4	4,5	5	5,5	6
6	0,5	1,26	1,5	2,1	2,5	3	3,5	4	4,6	5,07	5,5	6
7	0,5	1,4	1,64	2,2	2,6	3,05	3,7	M	4,63	5,13	5,6	6
8	0,5	1,4	1,64	2,2	2,67	3,18	3,8	M	4,7	5,2	5,63	6,07
9	0,5	1,4	1,64	2,2	2,67	3,18	3,8	M	4,7	5,2	5,63	6,07
10	0,5	1,4	1,64	2,2	2,67	3,18	3,8	M	4,83	5,2	5,63	6,07
11	0,5	1,4	1,64	2,43	2,67	3,18	4	M	4,83	5,2	5,63	6,07
12	0,5	1,4	1,64	2,43	2,67	3,2	4,1	M	4,86	5,2	5,8	6,07
13	0,5	1,4	1,64	2,43	2,67	3,2	4,1	M	4,86	5,2	5,8	6,07
14	0,5	1,4	1,64	2,43	2,67	3,2	4,1	M	4,86	5,2	5,8	6,07
15	0,5	1,4	1,64	2,43	2,67	3,2	4,1	M	4,86	5,2	5,8	6,07
16	0,5	1,4	1,64	2,43	2,67	3,2	4,1	M	4,86	5,2	5,8	6,07
17	0,5	1,4	1,64	2,43	3,04	3,2	4,25	M	4,86	5,2	5,8	6,07
18	0,5	1,5	4,5	M	4,3	3,3	M	M	4,86	5,2	M	10,0
19	0,5	1,5	4,5	M	4,3	3,3	M	M	4,86	5,2	M	13,0
Σ cm	0	50	300	43+	153	30	75+	0	36	20	30	700

M : Particle missing.

Table A.12. Record of movement of six numbered tracer particles at the head of the main tributary channel at site 5 (m).

Day 1 records the original distance from the pin.

Size (cm) Long Axis	13	10	7	7,5	2,5	17
Day \ No.	1	2	3	4	5	6
1	0	1	1,45	2,02	2,48	5
2	0	1	1,45	2,02	2,48	5
3	0	1	1,45	2,02	2,48	5
4	0	1,06	1,48	2,04	2,49	5,04
5	0	1,06	1,48	2,04	2,49	5,08
6	0	1,06	1,5	2,04	2,53	5,14
7	0	1,1	1,5	2,04	2,53	5,14
8	0	1,1	1,5	2,04	M	5,4
9	0	1,22	1,5	2,04	M	5,5
10	0	1,13	1,5	2,04	M	5,5
11	0	1,3	1,5	2,04	M	5,5
12	0	1,3	1,5	2,04	M	5,5
13	0	1,3	1,5	2,04	M	5,5
14	0	1,3	1,5	2,04	M	5,5
15	0	1,3	1,5	2,04	M	5,5
16	0	1,3	1,5	2,04	M	5,5
17	0	1,3	1,5	2,04	M	5,5
18	4,8	6,17	30,0	2,5	M	5,5
19	4,8	1,17	30,0	2,5	M	5,5
Σ	4,80	5,17	28,55	0,48	0	0,50

M = Missing particle.

Note : All moves are underlined.

Table A.13 Sieve analysis of pan collected sediments : Mean grain size (M) and sorting (S) values for each sample day.

Day	Site 1		Site 2		Site 3		Site 4		Site 5	
	M (mm)	S	M (mm)	S	M (mm)	S	M (mm)	S	M (mm)	S
1	4,3	1,9	M				5,8	3,7	6,4	1,0
2	6,8	2,0	M				25,0	1,8	M	
3	4,1	1,9	7,8	1,4			8,1	1,3	1,8	2,7
4	3,6	2,0	6,7	1,3			34,9	1,7	1,6	2,5
5	4,9	1,8	7,2	1,5			23,4	1,9	M	
6	6,3	1,9	10,4	2,1			34,8	2,7	1,6	3,3
7	4,0	1,9	6,2	1,4	4,2	5,8	14,4	3,1	1,6	2,9
8	5,1	1,7	8,4	1,8	2,9	1,7	16,1	2,5	M	
9	6,3	2,0	9,7	1,7	6,4	2,7	38,6	1,6	1,0	3,2
10	6,6	2,4	M		3,2	1,6	25,1	1,7	M	
11	7,2	2,1	8,7	1,8	3,3	2,4	58,0	1,9	0,7	3,2
12	8,1	2,8	6,5	1,6	2,0	1,9	38,9	2,5	1,2	2,4
13	5,8	1,7	13,4	1,6	2,9	1,8	1,7	4,5	M	
14	10,8	2,1	10,5	1,4	3,6	1,8	18,8	1,9	M	
15	5,0	1,5	13,6	1,7	2,1	2,4	15,0	3,3	1,2	3,6
16	5,1	1,5	18,5	1,5	1,6	2,5	13,2	2,2	M	
17	4,2	1,9	M		1,6	2,5	6,0	3,4	M	
18	6,0	2,3	M		1,7	2,7	3,2	2,2	M	
19	3,8	2,9	M		1,0	4	1,4	5,9	3	4,6
Averages	5,6	2,0	9,8	1,6	2,8	2,6	19,9	2,6	2	2,9

M : Missing data.

Table A.14 Record of peak discharge (m^3,s^{-1}) recorded at the weir (Q9M21) 1976-1985.

Year	Date	Discharge	Year	Date	Discharge	Year	Date	Discharge
1976	3/1	0.170	1979	21/2	0.012	1983	3/10	0.183
	9/1	0.854		28/2	0.279		12/11	0.115
	6/2	0.440		21/7	4.683	1984	20/6	0.005
	2/3	0.020		24/7	1.819	1985	8/2	0.050
	22/3	1.035		21/8	2.496		10/2	0.085
	28/3	0.046	1980	1/12	0.241		2/3	0.127
1977	27/2	0.856	1981	25/3	0.118		14/3	0.044
	28/2	0.840		26/3	0.205		22/4	0.008
	6/3	1.384		30/5	0.059		16/10	0.111
	24/4	0.058		28/8	0.015		30/10	0.232
	7/5	1.234		31/8	0.040		2/11	1.736
	26/11	0.035		26/10	0.356		4/11	1.350
	1/12	0.683		23/12	0.508		9/11	0.103
	30/12	0.128		15/6	0.024		29/11	0.100
1978	10/1	0.304		5/12	0.028		3/12	1.123
	20/4	0.103	1983	24/7	0.061		8/12	0.514
	21/4	0.431		25/7	0.102		19/12	0.160
	7/10	0.006		26/7	0.071		24/12	0.132
	2/11	0.026		27/7	0.058			