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Laboratory experimentation for the statistical derivation of equations for soil erosion modelling and soil conservation design

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This thesis is submitted for the degree concerned

Diagrams in pocket at back of thesis

ABSTRACT

Since Ellison (1947) described the process of erosion as comprising

a) the detachment of soil particles from the soil mass by raindrop impact,

b) detachment by runoff,

c) the transport of the detached particles by raindrop impact, and

d) transport by runoff, research has been directed into the mechanics of each of these four phases and how the phases might be linked together in the form of a soil erosion model, such as the Meyer-Wischmeier (1969) model. From a literature review, it became evident that in spite of this work, gaps in knowledge still exist and that

i) most studies on soil erosion tend to lump the processes together;

ii) whilst a considerable amount of investigation has been carried out on splash erosion, the other processes have received very little attention;

iii) there is no explicit study on the effects of factor-interactions on the processes and the role of the laboratory as a place for studying interactions by controlling factors has not attracted much attention;

iv) equipment and techniques for the separate evaluation of the detachment and transport of soil particles by overland flow are not available; and

v) studies on the hydraulic characteristics of overland flow in relation to the detachment and transport of soil particles in such flows are scarce.

This study was therefore specifically aimed at establishing a sounder research base for modelling the subprocesses and ultimately for soil conservation design by:

i) evaluating separately each of the above subprocesses;

ii) assessing the influence of the factors affecting the processes, particularly their interactions; and

iii) examining the hydraulics of soil particle detachment and transport by overland flow with and without rain.

As a means to achieve these objectives, a factorial experiment was set up in the laboratory to examine both the individual effects of rainfall intensity (50, 80, 110, 140 mm h^{-1}), soil type (standard sand, sand, clay loam and clay) and slope steepness (3.5, 7.0, 10.5 and 14.0 per

cent) and their interactions on each of the above subprocesses. Additionally, the effects of four rates of runoff (1.0, 1.6, 2.2 and 2.8 l/min) on the hydraulic characteristics of flow such as velocity, depth, Reynolds number, Froude number and friction factor were examined and used in characterizing the detachment and transport of soil particles in these flows. For each subprocess, these variables were replicated four times.

Splash detachment and transport were determined by simulating rainfall from a nozzle simulator over a target soil placed in a rectangular soil tray (10 x 20 x 4 cm) which being set in the centre of a catching tray (90 x 80 x 30 cm) allows for the separate determination of upslope and downslope splash.

The separate measurement of the detachment and transport of soil particles by overland flow with and without rain was carried out by using a specially designed rainfall simulator - bed flume facility with runoff and sediment input and measuring devices.

The results were analysed by analysis of variance to show the significance of soil type, rainfall intensity, flow rate, slope steepness and their first and second order interactions in influencing the processes studied. Multiple correlation techniques were used to search for the best associations between the erosion influencing variables and soil loss. Regression analysis was used for establishing predictive equations for detachment and transport rates.

Detachment of the test soils by splash can be placed in rank order of standard sand, sand, clay and clay loam with increasing resistance. For splash transport the order is standard sand > clay > sand > clay loam. For each soil type there are significant increases in splash detachment and transport with increasing rain intensity and slope steepness.

The most significant interactions influencing the two splash processes are soil x intensity and slope x intensity for detachment and transport respectively. Significant interactions show that the factors are not independent of each other; the simple effects of a factor differ, and the magnitude of any simple effect varies according to the level of the other factors of the interaction term.

The factors influencing detachment by flow without rain rank in an order of importance as soil type, slope steepness and discharge. The corresponding order for flow with rain is discharge, slope steepness and soil type. The order of soil detachability for both flow with and without rain is standard sand > sand > clay loam > clay. There are also significant increases in detachment rate as slope steepness and flow rate increase.

It is further shown that the first and second order interactions of the above factors significantly influence detachment by flow. On a relative basis, the second order interaction is small and the importance of the first order interactions can be placed in an increasing order of slope x soil, slope x discharge, and discharge x soil for flow without rain. For flow with rain, they rank as slope x soil, discharge x soil, and slope x discharge.

The slope x soil interaction showed that as slope steepens the influence of each soil on detachment rates increases with the proportionate increase being greater for sand and standard sand than for clay and clay loam. The slope x discharge interaction revealed significant increases in detachment rate for all slopes as discharge increased. The magnitude of the response is however greater at the lower than higher slopes. As slope steepness increases, detachment rates by flow with and without rain are also enhanced. The increase was proportionately more for the 1.0 and 1.6 l/min than 2.2 and 2.8 l/min flows. The soil x discharge interaction also indicated that, for flow without rain, detachability increases more for clay and clay loam than for the sand and standard sand as discharge increases. In the presence of rain however, the response of the soils did not differ much.

Detachment by flow without rain is predominantly by rilling. In the presence of rain, detachment rates by flow are increased about three fold and relatively even removal of soil particles from the eroding bed is characteristic. Raindrop impact thus appears to inhibit rill formation by overland flow especially on small slope steepnesses.

There is a critical slope steepness at which both raindrop impact and overland flow contribute equally to total detachment. At slopes lower than the critical value, raindrop impact is the main detaching agent whilst flow predominates the detachment process at steeper slopes. The critical slope steepness is soil specific and decreases in the order of clay > clay loam > sand > standard sand.

The transport of soil particles by combined flow and rain is significantly influenced by soil type, slope steepness, flow rate and their first and second order interactions. Transport rates decreased in the order of sand > standard sand > clay > clay loam. Increases in discharge and slope steepness significantly increased transport capacity. For a discharge range of 1.0 - 2.8 l/min, transport capacity increased four fold.

The most significant interaction that influences transport capacity is slope x soil. Where factors interact significantly, interpretation of results based solely on the main effects of the influencing factors may result in loss of vital information and lead to wrong conclusions. For example, examination of the slope x soil interaction showed that at lower slopes (3.5 and 7.0 per cent) combined flow and rain has a greater transport capacity for the larger clay and clay loam aggregates than for the fine grains of sand and standard sand. This is obscured when effects are averaged over all the slopes as is the case when only main effects are considered.

With combined flow and rain, clay and clay loam particles are transported as aggregates whilst those of sand and standard sand proceed mainly as individual grains with rolling and saltation dominating the movement of the clay aggregates and sand grains respectively. Movement of particles particularly sand and standard sand with porridge-like consistency and maintaining constant contact with each other was also observed.

In order to characterize the detachment and transport of soil particles by the hydraulic properties of flow, velocity and depth were measured and used for the calculation of other flow parameters.

Flow velocities and depths were generally small. The mean values of velocity ranged from 44.13 - 88.58 and 46.47 - 94.13 mm s^{-1} for flow with and without rain respectively. The corresponding values for flow depth were 0.76 - 1.06 and 0.70 - 0.92 mm.

Reynolds numbers were in the laminar range with mean values varying from 24 - 65.93. The values for Froude number, 0.55 - 0.92 and 0.60 - 1.04 for flow with and without rain respectively, show that overland flow can be either supercritical or subcritical. However flow was predominantly subcritical - laminar and the critical Froude number beyond which appreciable numbers of rills were formed was 0.55 for standard sand and sand and 0.68 for clay and clay loam.

Friction factor (f) ranged between 5.21 - 1.71 and 3.9 - 1.20 for flow with and without rain. The value of k in the relationship, $f = k/Re$, always exceeded the theoretical value of 24 for laminar flow over smooth surfaces. Manning's n ranged from 0.18 - 0.14 and 0.14 - 0.10 for flow with and without rain respectively. These values are about 7.5 times greater than the value of 0.02 commonly used for bare erodible soils in channel design and about 25 per cent lower than the lower range value of 0.2 reported for field conditions.

In most cases the mean values of tractive force, 1.02 - 1.40 N m^{-2} for flow with rain and 0.95 - 1.26 N m^{-2} for flow without rain, were greater than the critical value for most agricultural soils. The maximum permissible values of tractive force and velocity used in soil conservation design are, however, several orders of magnitude higher than the forces and velocities used in this study although the latter have been found to cause significant erosion. Flow power ranged between 0.05 and 0.13 J s^{-1} m^{-2}. Total runoff energy was significantly smaller than that of rain with about 11.5 per cent of the rainfall energy contributing the overland flow energy which varied from 55.28 - 151.88 J m^{-2}.

The most important flow parameter that singly predicted detachment rate by flow with rain was velocity. In the absence of rain, flow velocity, flow power and total kinetic energy of flow were the most significant. Detachment rate was negatively correlated with flow depth and friction factor. For transport rates by flow with rain, the major flow variables were velocity, flow power, total kinetic energy of flow, friction factor and tractive force with values of the coefficient of determination ranging from 0.85 - 0.98.

For each subprocess, new predictive equations, such as those in Table 1a, accommodating the effects of other factors which are important but are not incorporated into existing equations are established. These include slope steepness for splash detachment, a grain size term for splash detachment and transport and for overland flow detachment.

Rainfall-runoff interaction contributes significantly to soil loss and therefore predictive equations which do not account for this interaction underestimate soil loss. The use of such equations for design work in soil conservation may lead to under design and therefore they must be replaced by new equations that accommodate rainfall-runoff interactions, such as those provided in this study (Table 1a). Guidelines are also provided for incorporating rainfall-runoff interactions into some of the current erosion models for improvement.

When used in the Meyer-Wischmeier-type models, the equations can help determine the erosion-limiting process. This facilitates the selection of erosion control measures by allowing them to be directed at the limiting process. This approach is illustrated and guidelines are provided for establishing a sounder research base for modelling the hydraulic effects of plant cover on the same lines as the maximum permissible velocity and tractive force approaches currently adopted in waterway design.

The results of the study have shown the need to direct more attention to the effects of factor-interactions to enhance our understanding of the mechanics of the erosion process. This may in turn point the way to better control measures.

The initiation and development of rills and the processes that occur within them also need further study. This should be examined in relation to soil properties and the temporal and spatial variations in flow characteristics.

Further development of erosion models should consider incorporating the effects of rainfall-runoff interactions and the effects of soil conservation practices. Since the usefulness of erosion models is ultimately judged by their applicability to field conditions, their validation for such conditions should be encouraged.

TABLE 1a Predictive equations for estimating detachment and transport rates on all soils*

	R^2	Eq.No.
Splash detachment (Q_{det}; kg m^{-2})		
$Q_{det} = 0.00004\ KE^{1.10}\ S^{0.20}\ d_{50}^{-0.43}$	0.84	58
Splash transport (Q_{trans}; kg m^{-2})		
$Q_{trans} = 0.00004\ KE^{0.81}\ S^{0.98}\ d_{50}^{-0.34}$	0.73	61
Detachment by overland flow (Q_{odet}; kg m^{-2})		
$Q_{odet} = e^{16.37}\ q^{1.50}\ \sin S^{1.44}\ d_{50}^{-1.54}$	0.91	259
$Q_{odet} = e^{0.04}\ (qs)^{1.41}\ d_{50}^{-1.54}$	0.91	261
Detachment by overland flow with rain (Q_{rodet}; kg m^{-2})		
$Q_{rodet} = e^{13.40}\ q^{1.12}\ \sin S^{0.66}\ d_{50}^{-0.47}$	0.90	284
$Q_{rodet} = e^{2.07}\ (qs)^{0.82}\ d_{50}^{-0.47}$	0.85	292
Transport capacity of overland flow with rain (T_c; kg m^{-1} min^{-1})		
$T_c = e^{22.34}\ q^{2.13}\ \sin S^{2.27}$	0.88	400
$T_c = e^{-1.43}\ (qs)^{2.22}$	0.88	402
Sediment yield by overland flow with rain (Q_y; kg m^{-1})		
$Q_y = e^{28.85}\ q^{2.63}\ \sin S^{2.79}$	0.90	415
$Q_y = e^{2.13}\ (qs)^{2.71}$	0.90	417

where

KE = total kinetic energy of rain (J m^{-2})

S = per cent slope

d_{50} = the grain size at which 50 per cent of the soil particles are finer (mm)

q = discharge per unit width (m^3 s^{-1} m^{-1})

qs = flow power (l m^{-1} min^{-1})

Table 1a (continued)

* 1) The equations for flow are for overland flow and incipient rill flow. They should not be used for predicting gully erosion.
  2) They are valid for detachment and transport capacity limited conditions and for instantaneous conditions.
  3) The equations have not been verified in the field. Until validated their use in predicting detachment and transport rates or soil loss in the field should be considered only as a first approximation.
  4) The equations were produced under laboratory conditions with simulated rainfall intensities of 50 - 140 mm h^{-1}, 3.5 - 14 per cent slope, 1.0 - 2.8 l/min flow rate and bare disturbed soil samples (sand, clay loam and clay).

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CHAPTER 1

INTRODUCTION

1.1 THE SOIL EROSION PROBLEM

The problem of soil erosion has been a major concern to mankind throughout the ages and it is still an active research area because of its threat to continued and sustained agricultural production.

Two major types are distinguished: geological and accelerated erosion. Geological erosion, sometimes referred to as natural or normal erosion, is found when the soil is in its natural environment under the protective cover of native vegetation. Under these conditions the soil forming and soil eroding processes maintain the soil in a favourable balance suitable for the growth of most plants. However, the removal of the vegetation for agricultural production as well as urban and industrial development directly exposes the soil to the destructive effects of the erosive agents such as water and wind. This greatly increases the rate of erosion and gives rise to accelerated erosion. The occurrence of the latter type of erosion upsets the natural balance between the rate of pedogenesis and the rate of erosion and becomes the most potent single factor contributing to the loss of soil productivity (FAO, 1965).

It has been shown (Dudal, 1981) that by the year 2000, an estimated 200 million hectares of additional land will be required for food production just to compensate for soil loss. This land would not therefore add to agricultural production, but merely maintain it at its present level. This figure is particularly distressing in a hungry world where demand for agricultural products is ever increasing. It shows the need for a better understanding of the erosion process and its control to conserve our most basic nonrenewable natural resource, productive soil.

The erosion process has been a subject of considerable investigation especially in the U.S.A., using runoff plots, small watersheds, and rainfall simulation (Moldenhauer and Foster, 1981). These investigations have identified the erosion process as being a response to the interaction of rainfall, slope, vegetation, and management factors and have produced data including approximately 65,000 individual storms, 8,250 plot years and 2,500 watershed years of runoff information, and nearly as many soil loss records (Wischmeier, 1955). From this mass of data, Wischmeier and Smith (1965) developed and recently refined (Wischmeier and Smith, 1978) the Universal Soil Loss Equation as a tool for conservation planning to maintain productivity of cropland.

The process of erosion by water, which is considered in this study, comprises four major phases: the detachment of soil particles from the soil by raindrop impact; detachment by runoff; the transport of the detached particles by raindrop impact; and transport by runoff. When sufficient energy is no longer available to transport the particles, deposition occurs. In a given field condition either detachment rate or transport capacity may limit or control the rate of erosion. The recognition of the limiting phase is therefore important because the success or failure of erosion control practices relies upon applying remedies to the correct one (Morgan, 1979). Because of this, current approaches to modelling erosion require the subprocesses to be considered separately but also dynamically (Foster et al, 1980; Meyer, 1981; Thornes, 1981; and Foster, 1981). On this basis, and for a better understanding of the erosion process and control options, physically-based models are preferred. Such models are of limited value, however, until appropriate data are available to develop parameter values, and to validate and apply them to the broad range of conditions encountered in the field (Morgan and Morgan, 1981; Meyer, 1981; and Foster, 1981). Reliable experimental data have therefore become an urgent need in current modelling efforts (Meyer, 1981). To satisfy this need, it is necessary to revert to the approach suggested by Ellison (1947) in which the subprocesses of erosion are evaluated separately in contrast to the lumping together of the processes which characterize most of the earlier and many of the present studies on erosion.

Considering the four phases of the erosion process identified earlier and which are used in the Meyer - Wischmeier (1969) model, it is clear that so far development has been mainly in the field of splash erosion. This has led to the establishment of a number of power equations relating splash detachment to some physical characteristics of rain including intensity and kinetic energy. Splash transport has been similarly related to slope steepness. Most of these studies have been carried out in the laboratory and confined to non-cohesive soils. Hardly any work has been done on the effect of soil type or its interaction with kinetic energy on the exponents of the equations. Instead, the factors influencing the process have been treated as independent in single factor experiments. The interaction of slope steepness, soil type, and intensity of rain on the splash process has not been explicitly studied.

Also, there is virtually no study that has evaluated detachment by overland flow and although extensive literature exists on sediment transport by streamflow (Graf, 1971), much less is known about the transport of sediment by shallow flows normally found on hillslopes (Niebling and Foster, 1980). The combined effects of flow and raindrop impact in the detachment and transport of soil particles are also poorly understood. Nevertheless, the recognition of the differences in the manner in which the energy of these two erosive agents is expended on the soil surface is a prerequisite for planning strategies for controlling erosion. This is also important in the design of equipment and the development of techniques to simulate the processes for studying their mechanics. Moreover, little work has been done on the hydraulics of soil detachment and transport by overland flow, yet the development of methods for collecting and analysing hydraulic data would seem to be necessary for formulating and testing physically-based models of sediment transport in shallow flows.

Previous investigations indicate two major approaches to the study of sediment transport by shallow flows of infinite width. The first includes the adaptation of theoretically based stream flow sediment transport equations to overland flow because data are unavailable to develop an equation specifically for overland flow itself (Niebling and Foster, 1980; Morgan, 1980; and Carson and Kirkby, 1972). The second depends on empirical methods (Zingg, 1940; Wischmeier and Smith, 1965). Kilinc and Richardson (1973) found a purely theoretical approach impractical. Because of the complex nature of the soil erosion phenomenon a simulated model in which the factors can be controlled or altered is desired. This is the approach adopted for the present study.

The above review gives some indications of the extent of the soil erosion problem and identifies some aspects of the problem that need further research to enhance the understanding of the erosion process and its control. It is in the light of the above deficiencies in knowledge of the erosion process that this study is being undertaken.

1.2 SCOPE AND OBJECTIVES OF STUDY

The study aims to advance knowledge in the mechanics of the erosion process by carrying out detailed laboratory studies on the following problem areas.

1.2.1 The separate evaluation of each of the four major subprocesses of erosion identified earlier on.

As indicated in section 1.1 the lumping together of the subprocesses of erosion is a notable characteristic of most of the earlier and present studies on soil erosion. In contrast, this study considers each subprocess separately. To be able to do this, appropriate equipment and experimental techniques must be developed for each phase of the erosion process. Methods for studies of splash detachment and transport are well established but there are no standard techniques for the measurement of detachment and transport of soil particles by overland flow with and without raindrop impact. The first objective therefore is to fill the latter gap. The equipment and the experimental methods are described in Chapter 3.

1.2.2 The influence of the factors affecting the subprocesses of soil erosion.

Most laboratory experiments tend to be designed to investigate the effect of single factors on erosion. The equations produced from such studies cannot take account of the interactions between the factors which exist in reality in the field. The second objective is twofold:

i) to evaluate the individual effects of a range of slope steepnesses, types of soil, and rain intensities on each of the subprocesses; and particularly

ii) to take advantage of the hitherto neglected role of the laboratory as a place for studies of interactions in controlling factors with a view to confirming the validity of the equations derived from (i) and other similar studies over a range of conditions defined by the factors examined in (i) and considering them as a set of interacting variables.

1.2.3 The hydraulics of sediment detachment and transport by overland flow.

The detachment and transport of soil particles by overland flow are related, among other things, to the hydraulic characteristics of the flow. Therefore, to develop detachment and transport equations specific to overland flow, it is necessary to identify and relate its relevant flow properties to its detachment and transport capacities. One approach is to measure the hydraulic properties of the flow and through statistical techniques, particularly correlation and regression analyses, to seek the best relationships between such flow parameters and the corresponding detachment and transport capacities. Although relationships developed by this approach are empirical, they enhance the understanding of the processes at work and provide a sounder base and support for the assumptions needed for the development of theoretical equations for the erosion process. Moreover, sediment production in the field is largely due to the interactive effect of rainfall and overland flow on the soil. Because of the shallow depths of overland flow, raindrop impact affects its hydraulic characteristics and its detachment and transport capacities. Unfortunately, the relationship between these latter and rainfall parameters is not known. Yet, the effects of raindrop impact need to be incorporated into the current equations for the detachment and transport capacities of overland flow to improve their predictive capabilities and thereby make them better building blocks for modelling the erosion process as a base for designing effective control measures. At present, because relevant data are scarce, it has not been possible to precisely model these effects. With this in view, the third objective seeks to provide such information by:

i) measuring the hydraulic properties, specifically the depth and the velocity of overland flow with and without raindrop impact and using the data to calculate Reynolds and Froude numbers, boundary shear stress, stream power per unit boundary area, Darcy-Weisbach friction coefficient and Manning's n -- rainfall will also be characterized by its intensity and kinetic energy; and

ii) establishing relationships between the detachment and transport capacities of the flow and the parameters studied in (i).

It is believed that the achievement of the above objectives will help produce the right data needed for modelling the subprocesses of erosion. In particular, by improving the procedures for establishing parameter values, the study will allow a fuller validation of current physically-based models which, in turn, will enhance their usefulness as conservation tools.

CHAPTER 2

PROCESSES AND MECHANICS OF WATER EROSION

This Chapter examines some of the broad issues raised in Chapter 1 in order to justify the problem areas selected for the study. Attention is particularly focussed on previous work on the mechanics of soil erosional processes and the aim is to identify areas where gaps in knowledge exist and therefore need further investigation to enhance the understanding and the precise modelling of the processes. The constraints in carrying out satisfactory evaluation of some of the sub-processes are also discussed and possible solutions are suggested. These are then used as the basis for the design of equipment and development of techniques (Chapter 3) for measuring separately, each of the following four phases of erosion:

i) detachment by rainfall;
ii) transport by rainfall;
iii) detachment by runoff; and
iv) transport by runoff.

Of these processes discussed below, splash erosion has received a considerable amount of investigation and methods for its study are fairly well established (Ellison, 1947; Moeyersons and DePloey, 1976; DePloey and Gabriels, 1980). In spite of this, as outlined in the preceding Chapter, a lot more work remains to be done. Less work has been carried out on shallow flows on a hillside. These are known to vary greatly in the extent to which they are concentrated into depressions or channels (Carson and Kirkby, 1972) and therefore give rise to different patterns of flow with varying hydraulic as well as erosive characteristics. Because of the importance of these variations, some initial definition of shallow flows and their hydraulic properties is considered before the discussion of the detachment and transport processes in these flows.

2.1 RAINSPLASH DETACHMENT

The detachment of soil particles (primary and aggregated) from the soil mass by falling raindrops initiates soil erosion (Ellison, 1947) and may be quantitatively defined as the mass of soil actually dislodged per unit area (Rose, 1960).

When a raindrop strikes the soil surface, its impact force detaches soil particles and splashes them in all directions from the point of impact with net movement downslope. Current research (Ghadiri and Payne, 1977; 1981) directed at the magnitude, duration and distribution of raindrop impact stress shows the latter to be non-uniform, being locally much higher than predicted by average stress with a maximum of 2 - 6 MPa on the perimeter of circle which corresponds with the shape of the initial splash-crown. The force has to overcome the particle weight and the cohesive force binding the particles together and is also dependent on the slope of the surface (Fleming, 1977).

For slopes less than 15 per cent, splash detachment increases linearly as slope steepness increases (Meyer et al. 1975). However for steeper slopes, 33 to 100 per cent, Foster and Martin (1969) found that depending on soil's bulk density splash detachment rose to a maximum and then decreased again as the slope steepened. In spite of these observations, slope effects are not identified in previously determined detachment relationships. In order to do so, it appears two sets of equations will be required; one for lower slopes typical of arable lands and the other for steeper slopes. On the other hand the relationship may be parabolic.

The nature of particle detachment and movement is a reflection of the relationship between the characteristics of the rainfall and the soil. Because of this, Ellison (1947) expressed the susceptibility of soils to detachment as a function of the detaching capacity of the erosive agent and the soil's detachability (K). Since then, the capacity of raindrops to detach soil particles has been related to various physical characteristics of rainfall. Ellison (1944) studied the effect of various combinations of drop size, velocity and intensity of rain on splash erosion and expressed it as:

$$E = K V_1^{4.33} D^{1.07} I^{0.57} \qquad \text{Eq.1}$$

while Bisal (1960) obtained from similar laboratory studies

$$G = K D V_2^{1.4} \qquad \text{Eq.2}$$

where

E & G	=	grams of soil splashed
K	=	a constant of soil
D	=	drop diameter, mm
V_1 V_2	=	drop velocity (V_1, ft s^{-1}; V_2, m s^{-1})
I	=	rainfall intensity, in h^{-1}

Hudson (1965) shows that the combination of drop mass and drop velocity in the above equations is no different from combining mass and velocity into the parameter, kinetic energy, which is found in other splash relationships. Mihara (1951) thus reported soil splash as directly proportional to kinetic energy, and Free (1960) related splash to 0.9 power of kinetic energy for sand and 1.46 power for silt loam. Bubenzer and Jones (1971) found the exponent relating splash to kinetic energy to range from 0.83 to 1.40 for a range of soils; and further showed an inclusion of a per cent clay term in their splash equation

$$E = 7.50\, I^{0.41}\ KE^{1.14}\ \%\, Clay^{-0.52} \qquad \text{Eq.3}$$

where

E	=	splash loss in g cm^{-2}
I	=	rainfall intensity cm h^{-1}
KE	=	total kinetic energy J cm^{-2}

to improve the multiple correlation coefficient for rainfall intensity and kinetic energy from 0.87 to 0.93. From the above relationships, and for the fact that kinetic energy is commonly correlated with rain intensity, splash detachment is shown to be proportional to the square of rain intensity (Meyer and Wischmeier, 1969; Foster and Meyer, 1975; David and Beer, 1975). This provides a convenient model (Kirkby, 1980) and has a practical appeal because intensity is the only feature of rainfall which, in addition to amount, is frequently recorded at conventional meteorological stations (Hudson, 1971).

In all these power equations, soil detachability is assumed to be a constant. One problem in using the equations to model the rate of splash detachment is that it is often difficult to obtain values for the constant (K). This is because most of the work on splash detachment is conducted on sand. The application of these equations therefore requires the constant K to be determined experimentally for different soil types.

Previous studies indicate two major approaches to the establishment of soil erodibility values. The first consists of numerous erodibility indices expressed in terms of some physical characteristic of the soil including both primary and secondary particle sizes. Middleton (1930) considered the ratio of total weight of silt and clay content in the undispersed soil to that of the soil dispersed in water, referred to as dispersion ratio, to be the most significant index influencing soil erodibility. Bouyoucos (1935) suggested that erodibility was proportional to the clay ratio expressed as (% sand + % silt) / % clay. These indices have been extensively reviewed by Bryan (1968). Wischmeier et al. (1971) found that although soil erodibility tended to increase with greater silt and very fine sand content and decrease with greater sand, clay and organic matter, the ability of these parameters to predict erodibility (singly or in combination) was poor. Other workers therefore favour the use of aggregate stability as a measure of soil erodibility (Adams et al. 1958; Bryan, 1968).

The second approach uses the water drop technique in characterizing the stability of soil aggregates, a major factor governing soil detachability (Vilenski, 1945; Bruce-Okine and Lal, 1975; Imeson and Jungerius, 1976; Bergsma and Valenzuela, 1981). In this method, the number of falling drops of standard size and velocity required to destroy prewetted soil aggregates is used as a measure of resistance to aggregate breakdown.

These indices give some indications of the relative resistance of different soils to erosion and are very useful in surveys of soil erosion hazard and in development projects (Bergsma and Valenzuela, 1981). Nonetheless they fail to provide a quantitative estimate of the erosion which will occur when the soil is subjected to rain of known erosive power. However, if a linear relationship is assumed and the amount of soil detached and the kinetic energy that caused it are known, it is possible to calculate for each soil the kinetic energy needed to detach 1 kg of soil. This parameter is indicative of the resistance to detachment by raindrop impact while its reverse is a measure of detachability (Poesen and Savat, 1981). This parameter can also be used to assess the total amount of material detached by raindrop impact on a given surface. The problem with this approach is the underlying assumption, for, whilst the relationship between splash detachment and kinetic energy is generally linear for sand (Ekern, 1950; Free, 1960), it is non-linear for soils (Bubenzer and Jones, 1971; Free, 1960).

At a constant rain intensity, splash detachment appears to be a time-dependent function (Thornes, 1980). The data of Poesen (1981) show an irregular temporal variation in the splash rate of several sediments. With an initial air-dry sand, cumulative splash increases rapidly and peaks at about the 35th minute after which the rate remains fairly steady. For silty sand, it is initially high and reaches a maximum at the 15th minute. Thereafter, the rate becomes erratic till about the 50th minute after which steady state is attained. These differences were explained in terms of temporal variations in surface water content. Other important considerations are surface sealing, grain size distribution, initial soil moisture status and the changes in these conditions with time during and between rainstorms (Kirkby 1980).

Despite this, soil erodibility is often considered static as seen in its representation by a single constant in erosion models (Meyer and Wischmeier, 1969; Moeyersons and DePloey, 1976; Foster and Meyer, 1975; David and Beer, 1975) and the use of erodibility indices (Bryan, 1968). In reality, however, erodibility is dynamic in that it may change through a storm, from season to season and with soil management systems (Thornes, 1980). In order to obtain an expression that adequately represents erodibility, more work needs to be done on its dynamics. A precise delineation of soil properties which determine resistance to raindrop impact is required to lead the way to a more rational measurement and hence representation of soil erodibility (Ghadiri and Payne, 1981; Kirkby, 1980). Until then, the operation of models that incorporate a detachability factor (K) will continue to depend on the availability of K - values which, for most soils, are scarce.

2.2 RAINSPLASH TRANSPORT

The dissipation of rainfall energy on the soil may cause movement of soil particles (Bisal, 1960). On a bare level surface and for raindrops falling vertically, splashed material tends to scatter uniformly over the surface in all directions (Stallings, 1957). In such cases, little more than a random rearrangement of particles is achieved save for the forming of small craters and compaction of the surface, making it more susceptible to runoff. On a sloping surface, however, the pattern of movement becomes assymetrical and there is a net transport of material downhill. This is because the downslope component of the impact force acts directly to move soil particles and the same set of splash trajectories produces longer jumps when directed downhill rather than uphill (Carson and Kirkby, 1972).

The downslope movement of splashed material may account to a large extent for erosion on short, steep slopes (Ellison, 1947). Ekern (1950) noted that splash transport accounts for much of the accelerated sheet erosion on cultivated soils. Young and Wiersma (1973) and Morgan (1978) found that although the net movement of soil downslope by splash was minimal, the total amount of splashed material was positively correlated with the amount of soil transported off the plot by rill flow.

The size distribution of detached particles has important implications in their subsequent transport and deposition. Dispersed clay stays in suspension virtually as long as water is moving while aggregated materials high in clay settle according to their size and density (Gabriels and Moldenhauer, 1978). Rainsplash selectively transports the smaller particles. In experiments carried out by Ellison (1944) using raindrops of 3.5 to 5.1 mm diameter, 69 to 73 per cent of the splashed material was less than 0.1 mm in size and 0.4 to 2.4 per cent was greater than 2 mm; whereas the original soil was 54 per cent less than 0.1 mm and 13 per cent greater than 2 mm. He further showed that 5.1 mm drops falling at a velocity of 5.4 m s^{-1} moved some soil particles a distance of 1.5 m, and that even 4 mm stones could move as far as 20 cm while 2 mm aggregates and particles moved 40 cm. Kirkby and Kirkby (1974) observed the maximum size of particles moved by raindrops to be 50 mm and particles 5 mm in diameter were often thrown up to 15 cm at a time.

At a constant erosivity the net flux of soil due to splash is a function of slope since mean distances moved increase with slope gradient (Thornes, 1980). This effect is shown by data from several workers. Mosley (1973) showed that the quantity of soil caught on traps at varying distances away from a trough of sand subjected to rain declined exponentially with distance. The rate of decline was equal in all directions on level ground but as slope angle increased, downslope transport and maximum distances of travel increased. On a 25^{o} slope over 95 per cent of material travelled downslope. The percentage of total splashed soil that moves downslope may be approximately estimated as per cent slope plus 50 (Ekern, 1950). This relationship, however, gives a 15 per cent underestimation of what was obtained by Ellison (1947) on a 10 per cent slope. DePloey and Savat (1968) subjected sand grains (0.09 to 0.35 mm) on a range of slopes to the impact of a 3.8 mm raindrop with an impact velocity of 7 m s^{-1} and obtained the results in Table 1:

Table 1 Per Cent Downslope and Upslope Distribution of Splashed Particles

	Slope Angle				
	0°	8°	15°	30°	40°
			%		
Downslope splashes	50	64.0	69.5	81.0	82.5
Upslope splashes	50	36.0	30.5	19.0	17.5

From their values, Savat (1981) expressed the percentage downslope movement of splashed particles (% D) as:

$$\% D = 100 - 50\ e^{-0.042\ a} \qquad \text{Eq.4}$$

where

a = per cent slope steepness.

The use of total soil loss from a field as a measure of the magnitude of erosion tends to obscure the importance of in-field movement of ejected particles. However, under conditions of overland flow, the greater the downslope distance moved by ejected particles, the greater the chance of the particle being transported off the field. This effect would seem to be even more significant in the movement of particles which protrude above the surface of thin flows and are therefore subjected to the direct impact of raindrops. As observed by Ellison (1947) and Mihara (1951) splash losses increase in the presence of a thin film of surface flow. The significance of the latter however depends on its depth. Palmer (1964) found that for water layer depths ranging from 0.0 to 30.0 mm, maximum splash losses for drop sizes of 2.9, 4.7, and 5.9 mm occurred at a critical depth of the water layer of 2, 4, and 6 mm respectively. Thus the critical depth beyond which the flow essentially protects the soil from raindrop impact occurs in a region where a 1 : 1 relation exists between the drop diameter and the depth of water layer. On the contrary, 73 per cent of Poesen's (1981) observations indicated that for a rain intensity of about 30 mm h^{-1} with a median drop size of 4.1 mm, a thin film of surface flow (0.7 mm) had a marked negative effect on soil detachability. Similarly, Ghadiri and Payne (1981) observed that a thin film of water (2 mm) covering a solid target tended to reduce the impact stress. As a result soil loss is also decreased.

At a constant rain intensity, the distance moved by ejected particles is a function of the angle of ejection and ejection velocity. These, in turn, are influenced by the particle size. In a horizontal plane, the range (S) and the maximum height (Ymax) travelled by ejected particles can be calculated using the following equations (DePloey and Savat, 1968):

$$S = \frac{V^2 \sin 2\theta}{g} \qquad \text{Eq.5}$$

$$Ymax = \frac{V^2}{2g} \sin^2 \theta \qquad \text{Eq.6}$$

where

V = ejection velocity

θ = angle of ejection

g = gravity constant

The latter authors measured θ for different grain size fractions (0.09 to 0.5 mm) and found that about 90 per cent of the particles had ejection angles up to 30°. It was also observed that although individual grains had higher ejection angles, the aggregates moved greater distances. Several calculations of ejection velocities (a typical value of 2 m s^{-1}) showed that the initial ejection velocities of the grains were at least less than twice those of the aggregates. The initial ejection velocity was found to be a function of the ejection angle, being lower for greater ejection angles.

The mode of particle movement by splash also varies with the size of the particle. Moeyersons and DePloey (1976) distinguish between saltation and splash creep for finer and coarser fractions respectively. Once soil particles are detached, the transport of the separate grains and aggregates remains a function of the properties of the individual particles (Vanoni, 1975). However, unlike in sediment transport equations for flow, the effect of particle size is distinguished neither in splash detachment nor transport relationships. Kirkby (1980) proposes the inclusion of a grain size term in both splash detachment and transport models. He observes however that, for splash detachment, the grain size term can only represent simple granular soils and that allowances must be made for inter-aggregate bonding, and for reductions due to the protective roles of vegetation crowns, mulches and large stones.

Splash transport has been related to slope steepness, rain intensity and kinetic energy of rain. Moeyersons and DePloey (1976) related it to 0.75 power of the slope angle. Kirkby (1971) suggested a range of 1.0 and 2.0 for the slope exponent while Gabriels et al. (1975) obtained 1.37. Morgan (1978) obtained for Cottenham sand the following relationship:

$$Q_{trans} = 0.0003\, KE^{0.84} \quad S^{2.29} \qquad \text{Eq.7}$$

where

Q_{trans} = splash transport g cm^{-1}

KE = total kinetic energy of rain J m^{-2}

S = slope angle in degrees.

Meyer and Wischmeier (1969) expressed splash transport (T_R) as

$$T_R = K\,S\,I \qquad \text{Eq.8}$$

where

K = a soil constant

I = rain intensity

S = slope steepness

in their mathematical model for the erosion process.

For the model to work, the constant, K, will have to be determined experimentally for different soil types.

Although the rainsplash process on its own does not cause significant soil loss from the field, its capacity to damage soil is considerable (Ellison, 1944; 1947; Stallings, 1957). The soil detached by the splash process may muddy the surface water over an entire field, and this along with the puddling that splash causes, has a major effect on impeding infiltration of water into the soil (Ellison and Ellison, 1947; Free, 1952). For the same rainfall intensity, the decrease in infiltration rate is greatest on flat land because the consolidation effect of the impact forces is increased as the slope angle decreases (Rowlison and Martin, 1971; Kohnke and Bertrand, 1959; Carson and Kirkby, 1972). The latter effect is seen in the formation of soil surface crust (Young, 1972). The compacted soil is more difficult to till and more susceptible to runoff. Finer particles rich in nutrients and pollutants, and organic matter are made available for transport by overland flow and this results in fertility erosion (Massey et al. 1953; Ellison, 1950; Menzel, 1980; Quansah and Baffoe-Bonnie, 1981) and degradation of water quality (Robinson, 1971).

The above review has shown the significant influence of particle size on splash transport and the need to incorporate a grain size term into splash transport relationships. The interaction of surface water depths and impacting raindrops also plays an important role in the splash process. The effects are, however, not clearly defined and therefore require further study. For the Meyer-Wischmeier type models to work, values for susceptibility to splash transport will have to be determined experimentally for a wide range of soils. Some of the effects of splash erosion on soil degradation also need to be highlighted.

2.3 SHALLOW FLOWS

Shallow flows produced by rainstorms on hillslopes also have the potential both to detach and transport soil particles and are therefore important erosive agents. Such flows encompass overland flow and the early stages of rill flow and are generally accepted as being those in which flow depths are very small in comparison with flow width so that the flow becomes analogous to a wide open channel flow (Chow, 1959). A channel is assumed infinitely wide if the bottom width is at least five times greater than the depths of flow (Glass and Smerdon, 1967).

Overland flow is the initial phase of surface runoff (Emmett, 1970; Robertson et al. 1966) and occurs on hillsides during a rainstorm when soil moisture and surface depression storages or, with intense rain, the infiltration capacity of the soil are exceeded (Morgan, 1979). It is sometimes referred to as sheet flow although the flow is more commonly characterized by down-slope concentrations of flow as a result of resistance to flow due to surface roughness elements.

The above definition distinguishes two types of overland flow: infiltration excess or Hortonian overland flow and saturated overland flow. Hortonian overland flow (Horton, 1970) occurs when rainfall intensity exceeds final infiltrability, a relatively rare event (Thornes, 1980) and is envisaged as being produced rather uniformly over whole catchment areas. Saturation overland flow, on the other hand, is produced when rainfall exceeds moisture storage rather than infiltration capacity of the soil (Kirkby, 1969; Carson and Kirkby, 1972; Dunne, 1978). It is most common near the base of slopes and in areas where rainfall intensities are generally less than infiltration capacities, where rainfall is frequent and where soil storage is very small (Thornes, 1980; Young, 1972).

The recognition of these types of flow is very important not only because different strategies will be required to control the erosion they cause but also it is pertinent to:

i) an accurate simulation of flow as it exists in the field for studying its erosive mechanics in the laboratory;

ii) the manner in which the flow is produced in (i) and hence the design or choice of equipment; and

iii) the limitations of the applicability of results obtained in (i).

In order to achieve these objectives for Hortonian overland flow which is the major concern of this study, a knowledge of its spatial distribution on hillsides is necessary. At the top of the slope is a belt of no runoff erosion because of the absence of flow. At some distance downslope, surface depressions begin to fill, water overflows between depressions and a thin layer of water develops. After a critical thickness of this layer is exceeded, water begins to flow downslope. At a critical distance the water depth increases up to a point where the flow becomes channelled and breaks up into rills.

The occurrence of this pattern over a hillslope depends on the vegetative cover (Kirkby, 1969) and although the widespread applicability of the Horton model in various geographical areas has been questioned (Thornes, 1980), it is generally accepted to operate commonly under semi-arid conditions or in areas of sparse plant cover (Dunne, 1978; Kirkby, 1969). In humid and well vegetated areas however, such flows occur infrequently. Hortonian overland flow produced in the laboratory as shown in Chapter 3 will therefore be closer to reality if the above distribution pattern is simulated on bare soil surfaces.

2.3.1 Hydraulics of Shallow Flows.

The hydraulic characteristics of overland flow are required for (i) a better understanding of the detachment and subsequent transport of soil particles in thin flows (Carson and Kirkby, 1972); (ii) developing detachment and transport capacity equations specific to overland flow (Foster and Meyer, 1975; Niebling and Foster, 1980); and (iii) providing a sounder base for erosion modelling and design of conservation strategies (Morgan, 1980). These notwithstanding, the relation of overland flow variables to detachment and transport capacities has received little attention. Since this study aims to fill this gap, a background information of the hydraulics of flow is needed initially to identify the relevant flow parameters which will then be measured (Chapters 3 and 5) and used in modelling the detachment and transport processes (Chapters 6 and 7).

Flow may be laminar, turbulent, or transitional depending on the effects of viscosity relative to inertia (Chow, 1959) and represented by the dimensionless Reynolds number (Re) expressed as:

$$Re = \frac{rV}{\nu} \qquad \text{Eq.9}$$

where

V = mean velocity of flow

r = hydraulic radius

ν = kinematic viscosity

The flow is laminar when Re is less than 500 and at values above 2000, it is fully turbulent (Webber, 1971). Intermediate values are indicative of transitional or disturbed flow, often a result of turbulence being imparted to laminar flow by raindrop impact (Emmett, 1970; Chow, 1959).

Depending on the effect of gravity relative to inertia expressed as

$$F = \frac{V}{\sqrt{gr}} \qquad \text{Eq.10}$$

where

F = dimensionless Froude number

g = gravity constant,

flow may be critical, subcritical or supercritical. When F is equal to 1.0, the flow is critical and is supercritical or rapid with values of F greater than 1.0. Values less than

1.0 denote subcritical flow where the effect of gravity forces is pronounced so the flow has a low velocity and is often described as tranquil.

Kilinc and Richardson (1973) obtained from flume studies Re values ranging from 0 - 130 for flow produced by rain intensities of 31 to 115 mm h^{-1} on a sandy soil with a slope range of 5.7 to 40 per cent. Their F values varied from 0.5 to 5.4 and flow was described as agitated laminar. Field studies of overland flow (Morgan, 1979) on the other hand, reveal Re values between 1.0 and 50 and F values ranging from 0.01 to 0.1. The latter values compare with the ranges 0.05 to 0.20, and 0.05 to 0.09 obtained by Emmett (1970) and Pearce (1976) respectively. According to the above flume studies and those of Savat (1977) most overland flow is supercritical laminar. However, the field values suggest that erosion by overland flow takes place with subcritical flow. It must be stressed, however, that these values are average values and ignore the effects of localized surges of flow which can cause considerable variations in Reynolds and Froude numbers within the flow, both temporally and spatially.

If the hydraulics of a flow are to be understood then certain parameters must be known accurately. When either the depth or flow velocity and unit discharge are measured correctly, many other parameters such as Reynolds and Froude numbers and friction factors can be calculated. This approach has been used by several workers to study overland flow hydraulics in the laboratory (Savat, 1977; 1980; Glass and Smerdon, 1967) and in the field (Emmett, 1970; Pearce, 1976). However, because man has no control on the occurrence of erosive rains and observations are therefore made after the event, it is often difficult to obtain depth and velocity values for overland flow in the field. Attempts to relate erosion to flow parameters tend to depend on values obtained through reasoned assumptions and the use of relevant channel flow equations. Flow velocity and depth equations are therefore very useful in erosion studies and are even more so if they are expressed in terms of unit discharge which is relatively easy to measure and often used both in the design of runoff disposal systems (Schwab et al. 1966; Hudson, 1971) and modelling of the subprocesses of erosion (Meyer and Wischmeier, 1969).

From the continuity equation, the discharge at a channel section (Q) is expressed by

$$Q = d\,w\,v \qquad \text{Eq. 11}$$

and this gives discharge per unit width (q) as:

$$q = Q/w = dv \qquad \text{Eq. 12}$$

where

d = depth of flow

v = velocity of flow

w = channel width.

Since for wide open channels typical of overland flow, $r = d$,

$$Re = q/\nu \qquad \text{Eq. 13}$$

The velocity of uniform laminar flow can be expressed (Chow, 1959; Savat, 1977) as:

$$v = \frac{g\,s\,d^2}{3\nu} \qquad \text{Eq. 14}$$

which combines with equation 11 to give

$$q = \frac{g\,s\,d^3}{3\nu} \qquad \text{Eq. 15}$$

and

$$d = \left(\frac{q\,3\nu}{gs}\right)^{0.33} \qquad \text{Eq. 16}$$

The flow of water on rough surfaces at very shallow depths is of considerable practical interest (Phelps, 1975) especially in the study of the causes and control of erosion on arable land. Surface roughness has been found to retard flow velocity and to increase flow depth and friction factor (f) (Emmett, 1978). A measure of the resistance to flow is given by the Darcy-Weisbach formula:

$$f = \frac{8 g d s}{v^2} \qquad \text{Eq. 17}$$

which gives

$$f = \frac{8 g d^3 s}{q^2} \qquad \text{Eq. 18}$$

when combined with Eq. 11.

From equations 9 and 14 it can be deduced that

$$Re = \frac{d^3 g s}{3 \nu} \qquad \text{Eq. 19}$$

and in combination with Eq. 17

$$f = 24 / Re \qquad \text{Eq. 20}$$

The laminar resistance coefficient is thus inversely proportional to the Reynolds number. Experiments (Phelps, 1975) have shown that Eq. 20 is only correct when the bottom is smooth. For rough boundaries like those used in this study, the relationship becomes

$$f = k / Re \qquad \text{Eq. 21}$$

in which k is constant for a given roughness value. Savat (1980) shows that k deviates more from 24 when the bottom roughness increases and when the flume is steeper. Typical k values have been listed by Thornes (1980).

The importance of increased surface roughness in reducing erosion has been stressed by various authors (Allmaras, et al. 1964; Peterson, 1960; Quansah and Baffoe-Bonnie, 1981; Meyer, 1980). A further evidence is the inclusion of a roughness parameter in equations for predicting sediment yield from hillslopes subjected to overland flow. The roughness term may, apart from friction factor, be expressed as equivalent grain size parameter (Carson and Kirkby, 1972; Komura, 1976; Meyer and Monke, 1965) or as Manning's n expressed as

$$n = \frac{s^{0.50}\, d^{0.67}}{v} \qquad \text{Eq. 22}$$

where

n = Manning coefficient of roughness

s = slope steepness

The use of Manning's n in addition to grain size term is preferred by Morgan (1980) because it is potentially helpful in designing suitable conservation strategies and assessing their effects as many conservation measures rely on increased roughness created by either a plant cover or tillage operations. However, the effects of these latter on the magnitude of n will have to be precisely modelled for the desired improvement in conservation design to be realized.

The selection of n is usually based on values determined for turbulent channel flow. Field studies however suggest that such values, some of which are listed in various sources (Hudson, 1971; Chow, 1959; Morgan, 1980), are an order of magnitude too low for overland flow. This is because the magnitude of n as shown by Eq. 22 is very sensitive to flow velocity which is greater for turbulent than laminar flow. To allow for this discrepancy, the modified version of Manning equation (Savat, 1977)

$$n = \frac{\sin^{0.95} S\, d^{1.7}}{v} \qquad \text{Eq. 23}$$

for laminar flow disturbed by raindrop impact can be used to obtain values for overland flow. While 0.02 is commonly used for bare soil (Hudson, 1971), values of 0.2 - 1.0 (Emmett, 1970), 0.35 (Pearce, 1976) and 0.2 to 1.7 (Morgan, 1980) have been reported for overland flow over bare or partially vegetated soil surfaces. Studies of overland flow over rough surfaces in the laboratory should therefore be accompanied by estimates of n for meaningful comparisons to be made with field values.

The detachment and transport of soil particles are further related to the shear stress exerted by flow on one hand and what the soil can withstand on the other (Partheniades, 1972; Smerdon, 1964; Smerdon and Beasley, 1961; Foster and Meyer, 1975; Foster et al. 1980). Shear stress is expressed as

$$\tau_o = \gamma_w \, d \, s = \rho \, g \, d \, s \qquad \text{Eq.24}$$

where

γ_w = unit weight of water

ρ = fluid density

and when multiplied by flow velocity gives stream power per unit area (P_s) as

$$P_s = \tau_o V = \gamma_w \, d \, v \, s = \gamma_w \, q \, s \qquad \text{Eq. 25}$$

One problem in using these equations for overland flow is the underlying assumption of turbulent flow (D'Souza and Morgan, 1976). Thus as with Manning's equation, Savat (1977) recognizes the following variations with Reynolds number:

$$V \propto r^{1.7} \, s^{0.95} \quad \text{for} \quad Re = 250 \qquad \text{Eq. 26}$$

$$V \propto r^{0.95} \, s^{0.70} \quad Re = 500 \qquad \text{Eq. 27}$$

$$V \propto r^{0.50} \, s^{0.40} \quad Re = 1000 \qquad \text{Eq. 28}$$

A further problem concerns the fact that the equations do not take account of the effects of raindrop impact into the flow although this is a common phenomenon in reality. The need to modify the above equations to include rainfall effects is therefore of vital importance especially considering that sediment production on hillsides is the result of the combined action of rainfall and flow. Moreover, raindrop impact has been shown to affect flow characteristics such as velocity, depth and friction factor.

Smerdon (1964) and Glass and Smerdon (1967) examined the effect of intense rainfall (100 cm h^{-1}) on the vertical velocity profile of flows ranging from 30 to 150 mm in depth. Rainfall reduced the mean velocity of the flow and the amount of reduction was greater for shallow depths and at the surface of flow. Yoon and Wenzel (1971) made similar observations and showed that these effects were pronounced at low Reynolds numbers. As the Reynolds number increased beyond 1500, the rainfall effect became much smaller except near the surface.

Since the main velocity is retarded as a result of raindrop impact, the flow depth must be increased for the same unit discharge. On a smooth surface, Emmett (1970; 1978) obtained about 60 and 35 per cent increases in depth at Reynolds numbers of 100 and 1000 respectively. The corresponding values on a rough surface were 50 per cent for Re of 200 and 65 per cent for Re of 1000. The effect of rainfall on the depth of flow is, however, often complicated by surface roughness. This is because surface roughness also reduces flow velocity and tends to increase flow depths. For flows of infinite width the elements which contribute roughness to the flow are relatively large and may even protrude above the surface (Carson and Kirkby, 1972). This presents a major problem in the definition of a datum for measuring depths of shallow flows over rough surfaces. Because of this, several readings must be taken to give reasonable results.

Studies by Shen and Li (1973), Glass and Smerdon (1967) and Yoon and Wenzel (1971) all show that rainfall increases the friction factor of flows and the magnitude of increase is greatest for flows with the smallest depths.

From the Darcy-Weisbach equation this will be expected since the velocity of the flow is reduced by impacting raindrops.

The temporal and spatial variability and the shallow depths of overland flow, with a surface disturbed by rainfall impact pose problems in the study of its hydraulic characteristics. Because of this, equations developed for turbulent channel flows are often adapted to overland flow. In using these equations, there is a need for modifications to take account of the small depths and velocities of overland flow and the effects of raindrop impact and surface roughness. However, to develop equations specific to overland flow, its flow characteristics must be precisely measured. Whilst this is difficult in the field, reasonable values can be obtained in the laboratory where factors are easier to control. Only after these measurements can erosion in these flows be adequately characterized by their hydraulic parameters.

2.3.2 Detachment of Soil Particles by Overland Flow

Much attention has been paid to raindrop impact to the neglect of overland flow as a detaching agent. This has resulted in the absence of methods for studying detachment by thin flows and a scarcity of data on detachment by overland flow. However, Woodruff (1947) shows that the contribution to detachment by such flows can be considerable especially on steep slopes. Moreover, the need for such studies as they enhance the understanding of the erosion process (Ellison, 1947; Ellison and Ellison, 1947), the modelling of the erosion process (Foster et al. 1980; Kirkby, 1980; Meyer and Wischmeier, 1969; Rowlison and Martin, 1971) and the design of effective erosion control strategies (Morgan, 1980; Meyer et al. 1975) has been stressed.

The spatial distribution of Hortonian overland flow suggests that flow starts as a true sheet flow and has to overcome a critical resistance before appreciable erosion occurs. Kirkby (1978) notes that this threshold resistance is very small and that any appreciable overland flow will produce significant erosion as evidenced by the existence of rills within one meter from the top of the slope in semi-arid badlands. True sheet flow therefore seems to occur for only very short distances. With the formation of rills, two distinct sediment source areas, rill and interrill, can be distinguished (Meyer et al. 1975; Foster and Meyer, 1975).

Detachment in the rills is mainly by concentrated flow whilst splash is the predominant detaching process in the interrill area (Foster and Meyer, 1975; Young and Wiersma, 1973; Mosley, 1974). Considering for the moment flow without raindrop impact, interrill flow detachment is generally regarded as negligible on account of small flow rates, depths and shear stresses (Foster and Meyer, 1975; David and Beer, 1975; Morgan and Morgan, 1981). On the other hand, detachment by rill flow is several orders of magnitude greater and is a function of flow hydraulics and the susceptibility of the soil to detachment by flow (Foster and Meyer, 1977). The major part of the contribution by flow to total detachment therefore, according to current evidence, comes from rills. However, in the presence of rainfall, the situation is more complex. Through their direct effects on the hydraulic characteristics of shallow flows, impacting raindrops cause variations in the capacity of the latter flows to detach and transport soil particles. Other important considerations which have received less study include the interaction between splash and interrill wash processes, and between interrill and rill processes (Kirkby, 1980).

The detachment and subsequent transport of soil particles by flow can be explained fundamentally by considering the forces which act on the particles in contact with the flow (Carson and Kirkby, 1972). Flowing water exerts hydrodynamic forces on soil particles on both channel bed and sides (Graf, 1971; Vanoni, 1975). The magnitude of these forces is determined by specific conditions of flow (laminar or turbulent), the depth and the velocity which are in turn related to the channel section, roughness and slope (Webber, 1971). These forces are resisted by the weight of the particles, friction, and if the particles are either embedded in the soil (Carson and Kirby, 1972) or composed of silt and clay fractions (Vanoni, 1975), cohesive forces. A particle will however get dislodged and eventually start to move in response to an imbalance between these opposing forces, and the rate of movement and size of particles which can be carried will be related to the magnitude of the differences between the forces.

Ellison and Ellison (1947) recognized three different processes of soil detachment by surface flow; rolling, lifting and abrading. Rolling occurs where surface flow velocities reach such magnitudes that the forces dislodge particles from the soil mass by rolling or dragging them out of position. Lifting occurs when water moves upward past soil particles on the surface. Differences in velocities of flowing water over free water ponding in depressions with no horizontal velocity set up constantly changing pressure differences between these layers causing vertical currents and eddies which may lift particles of soil from the soil mass and set them in motion. Abrading on the other hand occurs when soil particles in transit dislodge other particles from the surface.

The amount of soil detached by the above processes depends on the detachability of the soil and the energy of the surface flow. The amount of abrasive material and its properties are also of vital importance. Thus Ellison and Ellison (1947) expressed detachment by surface flow as

$$D_1 = f\left(D_2 \left({}^{V^2}/_{2g}\right) M \beta\right) \qquad \text{Eq. 29}$$

where

D_1 = the soil detachment hazard

D_2 = the soil's detachability

${}^{V^2}/_{2g}$ = the energy gradient of the flow

M = the quantity of abrasive materials per unit of flow

β = a measure of the abrasive properties of the materials in transport.

However, very little is known about the independent variables in the above equation to establish the form of the function. Because relation of flow variables to detachment capacity has received little attention (Foster and Meyer, 1975) it is often difficult to characterize the latter capacity by flow parameters. Attempts in this direction are often based on related studies such as those of deep channel and stream flows.

These studies show that a direct relationship exists between the detachment capacity of water flow and tractive stress. Therefore Foster and Meyer (1975) express rill flow detachment capacity (D_R) as

$$D_R = k(\tau_o - \tau_c)^n \qquad \text{Eq.30}$$

where

k = a factor related to the soils susceptibility to rilling

τ_o = shear stress at the bed of flow

${}_c$ = threshold shear stress

n = exponent in the range of 1 - 2.

If the bed shear stress is large compared to the critical shear stress, detachment can be approximated as proportional to τ_o^n, where n assumes values of 1.5 (Foster and Meyer, 1975) and 1.0 (Meyer and Wischmeier, 1969). Because the shear stress is proportional to flow velocity squared, detachment can also be assumed to be directly proportional to V^2. From the continuity and Manning velocity equations, Meyer (1965) shows that

$$V = S^{\frac{1}{3}} Q^{\frac{1}{3}} \qquad \text{Eq. 31}$$

for constant roughness conditions. Based on the above relationships, Meyer and Wischmeier (1969) expressed detachment by runoff (D_F) as

$$D_F = k\,Q^{\frac{2}{3}} S^{\frac{2}{3}} \qquad \text{Eq. 32}$$

where

Q = flow rate or water discharge, and

S = slope steepness.

Kirkby (1980) proposes a relationship of D_R to flow power in the form

$$D_R \propto (qS)^n \qquad \text{Eq. 33}$$

where $n = 2$

For these equations to be useful in practical soil conservation work, they must be verified experimentally. This is recognized by the authors and they stress the need for more attention in this research area. This includes studies designed specifically to investigate the detachment capacity of flows, relating such capacities to the hydraulic characteristics of flow, and examining the effects of raindrop impact. By designing experiments to cover a wide range of soils, slope steepnesses, rainfall intensities and flow rates, it will be possible to establish values for the soil constants and the exponents in the equations. This will also allow the validity of the exponents over a range of conditions as well as the individual effects and interactions of the factors affecting the detachment capacity of flow to be assessed. Experiments that take account of the separate contributions of rill and interrill detachment are also required for validating models that incorporate these processes (Foster and Meyer, 1975, Kirkby, 1980; Foster et al. 1977). All of these are needed for improving erosion process prediction models and for bridging the gap between model development and application.

This challenging demand can, at best, be met only in the long term considering that experimental techniques and hence data collection trail behind model development due to constraints of practicality and other reasons covered by Meyer (1981) and Thornes (1981). In the case of detachment by flow, the major problem is how to separate the latter process from that of transportation. In practice this is almost an impossibility since both processes involve movement of particles in the same plane. Nevertheless, a solution to the problem is a prerequisite for developing appropriate techniques for measuring the process. This is pursued further in Chapter 3. In the short term however, research efforts should be concentrated on those processes that contribute significantly to sediment yield because in practice spectacular soil loss is what is regarded a major erosion hazard.

2.3.3 Sediment Transport Capacity of Overland Flow.

The major transporting agent of detached particles is surface runoff (Ellison, 1947) of which overland flow is an important component (Emmett, 1970; Morgan, 1980). Where rills are formed, transportation is accomplished both by shallow interrill flow and concentrated rill flow. The transport processes in these sediment source areas have been extensively discussed in papers by Meyer et al. (1975) and Foster and Meyer (1975). For the purpose of this study, the following discussion is confined mainly to shallow prechannel flow and early stages of rill flow.

The amount of soil transported off a given field depends, among other things, on the availability of detached particles and the transport capacity of flow. Where the material available for transport exceeds the latter, deposition occurs, which limits sediment yield on many arable fields (Foster and Meyer, 1977). To effectively control sediment yield therefore, it is necessary to identify and examine in detail the factors that influence transport capacity. These include runoff rate, slope steepness, roughness of the surface, the transportability of detached soil particles and raindrop impact effects (Foster and Meyer, 1975).

For a given flow and particle size, surface roughness has a pronounced effect on the amount of material transported and the distance moved (critical distance) by particles before being deposited. Podmore and Merva (1971) found that although critical distances for flow over rough surfaces are shorter than those over smooth surfaces, a larger volume of material (8 - 10 m size range) was transported over the former surfaces. They reasoned that velocity fluctuations are present even in thin film flows (3 mm) and that the above increase in the amount of material transported may be due to increased turbulent fluctuations in the flow caused by surface roughness elements. The absence of a roughness parameter is notable in most expressions for the transport capacity of overland flow yet, as reported by Morgan (1980), an inclusion of a roughness or a resistance factor gives better predictions.

However, for combined flow and rainfall, the latter is the main source of turbulence in the flow (Yoon and Wenzel, 1971). By lifting detached particles into the flow and keeping them in suspension by the turbulent energy imparted to the flow, impacting raindrops increase the transport capacity of overland flow (Ellison, 1947; Meyer et al. 1975; Young and Wiersma, 1973).

The material available for transport consists of primary particles and aggregates with the latter being predominant on most agricultural soils (Swanson and Dedrick, 1967; Swanson et al. 1969). Detached particles may be transported as suspended or bedload. In shallow flows, however, bedload is the major mode of transportation (Meyer and Monke, 1965; Foster and Meyer, 1972). Even in this mode, rolling, sliding and saltation all occur (Horton, 1970) but on hillslopes, rolling seems to be much more important especially where water flow is in thin films (Thornes, 1980). In the presence of rills, transport of detached particles is accomplished mainly by rill-flow and any sediment produced in the interrill areas is eventually removed via the rill system (Young and Wiersma, 1973; Kirkby, 1980; Meyer et al. 1975).

As indicated in Chapter 1, no widely accepted transport-capacity equations have been developed for overland flow. Most of the studies have been directed to transport phenomena in rivers and canals largely because failure in these due to sedimentation or scour has had the greatest impact upon man (Vanoni, 1975). However, the transport of sediment in overland and rill flows merits no less attention since studies of sediment sources and sinks indicate them to supply sediment to both rivers and canals (Foster and Meyer, 1977; ASCE, 1970; Robinson, 1971). Carson and Kirkby (1972) have pointed out that sediment transport in shallow flows obeys similar laws to those operating in rivers. From this premise and until an equation specific to overland flow is developed, stream flow sediment equations are often adapted for overland flow (Foster and Meyer, 1972; Niebling and Foster, 1980).

Theoretical derivation of a sediment transport formula requires combining a flow resistance equation and a sediment transport capacity equation (Carson and Kirkby, 1972). Four such equations listed below have been examined by Morgan (1980) for predicting soil loss by overland flow:

$$G = 0.00611\ Q^{1.8}\ \sin S^{1.13}\ n^{-0.15}\ d_{35}^{-1} \quad \text{(Morgan, 1980)} \quad \text{Eq.34}$$

$$G = 0.0085\ Q^{1.75}\ d_{84}^{-1.11}\ \sin S^{1.625} \quad \text{(Carson and Kirkby, 1972)} \quad \text{Eq.35}$$

$$G = \frac{476\ Ca.Ce}{d50}\ Q^{5/8}\ L^{3/8}\ \sin S^{1/2} \quad \text{(Komura, 1976)} \quad \text{Eq.36}$$

$$G = cQ^{1.5}\ \sin S^{2.2}\ d_{50}^{-0.5} \quad \text{(Meyer and Monke, 1965)} \quad \text{Eq.37}$$

where

G = sediment yield
Q = discharge
d = particle size parameter
L = slope length
Ca = bare soil area ratio
Ce = erodibility index
c = constant
n = Manning's roughness coefficient.

By testing these equations against field data, Morgan found that although they were promising, none gave acceptably accurate predictions. This was attributed to the fact that the equations describe transport capacity and the data used were obtained from a site where erosion is rarely transport-capacity limited. In addition to improving the data base for validating these formulae, modifications to encompass the complete range of erosion conditions from detachment-limited to transport-capacity limited were recommended. The former refers to a situation where flow has the capacity to transport more material than is supplied by detachment whilst the latter applies where more material is supplied than can be transported. This is the approach adopted by Meyer and Wischmeier (1969) in their mathematical simulation of the erosion process where transport capacity of runoff (T_F) is expressed as:

$$T_F = k \; S^{5/3} \; Q^{5/3} \qquad \text{Eq. 38}$$

with k = soil's transportability.

In order to validate these equations, appropriate data, which presently are limited, must be available. A transportability factor must also be established for different soils before the Meyer-Wischmeier model can be operated. Since the above equations predict the maximum sediment that can be transported, experiments to test them must provide transport capacity-limited conditions. This can be achieved by introducing sediment into the flow till most of it is deposited. Data of this nature are difficult to obtain in the field but can be provided by controlled laboratory experiments. It must be stressed however that the validity of these sediment transport capacity models will ultimately have to be judged by their applicability to field conditions. This will depend on whether erosion in a given field satisfies the conditions on which the model operates. In some situations, the velocity of flow may be too low to carry the size of particles being detached although the transport capacity of the flow is not exceeded. If erosion models are to accomodate such conditions, then, as suggested by Morgan and Morgan (1981), transport capacity and competency must be separated.

2.3.4 Conclusion

A fuller understanding of the erosion process still awaits a detailed evaluation of each of the component subprocesses. While a lot of work has been done on the splash process, the detachment and transport of soil particles by overland flow have received very little attention. For progress to be made in this direction, the identification of problem areas which require further research is necessary. From the above review areas that need investigation include:

i) the direct effects and interaction of erosion influencing factors such as slope steepness, rain intensity and soil type on the processes;

ii) the evaluation of each of the processes over a range of the above factors with factor interactions being the most important for splash detachment and transport;

iii) a precise delineation of soil properties which determine resistance to raindrop impact;

iv) the dynamics of soil detachability and the interactive effect of surface water depths and impacting raindrops on the splash process;

v) establishing an effective grain size term for use in splash relationships;

vi) establishing splash detachment and transport relationships to incorporate the effects of both lower and higher slopes;

vii) the separation and evaluation of the detachment and transport processes of flow;

viii) the measurement of flow parameters to provide hydraulic data for characterizing detachment and transport processes in overland flow and assessing the effects of raindrop impact;

ix) developing detachment and transport capacity equations for overland flow:

x) establishing soil constants for use in erosion models; and

xi) providing data for validating models that incorporate the detachment and transport phases of erosion process in order to make them useful conservation tools.

Since methods are not available, these studies will require the development of special equipment and techniques and the choice of an appropriate experimental design. These topics are discussed in the next Chapter.

CHAPTER 3

MATERIALS AND METHODS

3.1 METHODS OF EROSION RESEARCH

The broad objective of erosion research is to understand when and how much erosion is likely to occur under given conditions. In order to achieve this, research is directed at:

i) the mechanics of the erosion process;
ii) establishing the manner in which various factors influence the process;
iii) providing experimental evidence of the numerical values of these factors; and
iv) determining the way in which these factors interact and should therefore be combined in formulating erosion models, either to formally represent the erosion process or to predict the frequency and magnitude of erosion. Methods used for the above investigations vary but two main approaches can be distinguished: applied and analytical research (Hudson, 1965).

Applied research involves the use of field experimental plots to measure erosion when the influencing factors are set up in a limited number of combinations. When significant differences are observed, e.g. in different soil management systems, they provide a basis for practical recommendations for solving local problems. Field plots have been extensively used in the U.S.A. (Moldenhauer and Foster, 1981) and by many research workers elsewhere (Valentin and Roose, 1981; Hatch, 1981; Barber et al., 1981; Bonsu, 1981; Hudson, 1965; and Baffoe-Bonnie and Quansah, 1975). They are expensive to install and operate and many years of continuous data collection are required for precise conclusions to be drawn. Although they provide realistic data on soil loss, it is often difficult to determine the main cause of erosion or to understand the processes at work because of the spatial and temporal variations in many of the factors. Because of this the mechanics of erosion are best studied analytically in the laboratory where the effects of many factors can be controlled and individual factors can be evaluated in isolation. Most of the laboratory studies reported in Chapter 2 used this approach. When individual factors have been evaluated in this way the study may be extended to groups of variables and their interactions. It is however possible to evaluate both the individual effects of the factors and their interactions in the same experiment if the appropriate experimental design is used. This is the approach adopted in this study (Section 3.4).

The two research approaches are, however, complementary. The evaluation of each variable by the analytical method allows more information to be drawn from results of field experiments whilst the results of field experiments show which variables or processes require closer analytical study. Ultimately, the choice of approach depends on the objective of the study. Nonetheless, a well-balanced research programme should combine the two approaches in order to make significant progress in understanding the mechanics of erosion and its control. This philosophy is adopted in the soil erosion research programme at the National College of Agricultural Engineering (Morgan, 1981). Field experiments are currently in progress to validate both the results obtained from laboratory studies and some of the present mathematical erosion models (Morgan and Morgan, 1981). The present study, an integral part of the programme, simulates the erosion process in the laboratory to evaluate in detail the subprocesses of the erosion process and the effects of some of the factors influencing them.

3.2 BASIC FORMAT OF EXPERIMENTS

The basic format of the study comprises a separate evaluation of each of four subprocesses of erosion, namely, the detachment of soil particles by raindrops; detachment by overland flow; transport of the detached particles by raindrops; and transport by overland flow. The experiments on detachment by overland flow comprised runs with and without raindrop impact. Although it was intended to carry out tests with and without rain also for transport by overland flow, because of time constraints, only the former were possible. Considering that in reality overland flow is produced as rainfall excess and its surface is disturbed by impacting raindrops, restricting the experiment to tests with rain seems reasonable. In all a total of 1088 runs were made.

Experiments of this nature require the use of special equipment and techniques. Since methods for measuring the splash process are fairly well established as indicated earlier, existing equipment was used for this phase of the work. However, in the absence of any work and therefore any standard technique for the measurement of detachment by overland flow, equipment and techniques were developed to permit separate evaluations of soil detachment and transport processes.

All the experiments were carried out at the Project Laboratory of the National College of Agricultural Engineering, Silsoe, Bedford. The equipment, experimental design and the variables are described in Sections 3.3, 3.4, and 3.5. Section 3.6 deals with the procedures used and their limitations.

3.3 APPARATUS

The basic experimental apparatus consisted of a rainfall simulator, a rainsplash tray, and a mobile-bed flume.

3.3.1 Rainfall Simulator.

Rain was simulated using a nozzle simulator (Plate 1) with a rotating sectored metal disc (Morin et al., 1967). The disc revolves at a constant speed (4.6 rad s^{-1} (44 rpm)) beneath a 1.5 H 30 Fulljet nozzle (from Spraying Systems Co. U.S.A.) which is directed vertically downwards and continuously sprays water supplied by a pump at a pressure range of 48 - 52 kN m^{-2}. The disc and nozzle are housed in a collecting pan such that anytime the slot in the disc comes directly beneath the nozzle, water is sprayed from a height of 2.5 m onto the working area. The proportion of the spray that falls on the

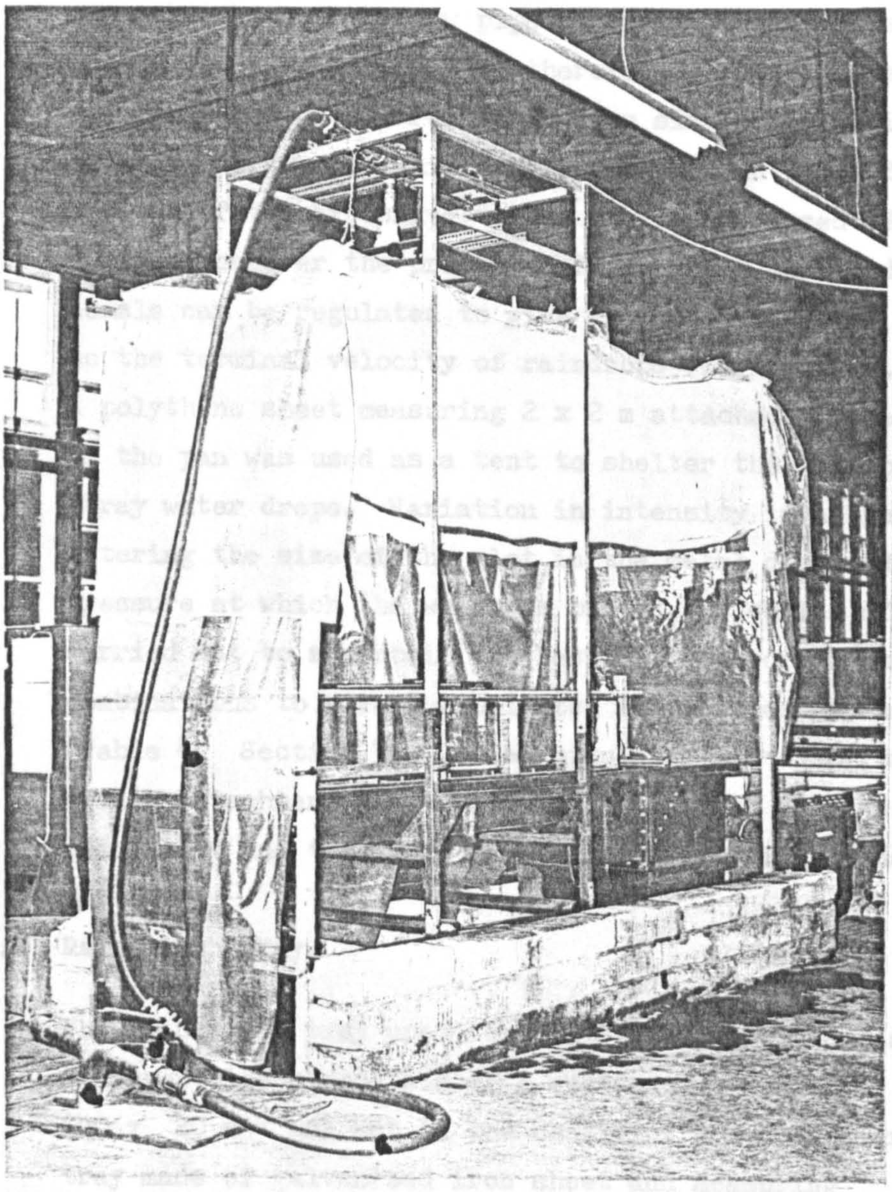

Plate: 1 Rainfall simulator mounted on mobile-bed flume.

a) collecting pan

b) overflow pipe

c) water supply hose

d) water supply and pressure control valve

e) to sump and pump

f) mobile-bed flume

test area is determined by the angle of the slot, for example a 10 degree slot passes $^{10}/_{360}$ or $^{1}/_{36}$ of the total flow. The excess water collects in the pan and flows back into the sump through an overflow pipe attached to the collecting pan. The design of the simulator therefore allows the use of large nozzles which give a realistic drop size distribution and kinetic energy, but which cannot be used in other designs because of the excessive volume of flow produced (Hudson, 1971). Moreover the pressure of the water supplied to the nozzle can be regulated to give an impact velocity similar to the terminal velocity of raindrops (Morin et al., 1967). A polythene sheet measuring 2 x 2 m attached to the underside of the pan was used as a tent to shelter the test plot from stray water drops. Variation in intensity is achieved by altering the size of the slot in the metal disc and the pressure at which the water is pumped. A series of tests was carried out to ascertain the best disc-sector and pressure combinations to give the selected intensities for the study (Table 4, Section 3.5). The simulator was used for the splash detachment and transport studies and for the work on detachment and transport by overland flow with raindrop impact.

3.3.2 Rainsplash Tray.

The rainsplash tray used for the splash detachment and transport tests consists of a rectangular soil tray (10 x 20 x 4 cm) set in the centre of a rectangular catching tray made of galvanized iron sheet and measuring (90 x 80 x 30 cm). The base of the tray is made of perforated metal which allows free drainage of water (Plate 2). The soil tray can be detached and refitted and has a perforated plywood base covered with a layer of lint to allow saturation of the soil through the base by capillarity.

For a test run, the soil tray is first detached from the catching tray, filled with the test soil and placed in a shallow layer of water for saturation. After saturation, it is refitted and the whole apparatus is placed under the rain

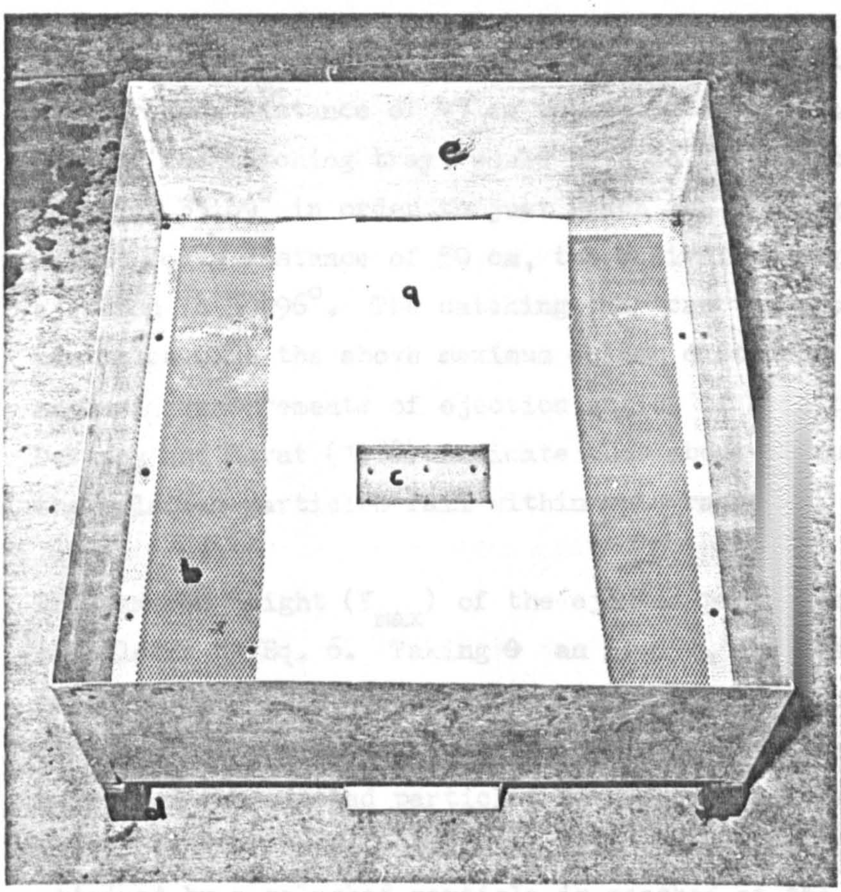

Plate: 2 Splash Tray

a) strips of white cloth
b) perforated metal base
c) soil tray with perforated bottom
d) wooden block
e) boundary wall of collecting tray
f) soil wash collection outlet

simulator for the start of the run. Splashed soil particles are caught on strips of cloth covering the upslope and downslope sections of the soil tray. The apparatus can be set at different slope angles by raising one end with wooden blocks cut to specific lengths and checking the accuracy of the angle by an Abney level. Although ejection angles of particles were not measured, calculations and observations made during the experiment give indications of the efficiency of the equipment in trapping the splashed particles.

On a horizontal surface a soil particle in the centre of the soil tray, a distance of 45 cm to the 30 cm - high boundary wall of the catching tray, would have to be projected at angle of 33.69° in order to just reach the top edge of the wall. For a distance of 50 cm, the equivalent angle of ejection is 30.96°. The catching tray can therefore trap all particles with the above maximum splash distances and ejection angles. Measurements of ejection angles of soil particles by DePloey and Savat (1968) indicate that about 90 per cent of the splashed particles fall within this range.

The maximum height (Y_{max}) of the ejected particles can be calculated by Eq. 6. Taking θ as 33.69°, and the horizontal range (s) as 45 cm, gives, from Eq. 5, an ejection velocity of 2.2 m s^{-1} which when substituted in Eq. 6 gives a maximum height of the ejected particles as 7.6 cm which is 0.17 of the horizontal range. Assuming that the maximum height attained by a splashed particle is reached at the mid-point of its trajectory, which in this example is one sixth of the horizontal range, then the 30 cm wall excludes all particles splashed up to 180 cm with ejection angles up to 33.69°.

Observations made during the experiments indicate that the bulk of the material that splashed as far as the boundary wall adhered to about the lower third of it. This could imply either that the particles were near the end of the falling phase of their trajectories or that further particle movement was obstructed by the wall. The equipment thus prevented the assessment of distances traversed by the particles but caught the bulk of the particles ejected from the soil tray. Since the catching tray was open to the simulated rain, splash-back of particles, which accords with the reality of field conditions, was possible.

3.3.3 Mobile-bed flume (Plate 3).

It was necessary to develop equipment and techniques for measuring detachment of soil particles by overland flow because, as stated earlier, there is no explicit study on this process. Before embarking on designing and making completely new equipment, the requirements for measuring the process were examined and a search was made for possibilities of adapting existing equipment for the purpose without altering its original use. The logic behind this was to reduce costs, save time, and make a more efficient use of equipment.

The features required of the rig were:

i) a flume with an interchangeable channel bed plate;
ii) slope formers;
iii) flow depth and flow rate measuring devices;
iv) soil plates; and
v) a sediment dispenser.

Since an existing Armfield Mobile-Bed Flume (Plate 3) possessed some of these features, it was modified to make possible separate evaluations of soil detachment and transport by overland flow.

The original flume (Plate 4), with its interchangeable channel bed plate, consists essentially of a 200 x 61 x 15 cm channel fitted with inflow and outflow tanks. A pump connected to both tanks makes it possible to recirculate water and the rate of flow is measured by a meter with a flow range of 0 - 6 $l\ s^{-1}$ mounted on the outflow tank. A rail at the top of the flume permits the use of a depth gauge and its carriage for flow depth measurements. There is no device

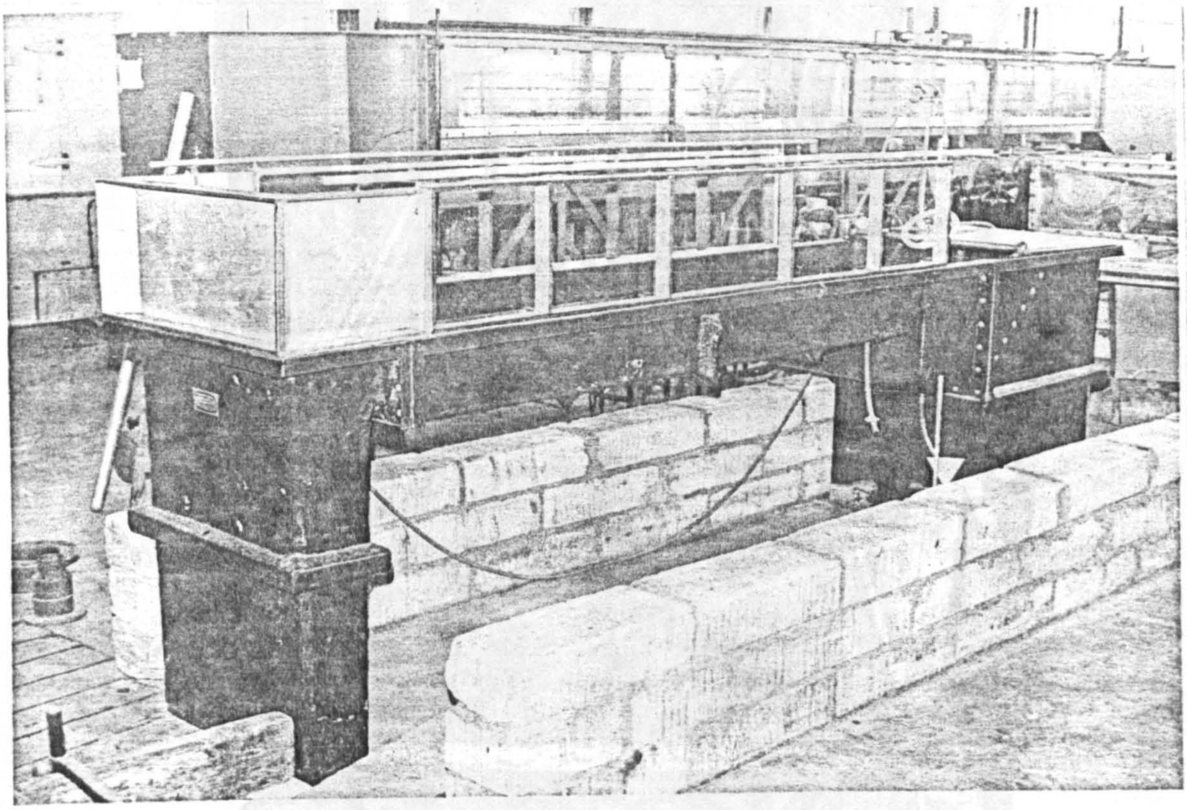

Plate: 3. Mobile-bed flume with extension frame.

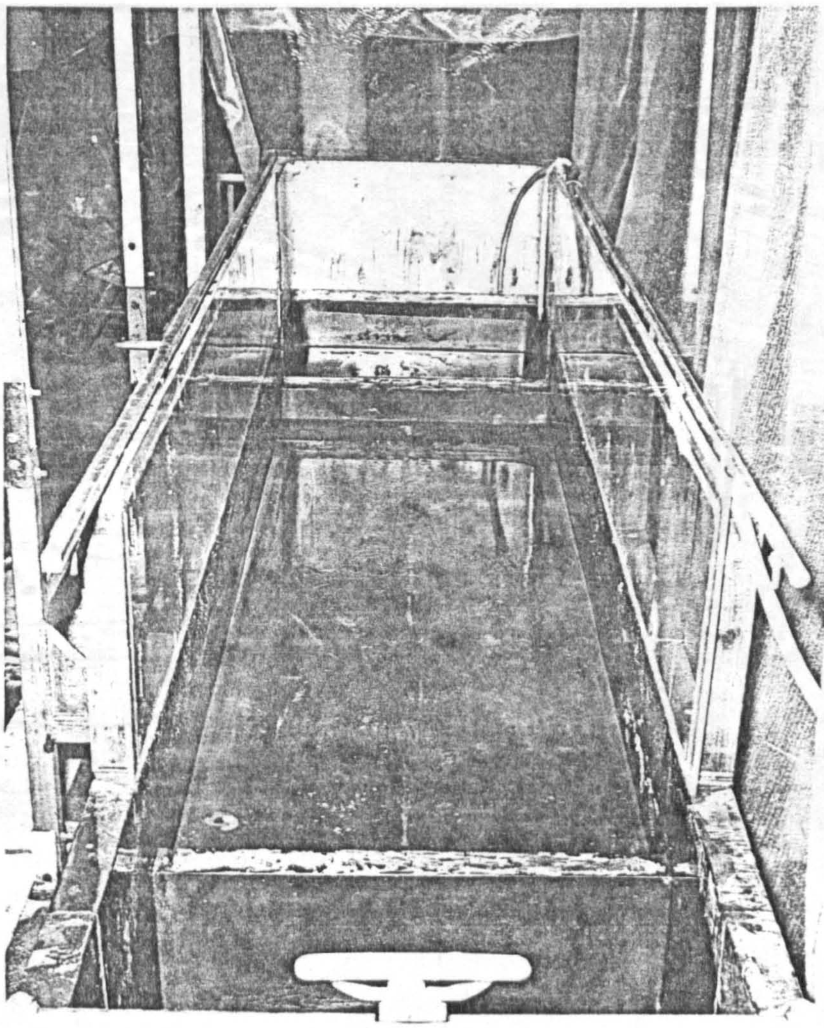

Plate: 4. Inside of mobile-bed flume with bed plate removed.

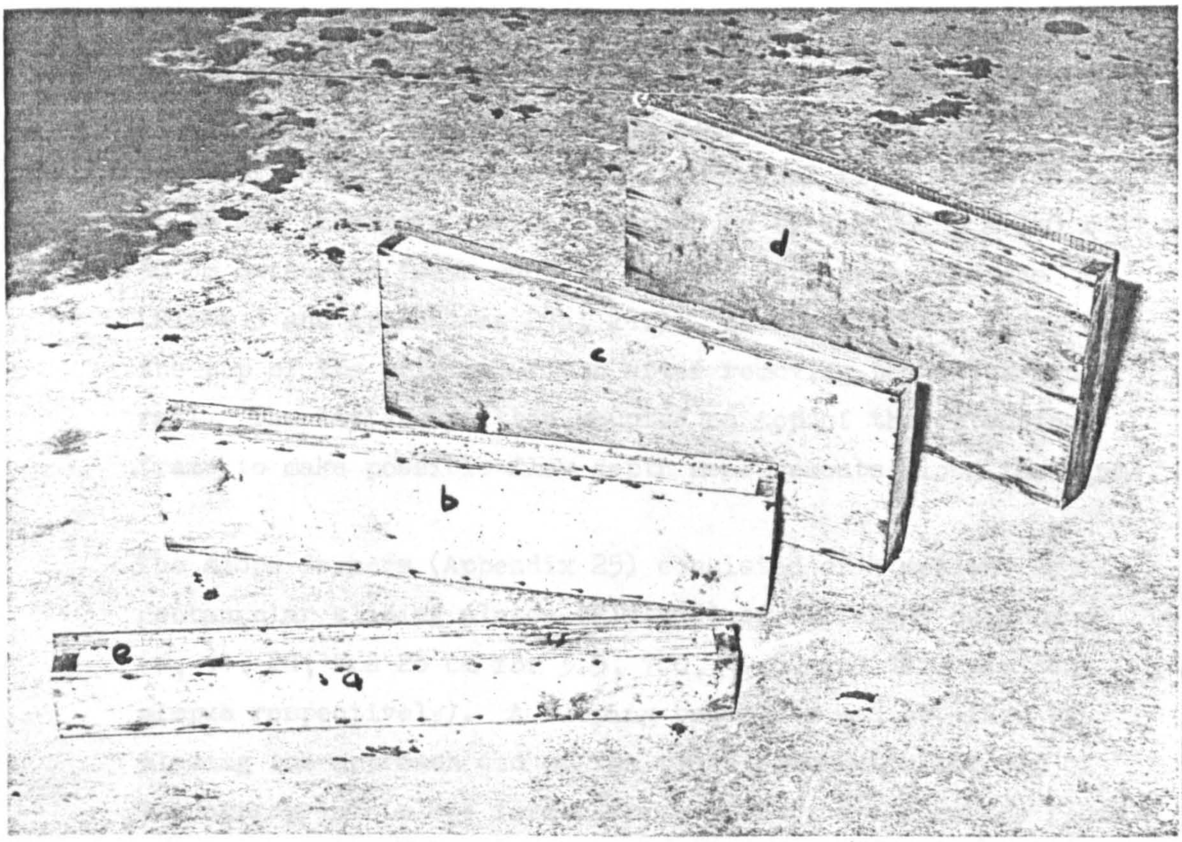

Plate: 5. Slope formers

a) 7 cm for 3.5 per cent slope

b) 14 cm for 7.0 per cent slope

c) 21 cm for 10.5 per cent slope

d) 28 cm for 14.0 per cent slope

e) Ledge on which soil plate rests

however for obtaining variable channel bed slopes. Because this was necessary in this study the following modifications were made.

For a flume length of 200 cm, one end of the bed plate can be raised to varying heights to obtain different slopes within the flume. For a maximum design slope of 20 per cent a flume depth of 40 cm was required. The original flume depth of 15 cm was therefore increased to 45 cm by designing a 240 x 71 x 30 cm extension frame made of plywood with perspex sides (Plate 3 and Appendices 24a, 24b). This was fitted flush with the top of the original flume after removing the depth gauge rail. The latter was then mounted on top of the extension frame to make possible flow depth measurements along the flume.

The slope formers (Appendix 25) consisted of 4 wooden rectangular sliding plates (Plate 5) of different heights (7, 14, 21, and 28 cm for 3.5, 7.0, 10.5, and 14.0 per cent slopes respectively). A sloping bed plate was obtained by placing the approach end of the plate flush with the top of the appropriate slope former which is fitted across the flume at the junction between the inflow tank and the channel. When operational, water rises uniformly in the inflow tank and spills over the bed plate when the tank is full to produce overland flow. To prevent any leakage of water, the edges of the plate were sealed with mastik (Plate 6).

In these experiments, an inclined bed plate represented a segment of a hillside. Two types of bed plates (referred to as soil plates in the rest of the text) were used, one for measuring the detachment and the other the transport of soil particles by overland flow. The separation of the detachment process from that of transport was critical to the design of the soil plate. Considering that the detachment process initiates movement of particles by dislodging them from the soil mass and setting them in motion (entrainment) to be carried further downslope by the transportation process, it seems reasonable to assume that detachment moves soil particles over relatively short distances. On this premise, it should be

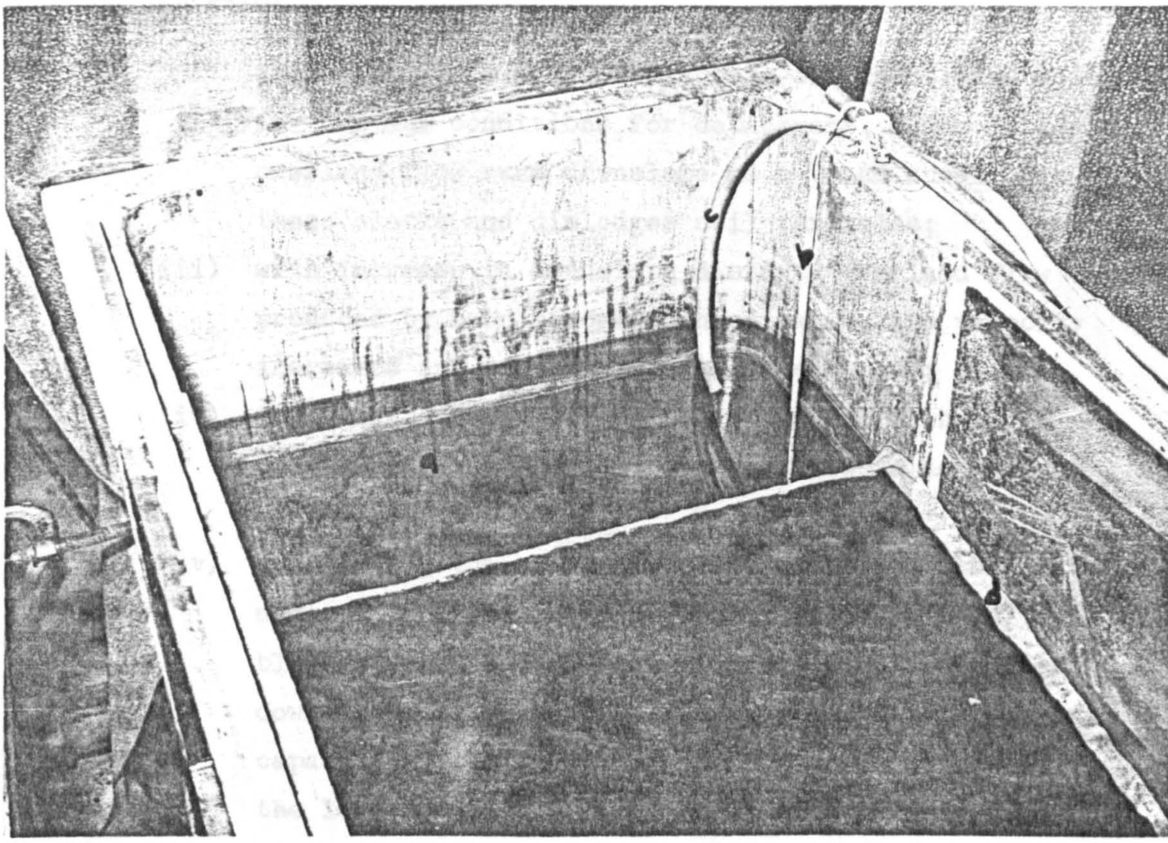

Plate: 6. Approach end of mobile-bed flume.

a) inflow and settling tank
b) thermometer
c) rubber tube supplying water to tank
d) mastik sealed edges

possible to assess the detachment capacity of a flow by reducing transportation as much as practicable. Based on this, and taking into account the simulation of field conditions in the laboratory, the following assumptions were made while designing the soil plate for measuring detachment by flow:

i) the hillside is made of discrete blocks of bare soil;

ii) for maximum conditions for detachment, clear Hortonian overland flow runs downslope as a broad sheet over these blocks and dislodges soil particles;

iii) with increase in downslope distance overland flow produced by rain becomes concentrated, its velocity increases and detachment rate is enhanced;

iv) the length of each block is reduced as much as practicable to exclude transport effects as much as possible;

v) considering the existence of rills in the field within a meter from the crest of slopes (Kirkby, 1978), a block of soil located a reasonable distance (120 cm) downslope can be sampled to represent the detachment capacity of the flow; and

vi) the location of the soil sample is constrained by the size of the area for which the simulated rainfall is effective which is 1.5 m^2 for the simulator used in this study (Morin et al., 1967).

A typical soil plate (Appendix 26) for detachment tests (Plates 7 & 8) consisted of a flat rectangular plywood board (220 x 60 cm) with a tray (10 x 56 x 4 cm) for holding the test soil fitted at a distance of 120 cm from the inflow (upslope) section of the plate. The tray had no drainage holes therefore the plate was impermeable. The inflow and outflow sections formed the approach to and exit from the soil plate. To simulate field surface roughness, the approach section of the plate up to the tray was uniformly coated, using a wooden spreader, with the test soil mixed thoroughly with an adhesive in the ratio of 2 : 1 by volume respectively. The adhesive, Aerodux 500 (obtained from the Plastics Division,

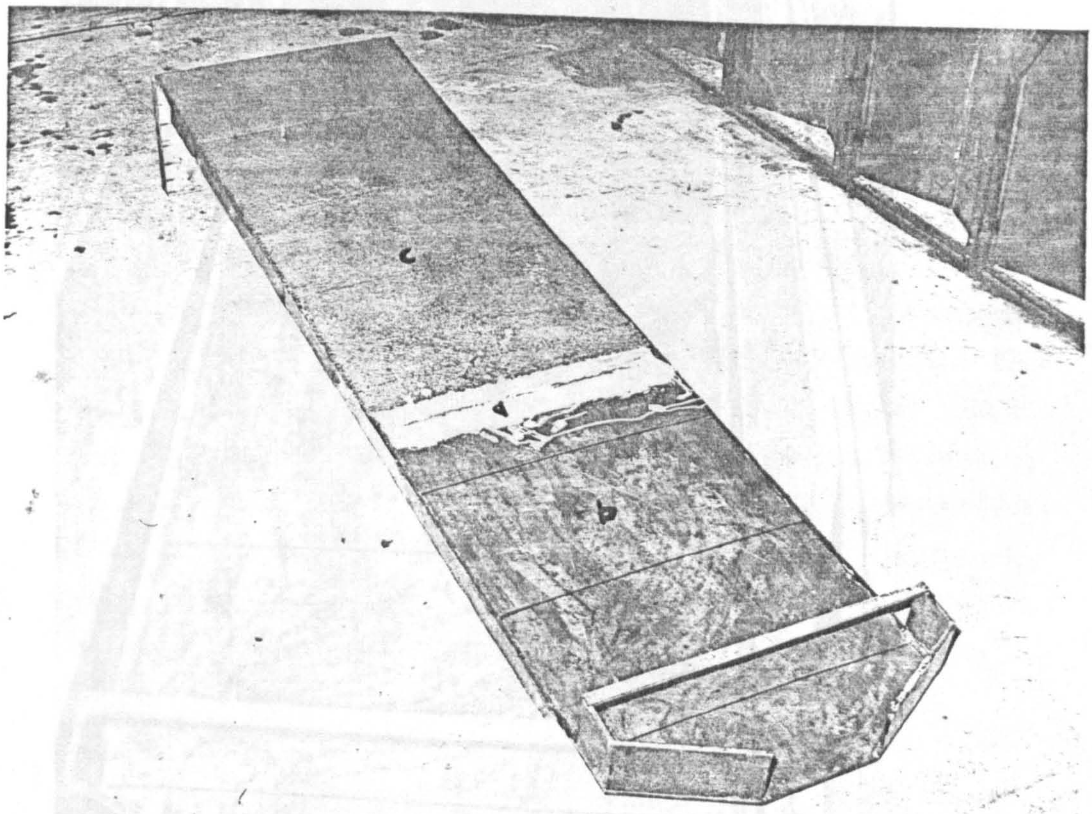

Plate: 7. Soil-plate for overland flow detachment tests.

a) soil tray

b) smooth exit end for retrieving detached particles

c) roughened approach end

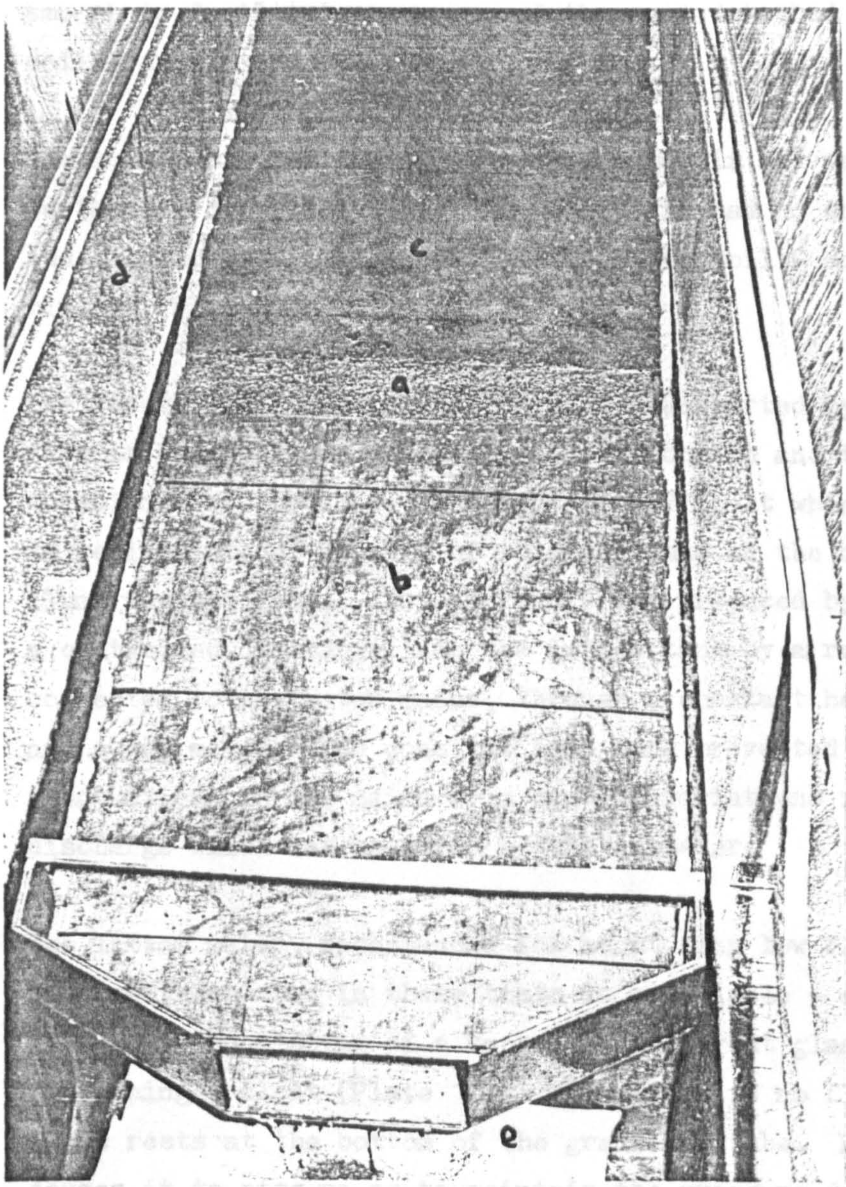

Plate: 8. A soil-plate for detachment tests fitted into flume.

a) soil tray
b) exit end (smooth)
c) approach end (roughened)
d) extension frame with perspex sides
e) collecting tray

Ciba Geigy, U.K.), comprised a thermoset resorcinol-formaldehyde resin and Hardner 501 mixed in the ratio of 1 : 1 by volume. The exit section of the plate was left smooth to facilitate recovery of the soil detached from the soil tray.

The soil plate for transport tests (Appendix 27) was similar to the one described above except that it had no soil tray and the whole surface was coated with the soil - adhesive mixture (Plate 9).

The recovery of material detached or transported by overland flow is essential in assessing the detachment and transport capacities of the flow. Recovery is difficult when the flow is recirculated. Because of this the pump of the original flume was not used. Instead runoff was produced by feeding a controlled discharge into the inflow tank by a rubber tube connected to the water mains, through a constant head tank, and a gap meter. The constant head tank prevented pressure fluctuations in the mains from causing variations in the discharge which was measured by the gapmeter.

The latter meter, recommended for monitoring low flow rates such as those used in these tests is a variable - area flow rate meter consisting of a tapered transparent glass tube containing a float (Plate 10). When there is no flow the float rests at the bottom of the graduated tube. Flow causes it to rise so as to maintain the pressure drop across the float in equilibrium with the effects of buoyancy and gravity upon it. Since the immersed weight of the float is a constant for any given fluid, the pressure drop must also remain constant. Consequently, as the flow increases the float will rise in the tapered tube to provide a wider annular aperture for the fluid to pass through. The amount of flow entering the meter is regulated by a control clip (Plate 10). It opens to allow increased flow and closes to reduce flow rate. Therefore it regulates the rise of the float in the tube. The height of the float is thus an

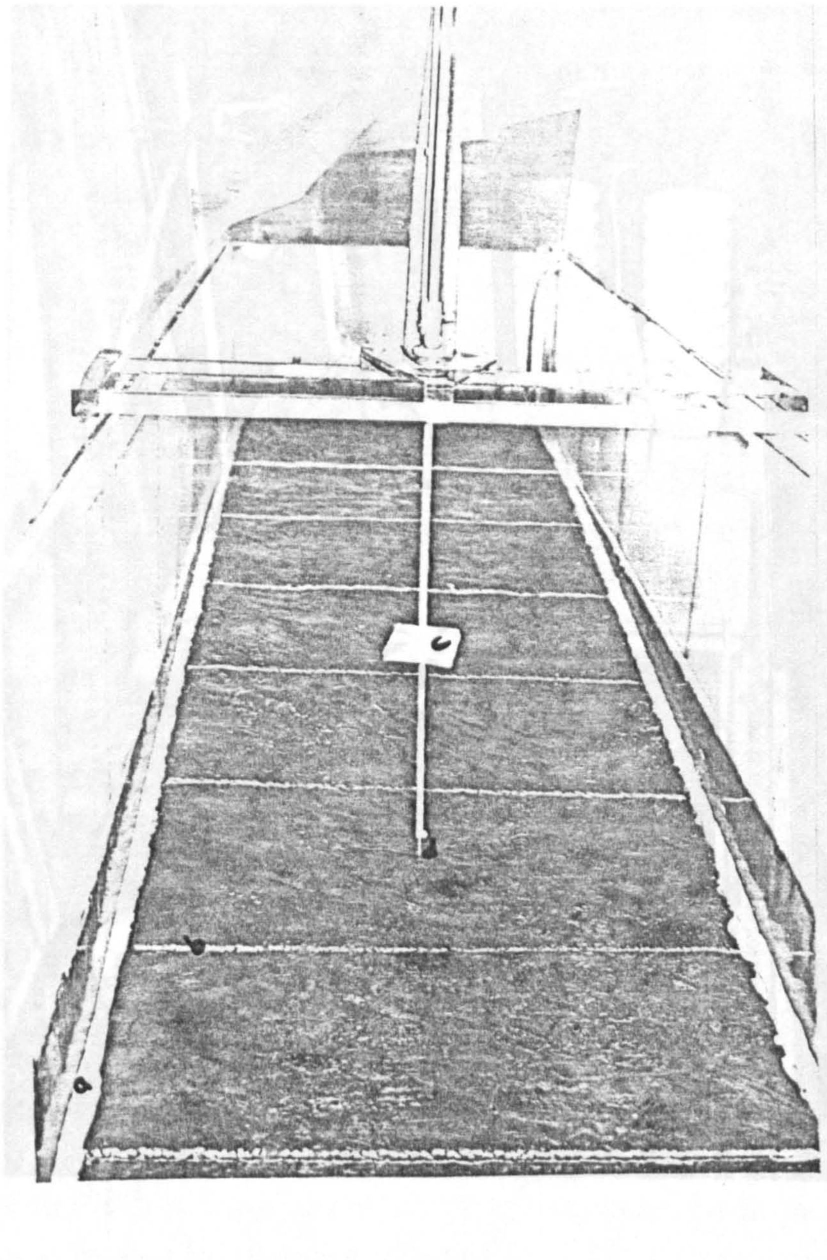

Plate: 9. Depth gauge and soil-plate for transport tests

a) mastik sealed edges
b) white markings for flow velocity and depth measurements
c) foam for wiping off drips of water on measuring rod
d) measuring pin

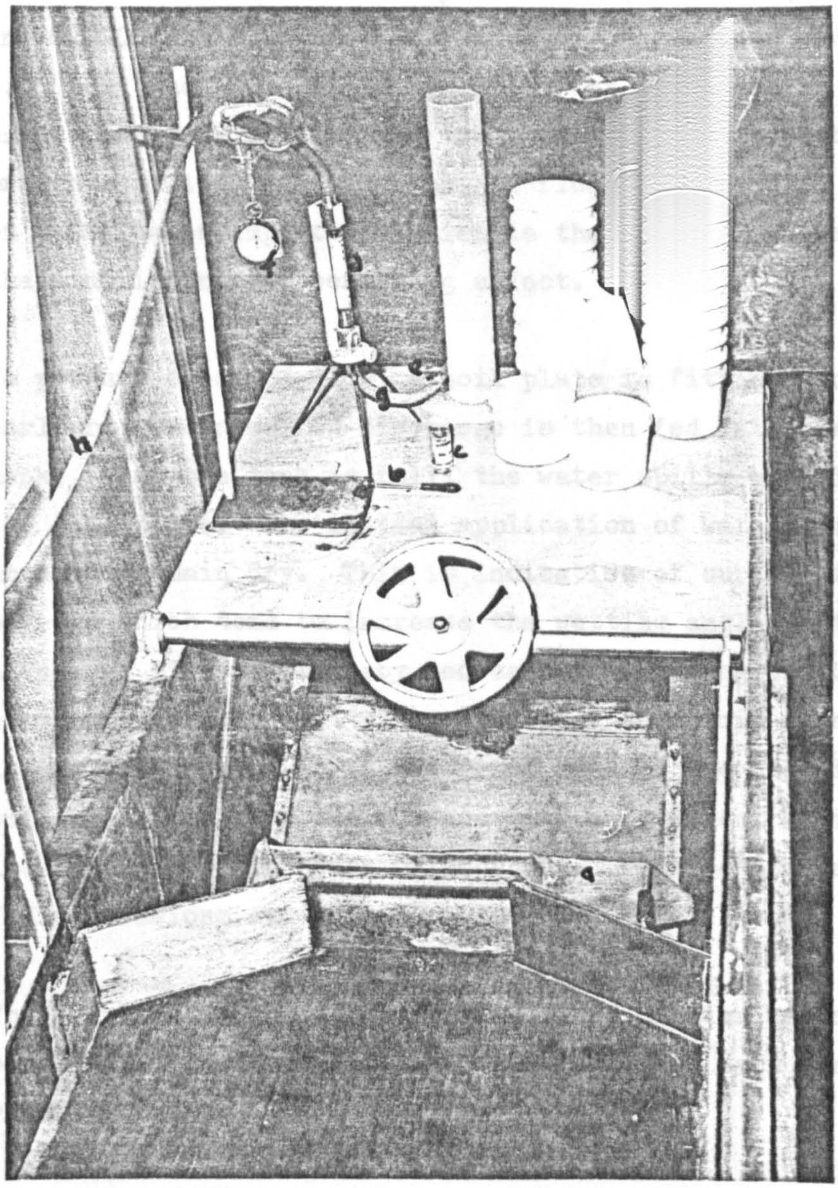

Plate: 10. Exit end of mobile-bed flume

a) collecting tray
b) dropper
c) vitrea oil 22
d) gap meter
e) control clip
f) stop watch
g) rubber tube from overhead tank
h) rubber tube supplying water to inflow tank

indication of the flow rate, and the scale on the tube is graduated directly in units of flow rate (1/min). For the flow rates used in this study (0.000017, 0.000027, 0.000037, and 0.000047 $m^3 s^{-1}$) the corresponding graduations were 2.8, 4.0, 5.6, and 7.0. It is essential for the float to be maintained coaxial with the tube. This is achieved by the presence of inclined vanes on the float. The action of flow on these vanes imparts rotation to the float which provides the stabilising and centering effect.

To produce overland flow, a soil plate is fitted as described earlier. The required discharge is then fed into the inflow tank. When the tank is full, the water spills and flows over the soil plate. The initial application of water showed some areas to remain dry. This is indicative of surface tension effects which tend to increase the wetting angle of the advancing flow and thereby decrease the wetting of the surface of the plate (Hillel, 1971). In order to obtain even flow, it was necessary, within the first week of the use of a new soil plate, to wash the surface with a detergent (Fairy liquid) before the start of each run. This decreases interfacial tensions and enhances wetting.

The nozzle rainfall simulator described earlier was mounted over the flume to provide rainfall input for test runs with rain.

Sediment input for overland flow transport tests was provided by a sediment dispenser (Plates 11 & 12). This consists of a V - shaped wooden box with a 1.0 x 56 cm slit along its base. A sliding plate fitted over the slit makes it possible to obtain by calibration variable sizes of slit for different rates of sediment feed. Full details of the design are given in Appendix 28a and 28b. Sediment introduction from above the surface of flow was achieved by resting the dispenser on top of the extension frame. This gave particle fall heights of 38, 31, 24, 17 cm for bed slopes of 3.5, 7.0, 10.5, and 14.0 per cent respectively. Because the soils used consisted

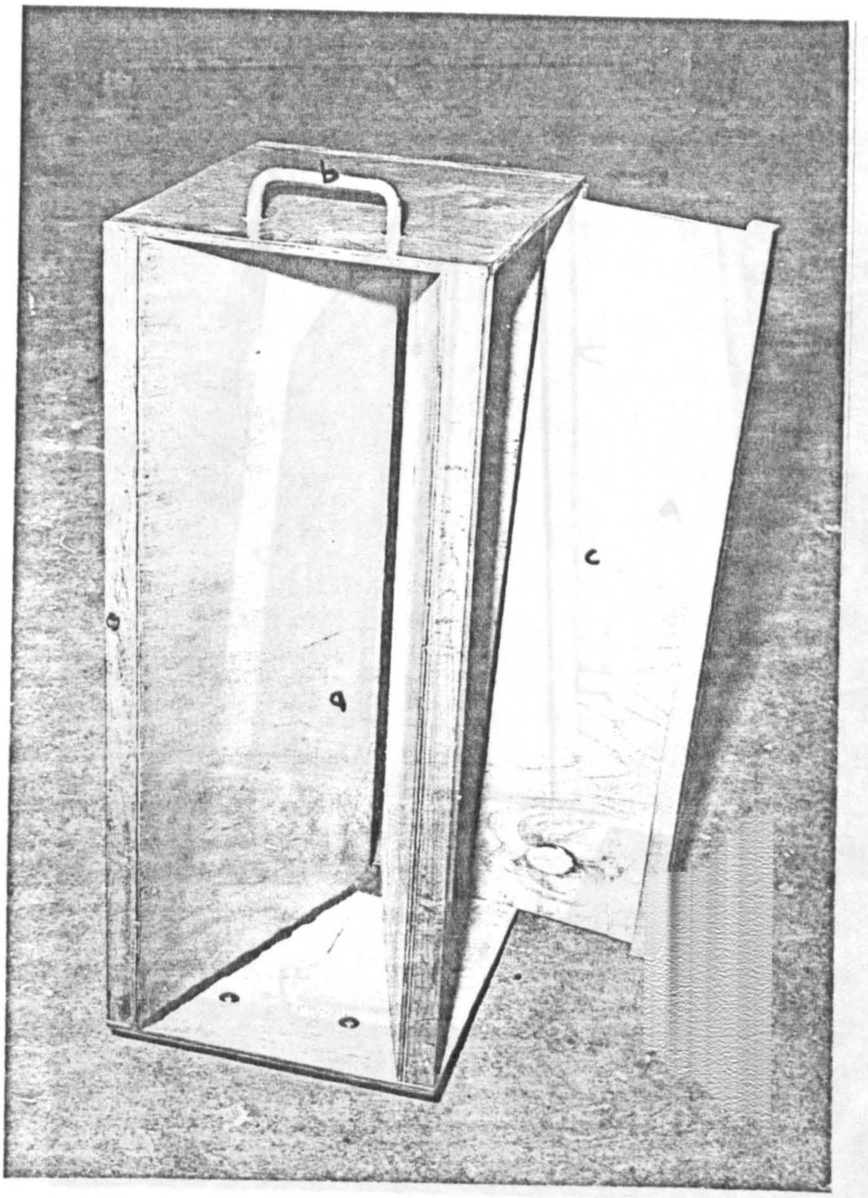

Plate: 11. Sediment dispenser

a) inside

b) handle

c) sliding plate for adjusting slit size

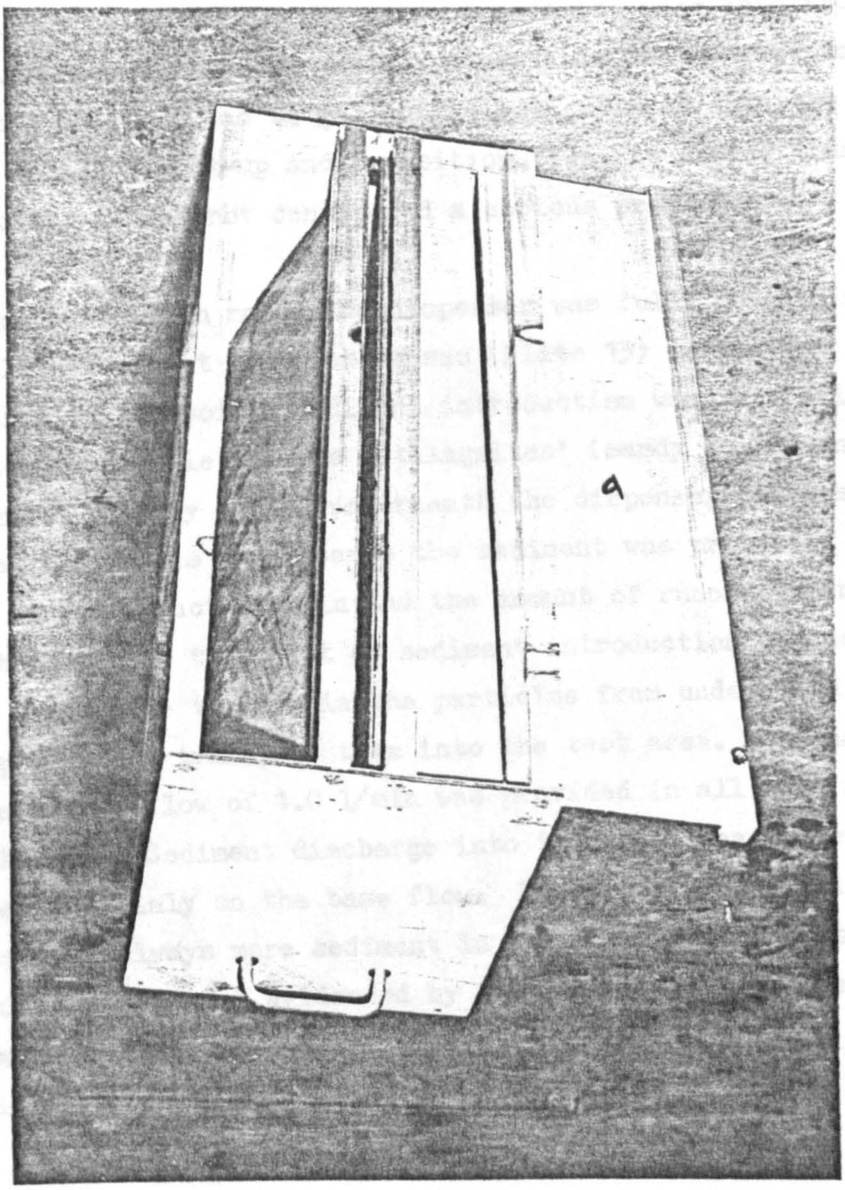

Plate: 12. Sediment dispenser (base)

a) slit for dispensing sediment into flow

b) sliding plate

of a mixture of grain sizes, the slit was often blocked by the larger particles. Although a tap on the sliding plate was enough to clear the blockage, it was often accompanied by a slump of soil particles into the flow. This made it difficult to ascertain the rate of sediment feed into the flow. Since the latter was not a variable in the experiments and the main aim was to get sufficient sediment into the test area to allow pick-up and deposition, i.e. to exceed transport capacity, it was not considered a serious problem.

During tests with rain, the dispenser was fully covered with a polythene sheet sewn into a sac (Plate 13) to prevent wetting of the soil. Sediment introduction was by gravity and it tended to pile up like 'stalagmites' (sandy soils) and 'mounds' (clayey soils) underneath the dispenser for test runs with rain. This was because the sediment was protected from the direct impact of rain and the amount of runoff produced by the rain at the point of sediment introduction did not have the competence to entrain the particles from underneath the dispenser and transport them into the test area. Because of this a base flow of 1.0 l/min was provided in all test runs with rain. Sediment discharge into the test area therefore depended mainly on the base flow. These problems notwithstanding, there was always more sediment in the test area than the flow could transport as evidenced by the deposition of sediment along the entire length of the soil-plate. Detachment was thus non-limiting.

3.4 EXPERIMENTAL DESIGN

The experiments were designed to study the effects of soil type, rainfall intensity and slope steepness and their interactions on each of the four subprocesses. For each subprocess, these variables were combined in a factorial experiment and replicated four times. Additionally, the effects of four rates of runoff on the detachment and transport by overland flow were examined. The levels of the variables used in the experiments are presented in Table 2.

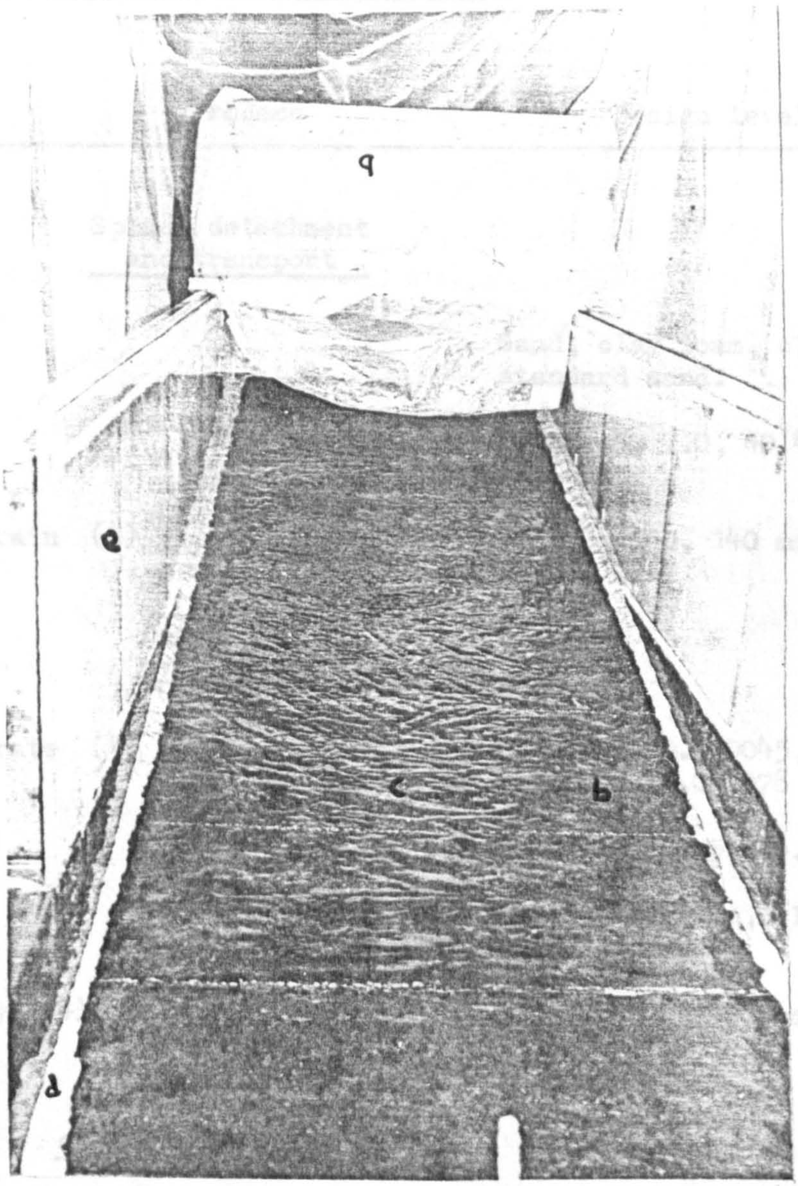

Plate: 13. Set up for transport capacity test

a) sediment dispenser covered with polythene sheet sac
b) soil-plate for transport tests
c) flow of clear water over roughened surface
d) mastik-sealed edges
e) perspex sides of extension frame

Table 2

Variables and their levels in the experiments

Variable	Process	Design level
	Splash detachment and transport	
Soil (4)		Sand, clay loam, clay, and standard sand.
Slope (5)		0.0, 3.5, 7.0, 10.4, 14.0 per cent
Intensity of rain (4)		50, 80, 110, 140 mm h^{-1}
	Detachment by overland flow	
Uniform flow rate (4)		0.000028, 0.000045, 0.000062, 0.000078 m^3 s^{-1} m^{-1} *
Slope (4)		3.5, 7.0, 10.5, 14.0 per cent
Soil (4)		Sand, clay loam, clay, and standard sand.
Rain intensity (4)		50, 80, 110, 140 mm h^{-1}
	Sediment transport by overland flow with rain	
Base flow rate (1)		0.000028 m^3 s^{-1} m^{-1}
Slope (4)		3.5, 7.0. 10.5, 14.0 per cent
Rain intensity		50, 80, 110, 140 mm h^{-1}
Soil (4)		Sand, clay loam, clay, and standard sand.

* converts to 0.28, 0.45, 0.62, and 0.78 cm^3 s^{-1} cm^{-1} or 1.67, 2.70, 3.70, and 4.70 1/min/m

The choice of the factorial as opposed to the single-factor approach was dictated by the objectives of the study (Section 1.2) and has several advantages as shown by Steel and Torrie (1980), Cochran and Cox (1957) and Rayner (1967). It permits a greater number of factors and levels to be studied in the same experiment and thus increases the generality with which inferences can be made. Interactions between factors can be examined to show the consistency in the response of the variables to the different levels of each other. While this is not possible by considering only the main effects, it is a prerequisite for identifying which levels and combinations of the factors need further experimentation. This is very important especially considering that most studies of the factors affecting erosion tend to be single-factor experiments in which each factor is isolated and treated as an independent variable. Where factors interact, a single-factor experiment will lead to disconnected and possibly misleading information.

The orthogonality of the experimental design, however, also allows the effects of the factors to be determined independently. This is not possible in field studies where the factors are generally correlated and their effects cannot be separated.

3.5 PARAMETERS AND MATERIALS

In selecting the levels of the variables in this study, attention was paid to those of erosional and practical agricultural significance. Soils were selected to include a wide range of agricultural soils in contrast to the sole use of graded sand which characterizes many studies on the mechanics of erosion. By this choice, it will be possible to:

i) simulate field conditions in the laboratory;

ii) bring out differences in the erosional behaviour of different soils under similar conditions;

iii) compare results obtained in this and other studies which are pertinent to the advancement of the understanding of the erosion process; and

iv) enhance the use and the scope of applicability of results obtained in the study.

Since storms with high intensity - duration values cause the major erosion, studies at these more critical rainfall conditions can be very useful in testing the erosional characteristics of most treatments (Meyer, 1965). Intensities for the study were therefore selected to lie in the range of storms producing medium to high rates of runoff and erosion.

Slope steepnesses were also chosen to cover the range commonly found on arable lands.

3.5.1 Soils.

The soils consisted of sand of the Cottenham series, derived from the underlying sandstone strata of the Lower Greensand, clay and clay loam belonging to the Wicken and Oak series of mid-Bedfordshire respectively (King, 1969) and a graded sand (passed 0.25 mm and retained on 0.21 mm sieve).

The Cottenham sand and clay loam were taken from field sites where soil loss has been monitored since May 1973 and February 1977 respectively (Morgan, 1980). These studies show erosion rates on the bare sand to be very high with an annual soil loss of 10.80 t/ha on 11° slope compared to 0.23 t/ha for the clay loam on 10° slope and cropped to spring barley. To provide basic soil erosion data on a wider range of agricultural soils in Britain, Wicken clay which is used for growing cereals in the Silsoe area of Bedfordshire was added to the soils of the study. Also, since most laboratory studies on the mechanics of erosion are conducted on standard sand, the latter was selected for comparative purposes.

Apart from the graded sand (standard sand), the soils were air-dried, crushed and screened with a 2 mm mechanical sieve. The silt and clay fractions were determined by the Bouyoncos hydrometer method (Bowles, 1970). The grain size distribution of the soils is presented in Table 3.

Table 3.

Grain size distribution of soils used in the experiment according to I.S.S.S. Classification.

Fraction	Standard sand	Sand (Cottenham Series)	Clay loam (Oak Series)	Clay (Wicken Series)
		Soil		
D_{50} (mm)	0.20	0.30	0.61	0.93
D_{84} (mm)	0.28	0.40	1.50	1.75
		% Fraction		
Clay	-	5.53	35.62	44.17
Silt	-	1.51	30.91	17.45
Fine sand	-	51.57	23.52	24.56
Coarse sand	-	42.55	11.96	12.82

3.5.2 Rainfall.

The simulated rainfall was characterized by its intensity, drop size distribution, uniformity, and kinetic energy (Table 4).

Intensity was determined by measuring the volume of water caught in 9 rain-cans each with a cross sectional area of 31.17 cm^2. The cans were placed in a grid in the test area (2 m^2) and after a 20 - minute run, the volume of water divided by the area of the can gave the depth of rain from which the intensity of rain in millimeters per hour was calculated (Appendices 1a, 2a, 3a and 4a).

Uniformity of distribution of the rain on the test area was expressed in terms of Christiansen's (1942) Uniformity Coefficient, Cu, expressed as:

$$Cu = 100 \left(1.0 - \frac{x}{mn} \right) \qquad \text{Eq. 39}$$

where

x is the sum of the deviations of individual observations (squares) from

m, the mean value of such observations and

n is the number of observations (squares).

Cu was computed from the depths of rain in the cans used above for measuring rain intensity. An absolutely uniform application would have a Cu of 100 per cent; and a lower percentage for a less uniform application. For the intensities used, the Cu ranged from 87.81 to 94.48 per cent (Table 4). This compares with a range of 77 - 94 and 78 - 82 per cent obtained respectively by Morin et al. (1967) and Barber et al. (1979) using a similar rainfall simulator.

The stain method was used to determine the drop-size distribution of the rainfall (Hall, 1970). This depends on the assumption that a drop falling on a uniform absorbent

Characteristics of the simulated rainstorms.

Intensity	Duration	Disc slot angle (degrees)	Amount of rain applied	Angular velocity of disc	Operating pressure	Median volume drop size	Coefficient of Uniformity	Kinetic energy per unit rain	Kinetic energy total
mm h^{-1}	min	^{o}	mm	rad s^{-1}	kN m^{-2}	mm	%	Jm^{-2} mm^{-1}	Jm^{-2}
48.30	20	1 x 10	16.10	4.6	52	2.51	87.81	27.55	443.56
79.90	20	1 x 20	26.63	4.6	48	2.55	94.48	28.85	768.28
109.60	20	3 x 6.7	36.53	4.6	52	2.90	93.51	29.82	1089.32
139.50	20	3 x 10	46.50	4.6	48	2.85	93.00	30.06	1397.79

surface dusted with a water soluble dye produces a stain whose diameter is proportional to the diameter of the drop. The distribution of drop sizes is obtained by comparing the size of the stains with those produced by drops of known diameter. The drop and stain diameters must be determined by prior calibration experiments.

The calibration curve (Appendix 5) of D'Souza (1973) was used. He produced a plot of stain diameter against drop size for a range of drop sizes which was obtained by dropping single drops of different sizes onto a Whatman No. 1 filter paper thinly dusted with methylene blue powder from a height of 5 m. The different drop sizes were produced from glass tubes which had been drawn out to a point at which they produced only a specific drop size under a given head.

In this experiment the same type of filter paper thinly dusted with methylene blue powder and held on two sampling boards was exposed to the simulated rainfall for a brief period of about 2 seconds. The sampling board measuring 45 cm x 45 cm (Plates 14 & 15) was made of plywood and the side holding the filter papers was padded with a foam material to prevent back splashes. For each intensity, 4 test runs, each consisting of eight filter papers (four per board) were made. After exposure, the filter papers were removed, dried and the stains were traced onto a permatrace sheet. The area of the stains was then measured by using an overlay with 0.25 cm square grid. Stain diameter was then calculated assuming drops of a circular shape and used to obtain drop diameter from the calibration curve. The number of drops in each drop size class was counted (Appendices 1b, 2b, 3b, 4b) and drop volume was obtained from Appendices 6 and 7 based on the data of Gunn and Kinzer (1949). The percentage of the total rain by volume in each drop size group (Appendices 1c, 2c, 3c, 4c) was converted to a cumulative percentage curve (Figs.1a & 1b)from which the median volume drop diameter (D_{50}) was read. For the four intensities studied, an overall average of 2,434 drops of all sizes was sampled.

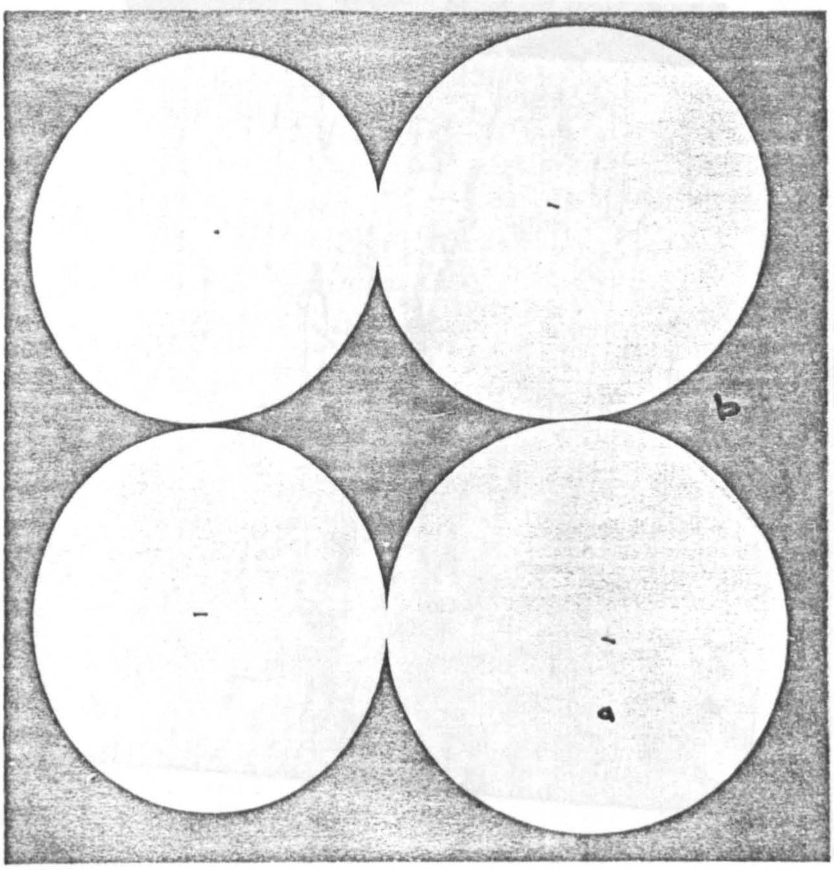

Plate: 14. Sampling board for drop size distribution.

a) four 18 cm - Whatman's filter papers pinned on

b) foam

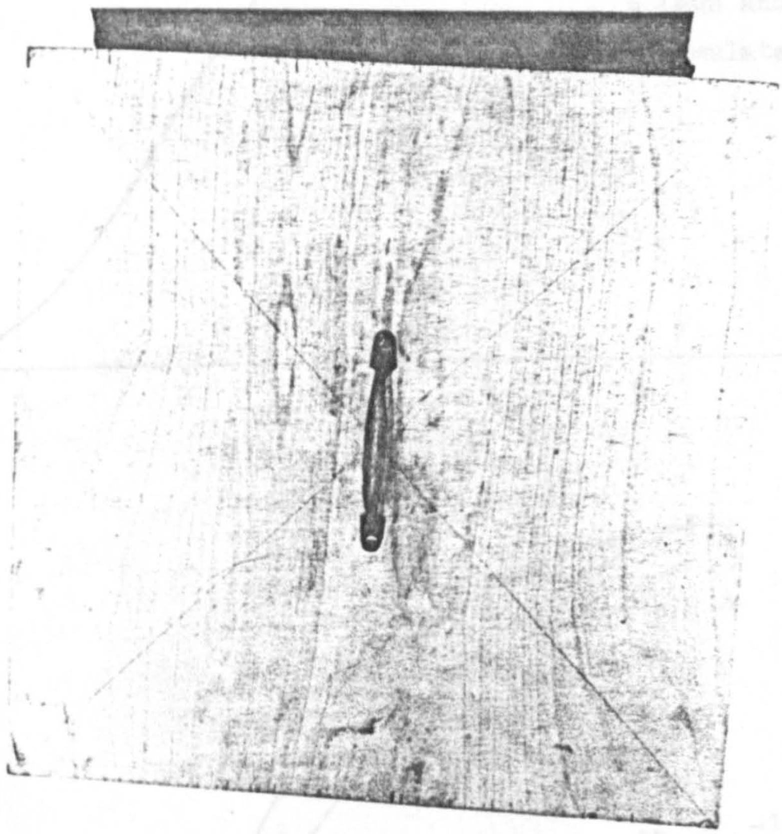

Plate: 15. Drop-size distribution sampling board cover showing handle.

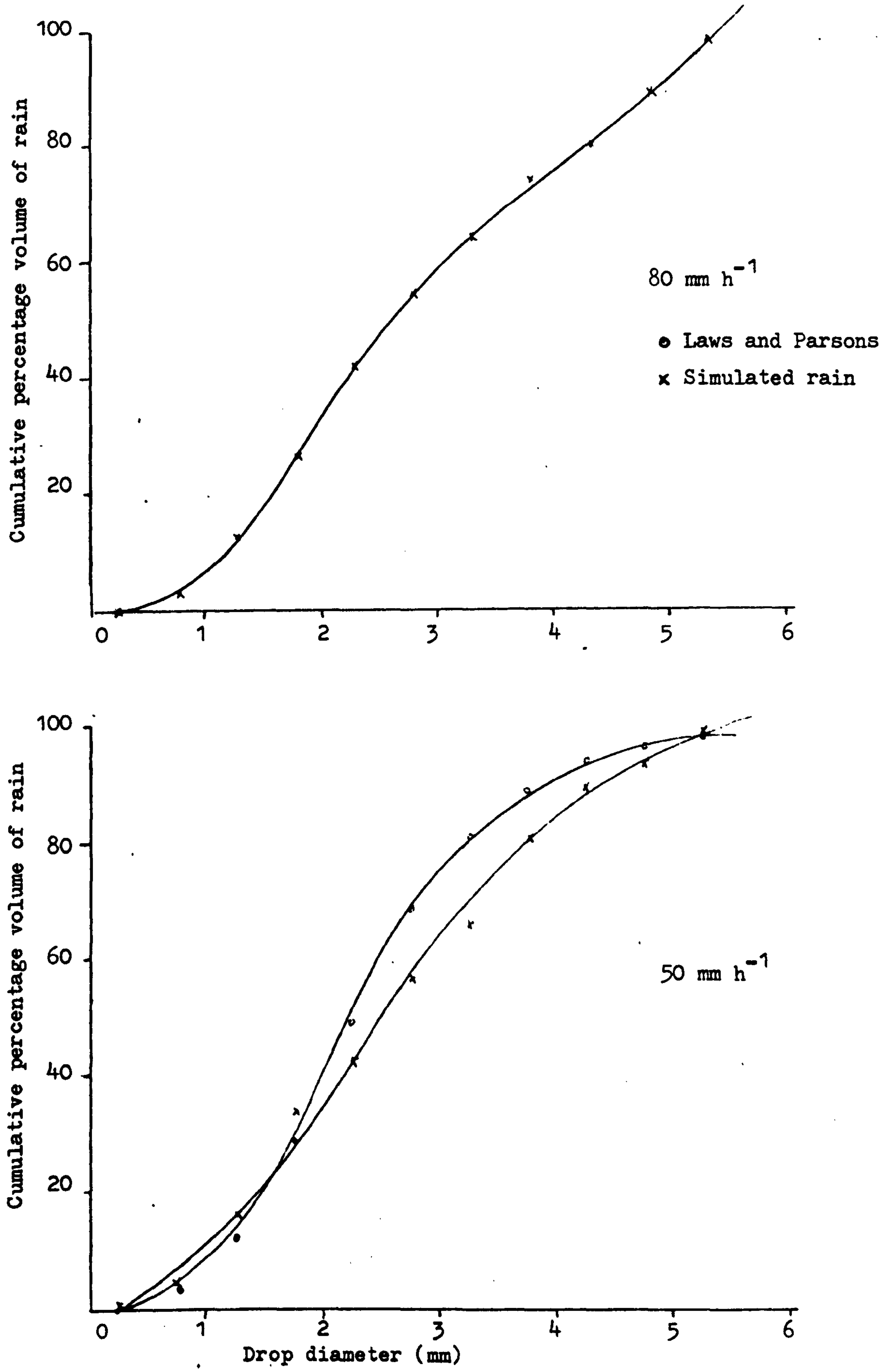

Fig. 1a Drop-size distribution of simulated rain compared with natural rain (Laws and Parsons, 1943).

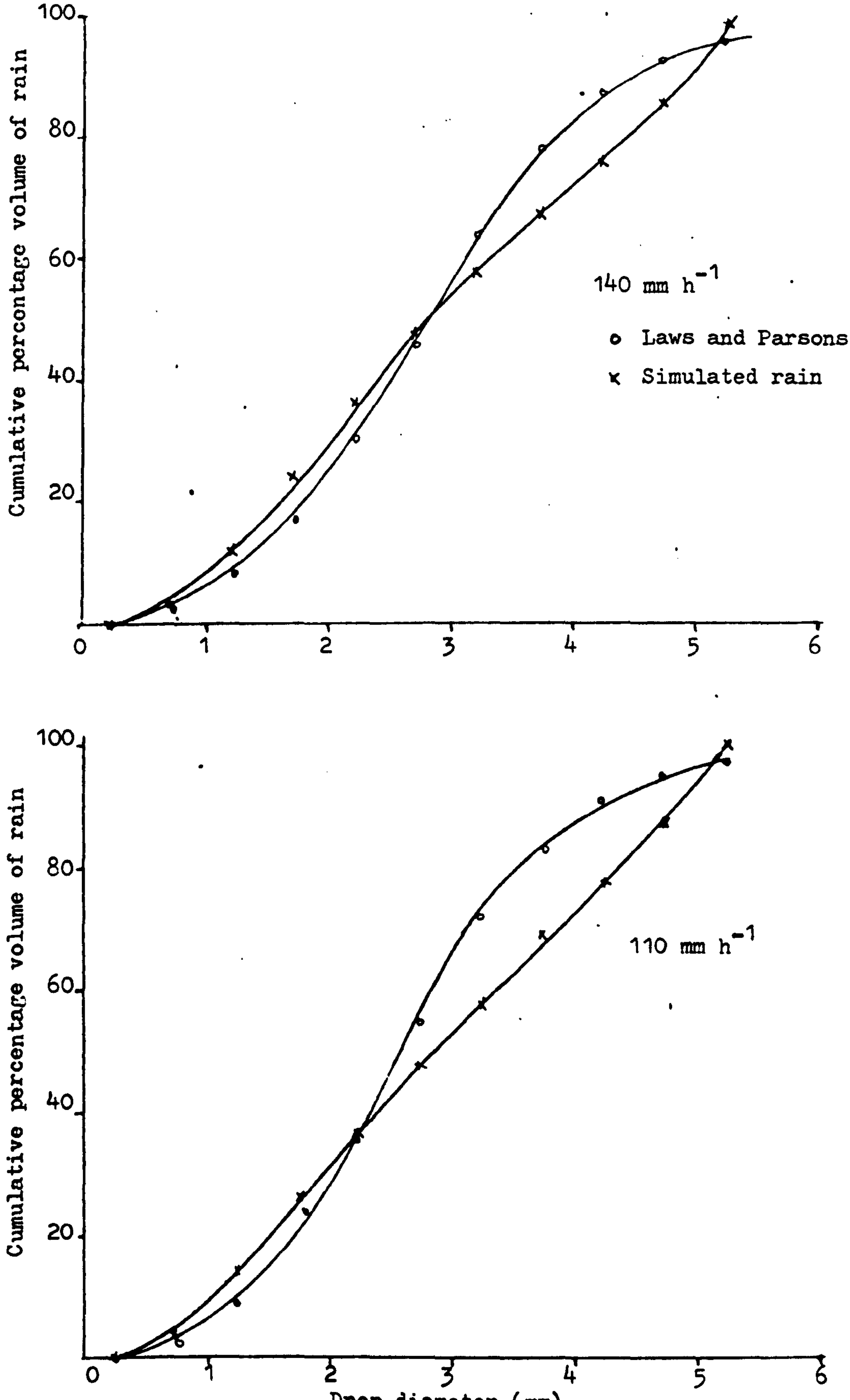

Fig. 1b Drop-size distribution of simulated rain compared with natural rain (Laws and Parsons, 1943).

Data on drop size distribution, total mass of drops (M) in each size class, and their fall velocities (V) are needed for the determination of kinetic energy (KE) of rain by the expression:

$$KE = \frac{1}{2} MV^2 \qquad \text{Eq. 40}$$

which in units of kg and $(m\ s^{-1})^2$ gives a value in joules (Table 5; Appendices 2d, 3d, 4d).

The values obtained above on drop size distribution and drop velocity values (Appendix 8) measured by Gunn and Kinzer (1949) were used with the assumption that the raindrops reached the soil surface at their terminal velocities. This assumption is based on the results obtained by Morin et al. (1967) where the authors determined the velocity of drops from the analysis of a series of multiple - exposure photographs using a GR stroboscope model 6484 at 6,000 flashes per minute as the source of light. The impact velocity values for drops (size range of 0 - 6 mm) from a 1.5 H 30 Nozzle simulator mounted 2 m above the test plot and a pressure of 60 kN m^{-2} were in close correspondence with the terminal velocity values obtained by Gunn and Kinzer (1949). Since the conditions under which this study was carried out are similar to those employed by Morin et al., the assumption is a reasonable working one.

In order to reproduce field conditions, the simulated rainfall should closely approach natural rainfall in terms of drop size distribution and kinetic energy (Meyer, 1965). For reasons of comparison, the cumulative drop-size distribution curves presented by Laws and Parsons (1943) for natural rainfall are drawn along side those obtained in this study (Figs. 1a and 1b). It must be pointed out however that their values for 100 and 150 mm h^{-1} were obtained by extrapolation. The median volume drop diameter (D_{50}) and kinetic energy are also compared to those of natural rainstorms (Table 6). The kinetic energy of the latter storms was calculated from

$$KE = 11.87 + 8.73 \log_{10} I \qquad \text{Eq. 41}$$

Table 5. **Sample Calculation of Kinetic Energy per Unit of Rain 48.30 mm hr^{-1}**

Drop Diameter mm 1	Av. No. Of Drops 2	Drop Mass gm 3	Mass of Water In Each Class (M) kg 4	Velocity ** V m s^{-1} 5	V^2 m^2 s^{-2} 6	MV^2 kg m^2 s^{-2} 7	½ MV^2 J 8
0 - 0.50	8.75	.025	.0002	1.480	2.190	.0004	.0002
0.51 - 1.00	292.50	.220	.064	3.000	9.000	.580	.290
1.01 - 1.50	143.00	1.200	.172	4.750	22.563	3.872	1.936
1.51 - 2.00	89.00	3.000	.267	5.950	35.403	9.453	4.727
2.01 - 2.50	21.00	6.000	.126	7.000	49.000	6.174	3.087
2.51 - 3.00	19.50	11.000	.215	7.800	60.840	13.050	6.525
3.01 - 3.50	7.25	18.000	.131	8.300	68.890	8.990	4.495
3.51 - 4.00	8.00	28.000	.224	8.700	75.690	16.955	8.478
4.01 - 4.50	3.00	40.000	.120	8.950	80.103	9.612	4.806
4.51 - 5.00	1.25	55.500	.069	9.050	81.903	5.684	2.842
5.01 - 5.5	1.00	75.000	.075	9.130	83.357	6.252	3.126
			1.4632				40.3122

K.E / Unit of rain $= \frac{1}{2} MV^2/M$

$= 40.3122 / 1.4632$

$= 27.551$ J kg^{-1}

$= 27.551$ J m^{-2} mm^{-1} *.

* 1 kg of water = 1 litre $= \frac{1}{1000}\ m^3 = \frac{1}{1000} \times m^2 \times m = \frac{1}{1000} \times m^2 \times 1000\ mm = m^2\ mm$

** Data obtained from Appendix 8 after Gunn and Kinzer (1949).

which is the SI unit version (Morgan, personal communication) of Wischmeier and Smiths' (1958) equation, and

$$KE = 29.8 - \frac{127.5}{I} \qquad \text{Eq. 42}$$

given by Hudson (1965) for tropical rainfall where

I = intensity, mm h^{-1} (in Eq.41 $I \leq 75$)
KE = kinetic energy, J m^{-2} mm^{-1}

The median drop-size and kinetic energy of the simulated rains were in close agreement with those recorded for natural rainfall (Table 6). The median drop diameter by volume ranges from 2.50 to 2.90 which compares with 2.3 - 2.85 (Laws and Parsons, 1943), 2.38 - 2.55 (Hudson, 1963), and 2.0 - 3.0 (Carter et al. 1974) obtained for natural rainfall of similar intensities. The median drop-size increased up to an intensity of 110 mm h^{-1} after which it decreased. This agrees with the observations of Hudson (1963) and Carter et al. (1974) for natural rain. However the median drop-size obtained in this study for 140 mm h^{-1} was 19.0 - 26.7 per cent larger than those of the latter authors. The values of kinetic energy ranged from 27.55 to 30.06 J m^{-2} mm compared with a range of 23.72 - 30.86 (Table 6) for natural rainfall.

3.5.3 Slopes.

As indicated earlier slope steepnesses (0.0, 3.5, 7.0, 10.5 and 14.0 per cent) which fall within the range often encountered on arable lands were selected for study. Since similar steepnesses and slope increments have been used in several studies on erosion (D'Souza and Morgan, 1976; Meyer and Monke, 1965; Bubenzer et al. 1966), results can easily be compared to enhance our understanding of the mechanics of erosion which is necessary for providing lasting solutions to erosion problems on farm lands.

Table 6.

Comparison of simulated rainfall characteristics with those of natural rainfall.

Parameter	Intensity (mm)						Source
	50	80	100	110	140	150	
D_{50} (mm)	2.50	2.55	-	2.90	2.85	-	Simulated rain
	2.30	-	2.60	-	-	2.85	Laws and Parsons (1943) Washington D.C.
	2.38	2.50	2.55	2.44	2.39	2.33	Hudson (1963) Zimbabwe
	3.00	3.20	2.88	2.80	2.25	2.0	Carter et al (1974) Louisiana and Mississippi
KE (J m^{-2} mm)	27.55	28.85	-	29.82	30.06	-	Simulated rain
	26.57	28.48	29.33	29.68	30.59	30.86	Wischmeier and Smith (1958) based on Laws and Parsons' (1943) data
	27.16	28.20	28.52	28.64	28.89	28.95	Hudson (1963) Zimbabwe
	28.64	29.64	28.98	28.01	25.03	23.72	Carter et al (1974), Louisiana and Mississippi

3.5.4 Overland Flow.

In order to compare the detachment of soil particles by overland flow with and without raindrop impact, it was necessary to use comparable outflow rates for the two conditions. Additional inflow equal to the rate applied as rain for runs with rainfall, was therefore added to runs without rainfall. The required inflow rates (Q; $m^3\ s^{-1}$) were obtained by measuring volumetrically the runoff produced by the test rainfall intensities. The discharge values (Table 7) were divided by 0.6 m, the width of the flume, to give discharge per unit width (q; $m^3\ s^{-1}\ m^{-1}$). In addition to discharge, other flow characteristics measured were velocity, depth and temperature.

Several methods are available for the measurement of velocity based on those used for channel flow, and the choice will depend upon the magnitude and character of the flow, the cost, and the accuracy required. Among available methods (U.S.B.R. Manual, 1974), the use of floats, pitot tubes, salt velocity, and colour velocity method were considered for this study. Because of the small depths of flow the first two methods could not be used. The salt-velocity method is also expensive and requires at least two people to take measurements. The latter requirement is also true for the colour-velocity method. Delineating the advancing dye front due to flow velocity from that resulting from diffusion is often difficult. Even so, this is commonly used in overland flow studies (Emmett, 1970; Kilinc and Richardson, 1973; Foster and Huggins, 1977). Because of the limitations of these methods, an alternative technique using oil-drops was employed in this study.

The technique is based on the fact that a drop of oil will float and drift in the direction of flowing water if the density of the drop is less than that of water. Among available oils, Shell Vitrea Oil 22 with a density of 0.86 g cm^{-3} and kinematic viscosity at 40°C of 0.0000022 $m^2\ s^{-1}$ was found to be the most suitable. To measure the velocity,

Table 7.

Flow rates used in the study.

Rain intensity	Discharge			
	Q		q	
mm h^{-1}	m^{3} s^{-1}	l min^{-1}	m^{3} s^{-1} m^{-1}	l min^{-1} m^{-1}
48.30	0.000017	1.0	0.000028	1.67
79.90	0.000027	1.6	0.000045	2.67
109.60	0.000037	2.2	0.000062	3.67
139.50	0.000047	2.8	0.000078	4.67

a drop of oil was introduced into the flow by a dropper and its drift with the flow was timed over predetermined distances. Five locations at 30, 60, 90, 120 and 150 cm downslope of the approach end of the soil-plate to the downslope edge of the soil-tray were marked for the detachment tests and eight positions (Plate 10) at 30, 60, 90, 120, 150, 180, 200, 230 cm for the transport tests. More positions are possible for the latter because of the greater length of the soil-plate being used. For the 30 cm increment between each location, 8 readings, 2 at each of four positions were taken across the soil plate. These measurements, totalling 32 and 56 for detachment and transport tests respectively, were averaged to give the mean flow velocity. By holding the dropper in one hand and a stop-watch (Plate 10) in the other, the introduction of the drop into the flow is easily controlled and its movement can be accurately timed over the 30 cm - distances between the above marked positions. Another advantage is that measurements can be taken by one person.

The technique presents no problems when used for flow without raindrop impact. However, in the presence of impacting raindrops, the oil-drops tend to break up. Some of the droplets are splashed about but since most of them move en masse the advancing front can still be timed with reasonable accuracy.

The small depths of overland flow render their measurement so difficult that at present there is no exact method available. Nevertheless a review of studies of overland flow shows that among available methods like manometers, electric capacitance, chemical staff gauge and the simple ruler, the use of a depth gauge (Plate 9) is common among workers (Emmett, 1970; Robertson et al., 1966; Podmore and Merva, 1971; Kilinc and Richardson, 1973). In order that results obtained in this study may be compared to those of other workers, a depth gauge was therefore used. It is easily obtainable, simple to operate and the other methods have no significant advantage over it. Thirty two and 56 readings for detachment and transport tests respectively were taken at the same positions marked for flow velocity measurements. Using the soil-adhesive surface as datum, the depth gauge was first zeroed and then raised to touch the surface of the flow to give a direct measure of the flow depth to 0.1 mm (Plate 16). The average of the above readings gave the mean depth of flow. The problems encountered in the use of the depth gauge are associated with the nature of the flow bed, the flow, and the gauge itself.

On a roughened surface, as that of the soil plates used in this study, the presence of microdepressions and humps made it impossible to define a common datum for the measurements. Because of the shallow depths, the surface roughness elements tended to protrude above the surface flow. This caused minor concentrations of flow which contributed to local increases in depth. The disturbance of the flow surface by raindrops and the presence of standing waves further complicate the visual assessment of the flow surface. Several readings are therefore necessary for reasonable results to be obtained.

After a dip of the depth rod into the flow, a drop of water is often retained at the measuring tip. When the rod is lowered again into the flow, the drop imparts an additional depth to the flow. This observation is pronounced when measurements are taken under rainfall. In this case, thin films of water, a result of splashes, tend to flow down the measuring rod and form drips at the tip thus rendering flow surface measurement extremely difficult. Although evidence is that rainfall impact increases the depth of uniform flows (Emmett, 1970) the magnitude of increase could be manifold if the above effects of dripping drops are not recognised.

To overcome these problems a piece of foam, 5 x 5 cm and 1 cm thick was used to shelter the measuring pin from drips of water (Plate 9). A hole slightly smaller than the diameter of the measuring rod was centrally made in the foam and the rod was then slipped through it. The foam absorbed water drops and frequent squeezing and sliding of the foam along the

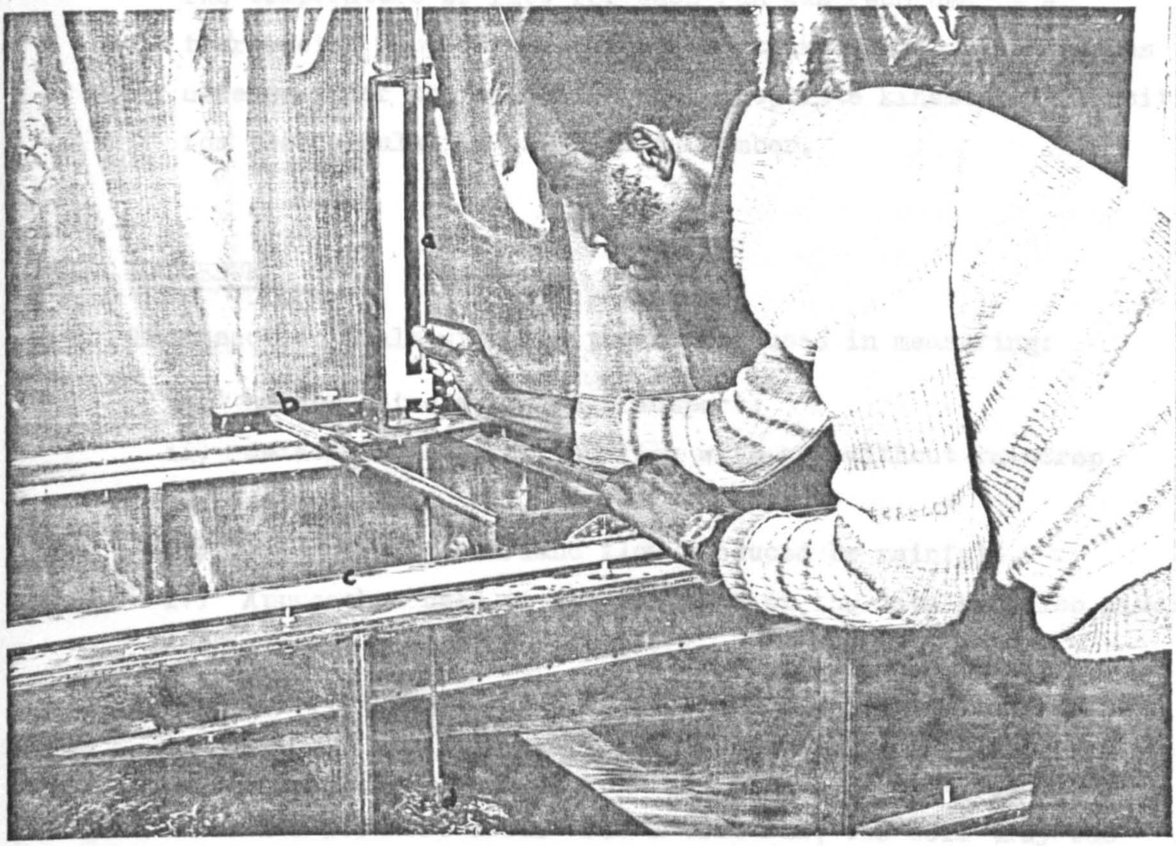

Plate: 16. Flow depth measurement

a) measuring rod of depth gauge

b) depth gauge carriage

c) depth gauge rail

d) measuring tip touching flow surface

rod and blotting of drops at the measuring tip prevented dripping of water. If this precaution is not taken, values greater than the actual depth of flow may be recorded and will lead to wrong conclusions.

The temperature of flow for each run was recorded by a thermometer dipped into the inflow tank (Plate 6). This was necessary for the selection of appropriate kinematic viscosities for the calculation of Reynolds number.

3.6 PROCEDURE

This section deals with the procedures used in measuring:

i) splash detachment and transport;
ii) detachment by overland flow with and without raindrop impact; and
iii) transport by overland flow produced by rainfall.
iv) Approaches used in the analysis of the data are also given.

3.6.1 Splash detachment and splash transport.

The splash tray and the rainfall simulator described in Section 3.3 were used. For a test run, the soil tray was filled with the test soil and saturated after scraping the surface with a straight-edged spatula to make it flush with the edge of the tray. The latter treatment applied only to the Cottenham sand and the graded sand. Saturation was necessary to ensure uniform soil moisture status for all the runs. In a saturated condition the Wicken clay and the clay loam tended to swell because of their content of montmorillonite. It was therefore necessary to make allowance for the latter effect when filling the soil tray. The choice of the duration of a run was also critical. With a prolonged test run, the soil surface is lowered, an edge effect develops, and splash erosion declines (Bisal, 1960; Hudson, 1965). After some trial runs it was found that filling the tray to a level about 3 mm below the edge was adequate for the clay and clay loam and a test duration of 20 minutes was sufficient to prevent the development of a significant edge effect yet allow enough time to produce steady state conditions.

After saturation, the upslope and downslope sections of the soil tray were covered with narrow strips (10 x 20 cm) of white cloth to catch splashes moving out of the soil tray in the upslope and downslope directions. The soil was then exposed to the simulated 20-minute rainstorm after which the soil on each strip of cloth was oven-dried at 105°C and weighed. The weight of the soil collected downslope less the weight of the soil collected upslope gave the net splash transport (Q_{trans}). The two weights combined were used as a measure of splash detachment (Q_{det}).

As pointed out earlier, it was not possible to assess the distances traversed by the particles because the size of the catching tray restricted particle movement to a distance of 45 cm. The piling of particles on the last strip of cloth near the boundary wall implied that the particles could move longer distances.

3.6.2 Soil detachment by overland flow without raindrop impact.

A soil plate for detachment was fitted into the flume at the desired slope angle with the boundaries sealed with mastik. With the soil-tray empty, water was sprinkled over the entire length of the plate to saturate the soil-adhesive coated surface. Water that accumulated in the soil tray was mopped with a piece of foam. Saturation of the soil plate enhances even flow as the runoff spills over the bed from the inflow tank. The impervious bottom of the tray was then covered with 5 mm - thick foam and before filling the tray with the test soil, one end of the foam was propped up with a wooden wedge to allow saturation of the soil from beneath the foam. This was necessary to prevent surface disturbance and a possible initiation of rilling which would occur by saturating the soil from the surface. Again, saturation was necessary to ensure uniform soil moisture conditions for each test run.

Immediately after saturation the test runoff was applied from the inflow tank. Soil particles detached from the soil tray and transported out of the flume were collected at the outflow end of the soil plate in a piece of white polyester cotton covering a rectangular catching tray (44 x 8 cm) with a wire gauze bottom.

After a 20 - minute run, a duration selected to match that of the splash test, the flow was turned off using the control clip (Plate 10) and any soil deposited on the soil plate was washed into cans and dried along with that collected in the catching tray. The total dry weight of the material detached was a measure of detachment by flow (Q_{odet}).

3.6.3 Soil detachment by overland flow produced by simulated rain.

The test procedure was the same as that described in Section 3.6.2 except that after saturating the soil, the rainfall simulator was turned on to produce the required flow. The total dry weight of the material was therefore a measure of detachment by a combined flow and raindrop impact. It must be pointed out that no baseflow was used in this test.

3.6.4 Transport of soil particles by overland flow produced by simulated rain.

Because of the need to assess transport capacity under as uniform flow conditions as possible, particularly with respect to surface roughness, the same soil plate, namely that coated with the standard sand - adhesive mix, was used for all tests, even though this resulted in the transport of clay and clay loam soils over a sandy substrate which is a departure from reality.

The equipment used for this test consisted of the mobile-bed flume, the sediment dispenser, and the rainfall simulator described in Section 3.3. The soil plate for transport was fitted into the flume at the test slope angle and the boundaries sealed with mastik. The plate was then saturated by a jet of water from the rubber tube that supplied water to the inflow tank. The sediment dispenser, filled with the test soil, was positioned 30 cm downslope of the upper end of the soil plate and covered (Plate 13). A base flow of 1 l/min was provided while the simulator was turned on to provide the test flow rate. The sliding plate of the dispenser was then gently pulled to open the slit to a predetermined size to allow sediment to drop by gravity into the flow. The problems encountered in the introduction of sediment into the flow have already been outlined in Section 3.3.

There was always more than enough sediment for the flow to transport. Detachment was thus non limiting. This is one of the conditions to satisfy if the transport capacity of the flow is to be established. Others are that there should be considerable deposition of sediment over the soil bed and sediment discharge should be constant. If equilibrium conditions are attained, sediment yield should be equal to rate of sediment input (Lawson and O'Neill, 1978; Foster and Huggins, 1977).

In order to establish whether sediment yield rate was constant and at what time during a run constancy occurred, some trial runs were carried out. The bulk density of the Cottenham sand and the graded sand were determined in a graduated cylinder. One-minute total catch samples of the transported sediment were collected at 3-minute intervals for a 45-minute run. Each 1-minute sample was washed into the graduated cylinder to obtain its volume. By multiplying the volume by the bulk density it was possible to determine rapidly the weight of sediment while the experiment was in progress. For the two sandy soils, a fairly constant yield was attained in the last 15 minutes of the run. This procedure was not possible to operate in the case of the clay and the clay loam. Trial runs of 1 hour duration were therefore carried out and the 1-minute samples were oven-dried. The weight of the samples revealed that a 45-minute test run was adequate.

Because of the above observations each test run lasted 45 minutes. Sediment transported out of the flume was caught in a piece of white polyester cotton covering a rectangular collecting tray (56 x 10 cm) with a perforated bottom and placed at the exit end of the soil-plate. In order to determine the sediment transport capacity of flow, a similar tray was used in collecting 1-minute total catch samples consisting only of solids at 3-minute intervals. In each test run, the oven dry weight of the last four samples collected when sediment transport rate was fairly constant were used to compute sediment transport capacity in kg m^{-1}. Total yield was the sum of oven-dry (105°C) weights of all the 1-minute samples and the sediment in the collecting tray.

3.6.5 Data processing.

In analysing the data, statistical procedures were selected to be appropriate to the experimental design and relevant to the achievement of the objectives of the study. (Section 1.2). Since the details are given in the succeeding Chapters, a general mention of the approaches adopted only is made in this section.

Analysis of variance was used to show the significance of soil type, slope steepness, rain intensity, flow rate and their interactions in influencing the processes studied. In this analysis, it was assumed that treatment and environmental effects are additive. Departure from the additive model may however occur due either to the interactive or multiplicative effects of factors. In the latter case, a log-transformation of the data restores additivity and analysis of variance of the logarithms is appropriate (Steel and Torrie, 1980; Rayner, 1967). To ascertain that significant interactions of the variables in this factorial experiment are not misrepresentations of multiplicative effects, the data were analysed in both the untransformed and transformed states as recommended by Rayner (1967) before drawing conclusions.

Multiple correlation and regression techniques were used as exploratory and predictive procedures respectively. In the former case, a search was made for associations between the variables and the closeness of the linear relationships was measured by the magnitude of the correlation coefficients which ranges between -1 and +1. As values approach one, the relationship becomes better. The best associations and results of other work were then used as the basis for selecting relationships to predict dependent from independent variables. The best predictive equations were those with the least standard error of estimate (SEE) and the highest coefficient of determination (R^2). The latter ranges between 0 and 1 and shows to what extent variations in the dependent variables are explained by the independent variables.

Because earlier studies had shown the relationships of interest to be nonlinear, the data were log-transformed prior to the analyses. This was necessary to make the parameters intrinsically linear and to give a normal distribution.

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CHAPTER 4

SPLASH DETACHMENT AND NET SPLASH TRANSPORT

The results and discussion of the experiments on splash detachment and transport are presented in this Chapter. A combination of the three variables, slope steepness, soil type and rainfall intensity (Table 2) used in this study as a factorial set of treatments gave 320 and 256 runs for the detachment and transport respectively. The data were analysed using analysis of variance to show the significance of the above, in influencing splash rates. Correlations between the variables and splash activity were also examined and relationships were established for predictive purposes. The distribution of total detached material in the upslope and downslope directions is also presented.

4.1 RESULTS

4.1.1 Factors Influencing Splash Detachment and Transport

The mean weights of soil detached and transported are presented in Table 8. The amount of soil detached and transported differed with the different soil types. The order of soil detached is standard sand > sand > clay > clay loam and that of splash transport is standard sand > clay > sand > clay loam. There are also significant increases in both splash detachment and transport with increasing rainfall intensity and slope steepness.

The analysis of variance (Tables 9 & 10) shows that the main effects of soil type, intensity of rain, slope steepness and their first and second order interactions significantly ($P = 0.001$) influence the amount of soil detached and transported. As a check for additivity, the data were log-transformed and analysed. The results confirmed the above significance of the main effects and interactions.

The significant interactions indicate that the factors are not independent; the soil x intensity interactions imply that the

Table 8

The mean weight of soil detached (n = 320) and net transported (n = 256) by splash.

Factor level	Mean weight of soil detached $kg\ m^{-2}$	Mean weight of soil transported $kg\ m^{-2}$
Soil		
Standard sand	0.3632 a*	0.1727 a
Sand	0.2395 b	0.1049 c
Clay loam	0.1608 d	0.0863 d
Clay	0.2095 c	0.1190 b
Intensity ($mm\ h^{-1}$)		
50	0.1154 d	0.0620 d
80	0.1832 c	0.1157 c
110	0.2729 b	0.1262 b
140	0.4015 a	0.1791 a
Slope (%)		
0.0	0.1892 e	-
3.5	0.2013 d	0.0539 d
7.0	0.2308 c	0.0819 c
10.5	0.2756 b	0.1433 b
14.0	0.3193 a	0.2043 a

* The differences between values followed by dissimilar letters are significant at 1% level.

LSD 5% = 0.0057	for soil and intensity means	)	
LSD 1% = 0.0075	for soil and intensity means	)	
LSD 5% = 0.0064	for slope means	)	DETACHMENT
LSD 1% = 0.0084	for slope means	)	
LSD 5% = 0.0044	for soil, slope, and intensity means	)	
LSD 1% = 0.0058	for soil, slope, and intensity means	)	TRANSPORT

Table 9 Analysis of variance of the effect of slope, intensity of rain, soil type, on splash detachment.

Source of Variation	Sums of squares	Degrees of freedom	Mean squares	F
Slope	0.74685	4	0.18671	549.15***
Replication	0.00120	3	0.00040	1.18 NS
Intensity	3.67191	3	1.22397	3599.91***
Slope x Intensity	0.21272	12	0.01773	52.15***
Soil	1.78720	3	0.59573	1752.15***
Slope x soil	0.03550	12	0.00296	8.71***
Intensity x soil	0.46642	9	0.05182	152.41***
Slope x Intensity x soil	0.10487	36	0.00291	8.56***
Residual	0.08004	237	0.00034	
Total	7.10669	319		

*** significant at 0.1%

NS not significant at 5%

Table 10 Analysis of variance of the effect of slope, intensity of rain, soil type, on splash transport.

Source of Variation	Sums of squares	Degrees of freedom	Mean squares	F
Slope	0.86405	3	0.28802	1800.13***
Replication	0.00101	3	0.00034	2.13 NS
Intensity	0.44237	3	0.14746	921.63***
Slope x Intensity	0.15427	9	0.01714	107.13***
Soil	0.26470	3	0.08823	551.44***
Slope x Soil	0.04118	9	0.00458	28.63***
Intensity x Soil	0.13177	9	0.01464	91.50***
Slope x Intensity x Soil	0.06162	27	0.00228	14.25***
Residual	0.02983	189	0.00016	
Total	1.99079	255		

*** significant at 0.1%

NS not significant at 5%

differences in both detachment and transport on a given slope between the levels of intensity, vary with the soil type. Conversely the effects of soil type depend on the level of rainfall intensity. The effects of both intensity for given soil and soil for given intensity vary with slope steepness as indicated by the intensity x slope and soil x slope interactions. The significant slope x intensity x soil interaction which is more difficult to interpret, may be considered as an interaction of the soil x intensity interaction with slope angle. It is clear from Tables 9 and 10 that the magnitude of the second order and the slope x soil interactions are relatively small compared with the main effects and the other first order interactions. Because of this, only these latter effects are examined further.

According to Steel and Torrie (1980) when treatment means are presented in a two-way table, sufficiently large changes in the magnitudes of the differences between the means in a column (or row), as columns or rows are examined in turn, constitute an interaction. Also changes in the rank of any treatment mean for a column (or row), as one changes columns (or rows), may constitute an interaction. In considering the interactions therefore, the approach was adopted whereby the responses of the factors to the increasing levels of each other were examined and any evidence of significant variations in the responses were reported.

When the soil x intensity interaction was considered, the effects of intensity at each level of soil showed significant increases in both splash detachment and transport for all the soil types as intensity increased except that the difference in the amount of clay transported at 80 and 110 mm h^{-1} was not significant.

On the other hand, an examination of the differences between soils at each level of intensity showed that at 140 mm h^{-1} significantly more clay than sand was detached and that there was no significant difference in the net soil transported between the Cottenham sand and Wicken clay at both 50 and 110 mm h^{-1}. The earlier observation about the greater amounts of clay than sand being transported occurred at the intensities of 80 and 140 mm h^{-1}.

Both splash detachment and transport increased with each increment in slope angle at all levels of intensity. However, the effects of intensity at each level of slope revealed a few departures from the general observation of increasing splash transport with increasing intensity. On the 3.5 per cent slope there were no significant differences in the net movement of soil between 80 and both 110 and 140 mm h^{-1}. Also, the 80 mm h^{-1} rain caused more splash transport than the 110 mm h^{-1} rain on the 7 per cent.

4.1.2 Splash Detachment and Transport Relationships

In order to establish relationships of splash activity with the factors influencing erosion, the splash detachment and transport measurements were examined for correlations with total kinetic energy of rain and slope steepness using multiple regression analysis. The data were first transformed logarithmically to give a normal distribution. Such a transformation could not be made for the zero slope. This resulted in excluding 16 and 64 observations from the detachment data for each soil and for all soils respectively. Therefore 64 observations were used for the analysis for each soil and 256 for all soils combined.

The coefficient of correlation, r (Table 11) shows a highly significant positive correlation ($P = 0.001$) between splash detachment and kinetic energy of rain. Slope steepness is also positively correlated to splash detachment and the values of r for the clay and clay loam are highly significant at 0.1 per cent level while the values for sand and standard sand are significant at 1.0 and 5.0 per cent levels respectively. The correlation of both kinetic energy and slope steepness with splash transport is highly significant.

Table 11 Coefficient of correlation : splash detachment (Q_{det}) and net splash transport (Q_{trans}) versus slope steepness, kinetic energy, and grain size.

Soil+	% Slope	Total Kinetic Energy	d_{50}	d_{84}
Standard sand				
Q_{det}	0.24*	0.92***		
Q_{trans}	0.63***	0.68***		
Sand				
Q_{det}	0.29**	0.85***		
Q_{trans}	0.78***	0.48***		
Clay loam				
Q_{det}	0.38***	0.81***		
Q_{trans}	0.82***	0.45***		
Clay				
Q_{det}	0.38***	0.86***		
Q_{trans}	0.79***	0.43***		
All soils (n = 256)				
Q_{det}	0.32***	0.77***	-	-
	-	0.77***	- 0.39***	-
	-	0.77***	-	- 0.42***
	0.32***	0.77***	- 0.39**	-
	0.32***	0.77***	-	- 0.42***
Q_{trans}	0.66***	0.46***		
	0.66***	0.46***	0.28***	-
	0.66***	0.46***	-	0.28***

+ n = 64 for each soil

* significant at 5%

** significant at 1%

*** significant at 0.1%

In order to incorporate a grain size factor into the relationships, the data for all the soils were bulked and analysed for correlations not only with kinetic energy and slope but also with d_{50} and d_{84} which refers respectively to the grain size at which 50 and 84 per cent of the soil particles are finer. There is a highly significant negative correlation between both splash detachment and transport and these grain size parameters.

Table 12 shows the regression equations in the form

$$Q = a\,KE^{b}\,S^{c}\,d^{e} \qquad \text{Eq. 43}$$

where

Q_{det} = splash detachment (kg m^{-2})

Q_{trans} = net splash transport (kg m^{-2})

KE = total kinetic energy (J m^{-2})

S = per cent slope

d_{50} and d_{84} as defined in text

a, b, c, e = empirically determined constants.

The kinetic energy of rain and slope steepness account for 79 to 90 and 81 to 88 per cent of the variance in the amounts of soil detached and transported respectively. The exponents relating splash detachment and transport to kinetic energy ranged from 0.84 to 1.35 and 0.68 to 0.97 respectively. The corresponding values for the slope exponent are 0.13 to 0.27 and 0.75 to 1.37.

In all cases, the multiple correlation for the individual soils is better than that for all soils. However, an inclusion of the grain size term significantly improved the multiple correlation coefficient, R, from 0.83 to 0.93 for splash detachment. The corresponding increase for splash transport was 0.81 to 0.85. The exponents for d_{50} were - 0.35 for splash transport to - 0.43 for splash detachment and d_{84} gave - 0.27 and - 0.34.

Table 12 Power equations relating splash detachment (Q_{det}) and transport (Q_{trans}) to slope (S), kinetic energy (KE) and grain size (d_{50}; d_{84}).

Soil	Equation	KE r^2	S r^2	d_{50} r^2	d_{84} r^2	R^2	Eq. No
Standard sand	$Q_{det} = 0.0002\ KE^{1.06}$	0.84	-	-	-	-	45
	$Q_{det} = 0.0002\ KE^{1.06}\ S^{0.13}$	0.84	0.06	-	-	0.90	46
	$Q_{trans} = 0.00005\ KE^{0.97}\ S^{0.75}$	0.46	0.40			0.86	47
Sand	$Q_{det} = 0.0007\ KE^{0.84}$	0.72	-	-	-	-	48
	$Q_{det} = 0.0003\ KE^{0.84}\ S^{0.13}$	0.72	0.08	-	-	0.81	49
	$Q_{trans} = 0.0001\ KE^{0.68}\ S^{0.92}$	0.23	0.61	-	-	0.85	50
Clay loam	$Q_{det} = 0.0004\ KE^{1.16}$	0.66	-	-	-	-	51
	$Q_{det} = 0.00003\ KE^{1.16}\ S^{0.25}$	0.66	0.14	-	-	0.79	52
	$Q_{trans} = 0.00004\ KE^{0.75}\ S^{1.15}$	0.20	0.67	-	-	0.88	53

/continued

Table 12 (Continued)

Soil	Equation	KE	S	d_{50}	d_{84}	R^2	Eq. No
Clay	$Q_{det} = 0.00002\ KE^{1.35}$	0.74	-	-	-		54
	$Q_{det} = 0.00001\ KE^{1.35}\ S^{0.27}$	0.74	0.14	-	-	0.88	55
	$Q_{trans} = 0.00001\ KE^{0.90}\ S^{1.37}$	0.19	0.62	-	-	0.81	56
All soils	$Q_{det} = 0.00005\ KE^{1.10}\ S^{0.20}$	0.59	0.10	-	0.69	0.69	57
	$Q_{det} = 0.00004\ KE^{1.10}\ S^{0.20}\ d_{50}^{-0.43}$	0.59	0.10	0.15	0.84	0.84	58
	$Q_{det} = 0.00003\ KE^{1.10}\ S^{0.20}\ d_{84}^{-0.34}$	0.59	0.10	0.18	0.87	0.87	59
	$Q_{trans} = 0.00005\ KE^{0.82}\ S^{0.98}$	0.21	0.44	-	0.65	0.65	60
	$Q_{trans} = 0.00004\ KE^{0.81}\ S^{0.98}\ d_{50}^{-0.34}$	0.21	0.44	0.08	0.73	0.73	61
	$Q_{trans} = 0.000045\ KE^{0.82}\ S^{0.98}\ d_{84}^{-0.27}$	0.21	0.44	0.08	0.73	0.73	62

4.1.3 Distribution of Splashed Material

The splash tray used in this study made it possible to assess the upslope and downslope distribution of detached particles. Table 13 shows the percentage of total detached material that moved downslope (% D) given by:

$$\% \text{ D} = \frac{\text{weight of downslope splashes}}{\text{of weights of downslope and upslope splashes}} \times 100 \qquad \text{Eq.44}$$

and 100 minus % D gives the percentage of material that moved upslope.

The % D increases with increasing slope steepness. The respective ranges of values for the 3.5, 7.0, 10.5, and 14.0 per cent slopes were 57.01 - 72.93, 64.59 - 80.87, 69.58 - 87.50, and 72.24 - 90.30. The values for each slope are similar for the 50 and 80 mm h^{-1} rain; and again for the 110 and 140 mm h^{-1}, with those of the former intensities being generally higher. Compared to the standard sand and Cottenham sand, greater percentage of the clay loam and clay moved downslope. The respective mean percentage downslope movements were 72.53, 71.27, 75.72 and 76.63. Absolute transport on the other hand increased in the order of clay loam $<$ sand $<$ clay $<$ standard sand. Because slope steepness is the major factor affecting % D, relationships were established between the two for predictive purposes (Table 14). The coefficient of determination, r^2, ranged between 0.74 and 0.92.

Table 13 Mean percentage downslope movement of splashed particles

Slope	Intensity	Soil			
%	mm h^{-1}	Standard sand	Sand	Clay loam	Clay
3.5	50	64.51	64.08	71.75	68.79
7.0	50	70.00	68.86	78.88	73.01
10.5	50	75.21	73.80	83.15	78.00
14.0	50	83.55	81.85	89.04	89.94
3.5	80	69.15	67.65	72.93	72.63
7.0	80	73.67	74.02	80.58	80.87
10.5	80	74.52	77.12	87.50	87.00
14.0	80	83.33	82.61	90.30	88.81
3.5	110	63.77	63.95	60.38	57.01
7.0	110	64.61	67.71	64.94	71.35
10.5	110	69.58	76.31	76.08	79.71
14.0	110	82.30	76.55	80.84	82.56
3.5	140	62.25	57.93	60.77	58.85
7.0	140	66.26	64.59	65.81	73.50
10.5	140	76.59	71.01	70.88	80.67
14.0	140	81.18	72.24	77.62	83.33

Table 14 Relationship between percentage downslope splash movement (%D) and per cent slope

Soil	Equation	r^2	Eq. No
Standard sand *	D = 57.94 + 1.67 S	0.92	63
Sand	D = 56.50 + 1.79 S	0.92	64
Clay loam	D = 61.44 + 1.42 S	0.74	65
Clay	D = 60.36 + 1.55 S	0.79	66
All soils	D = 58.92 + 1.73 S	0.80	67

* n = 16 for each soil

n = 64 for all soils

4.2 DISCUSSION

4.2.1 Factors Influencing Splash Detachment and Transport

Splash erosion is the result of the detachment and transport of soil particles by the impact force of raindrops. This force has to overcome the particle weight and the cohesive force binding the particles together and is also dependent on slope steepness (Fleming, 1977). It is logical therefore to assume that any factor affecting this force affects the detachment and transport processes. The significance of such factors as the type of soil, slope steepness, intensity of rain and their interactions, is clearly demonstrated in these experiments.

Soil type.

The variation in the amount of soil detached and transported between the soil types may be accounted for by examining the particle size distribution (Table 3) of the soils which according to Wischmeier et al. (1971) is a major determinant of the susceptibility of soils to erosion. With fine sand being the least resistant to splash action (Ellison, 1947; and Baver, 1966) it is not surprising that detachment increases as the fine sand content of the soils increases. The magnitude of the increases depends however, on which levels of intensity and slope are considered. This is implicit in the fact that the latter two factors interact significantly with soil type. For the same reason, even a deviation from the general observation may occur as that between the Wicken Clay and the Cottenham Sand at the 140 mm h^{-1} rain intensity.

Nevertheless, the significantly lower amounts of clay and clay loam detached imply that these soils are more stable than the sandy soils since splash is a measure of the resistance of the soil to raindrop impact forces (Ellison, 1947; Adams et al., 1958). The greater content of montmorillonitic clay fraction in these soils (King, 1969) is important in this regard because clay enhances aggregate formation and stability

(Baver, 1966; Greenland, 1977; Luk, 1979). Evidence of this is in the clay soils collected at the end of the splash experiment which were in the form of discrete aggregates and were visually larger in size than the sand grains.

Clay soils are thus detached as aggregates and once detached become a part of the non-cohesive population of soil particles the transport of which is a function of the properties of the separate particles themselves (Vanoni, 1975). Because of this, the amount of soil transported from each soil type may follow a different order from that detached since the latter depends mainly on the cohesive forces binding the particles. Moreover, a soil could have low detachment but with a high percentage downslope movement (% D) that would result in relatively high transport. This became evident when Cottenham sand and Wicken clay were compared. Although splash detachment was significantly greater in the former, because of a higher % D, a greater absolute amount of the latter was net transported.

In order to account for the source of the variations in the amount of soil transported, the homogeneity of the effects of soil at each level of intensity was examined. Similar amounts were transported at the intensities of 50 and 110 mm h^{-1} and the differences in the magnitude of their response to the 80 and 140 mm h^{-1} were the main source of variation.

Rain Intensity

The increases in both splash detachment and transport as intensity of rain increases confirm the observations of other workers (Ellison, 1944; Hudson, 1971), and are presumably due to increased kinetic energy associated with increasing intensity. The magnitude of the response is however influenced by slope steepness and soil type. This observation is not explicit in the earlier studies of the splash process.

Slope Steepness

Splash detachment increased with increasing slope angle as observed by Meyer et al. (1975). The significant slope x soil and slope x intensity interactions indicate however that this increase varies with the type of soil and rain intensity.

The significant increases in splash transport with increasing slope steepness accord with the observations of Ekern (1953) and DePloey and Savat (1968). The distribution of splashed particles expressed usually in terms of percentage downslope and upslope splashes (Ellison, 1947; Ekern, 1953; DePloey and Savat, 1968) is important especially where overland flow has the competence to transport the particles. For a given intensity, a greater percentage of clay and clay loam aggregates than sand particles moved downslope. The percentages for sand and standard sand were 64.35, 68.70, 74.27, and 80.4 for the 3.5, 7.0, 10.5, and 14 per cent slopes respectively. The corresponding values for clay and clay loam were 65.39, 73.62, 80.37, and 85.31. The value of 74 per cent for the sandy soils confirms the 75 per cent obtained by Ellison (1947) on a 10 per cent slope. Compared to the 64 per cent obtained by DePloey and Savat (1968) on a 14 per cent slope, the values reported in this study are higher presumably due to the effects of the slope x intensity interaction.

The coefficient of determination for the per cent downslope movement (% D) expressed in terms of slope ranged from 0.74 to 0.94 for the individual soils. With an r^2 of 0.80, the expression

$$\% D = 58.92 + 1.73 S \qquad \text{Eq. 68}$$

with S = per cent slope

for all soils compares well with Ekern's (1950) per cent slope plus 50 and Eq. 4 (Savat, 1981).

4.2.2 Splash Detachment and Transport Relationships

The values of the exponents relating detachment and transport to kinetic energy are comparable to those obtained by other investigators of splash detachment. Mihara (1951) reported splash as directly proportional to kinetic energy while Free (1960) obtained 0.9 for sand and 1.46 for soil. For a range of soils, Bubenzer and Jones (1971) found a range of 0.83 to 1.49, and in field studies Morgan (1978) obtained 0.84 for splash transport on Cottenham sand.

The values of the exponents differ with the soil type and are generally greater for clay soils. The greater exponent indicates that for an increase in kinetic energy, the proportionate effect is greater in clay than the other soil types. Thus although the clay is initially more stable as the lower intercept value indicates, it breaks down rapidly with increasing kinetic energy of rain.

The slope exponent in the detachment equations is quite low. However an analysis of variance has shown the addition of slope to the regression equation to be statistically significant. The additional variance accounted for as slope is added to the regression of kinetic energy on splash detachment ranges from 6.0 to 14.0 per cent. Although this may not be significant in a practical sense, it is important in the understanding of the working of the erosion process.

Splash transport is, however, more sensitive to increases in slope steepness. For the relationship between splash transport and slope, Meyer and Wischmeier (1969) assume an exponent of 1.0 and Kirkby (1971) suggested a range of 1.0 and 2.0. Moeyersons and DePloey (1976) obtained 0.75 and Gabriels et al. (1975) recommended 1.37 based on values for a range of soils. The latter two values correspond to the lower (standard sand) and upper (clay) values of the range 0.75 to 1.37 obtained in this study.

The inverse relationship between grain size and both splash detachment and transport indicates that both splash parameters increase as d_{50} and d_{84} decrease. Poesen and Savat (1981) made a similar observation for median grain size but found that below some critical minimum size, detachment decreased. By incorporating the grain size parameters into the splash equations, a greater proportion of the variances in both detachment and transport were explained. However this decreased the value of the intercept which, in the absence of a grain size term, represents the soil detachability and transportability in the splash detachment and transport equations respectively. Since soil detachability is a function of the particle sizes and their stability, which is a measure of the cohesive forces binding the particles together and inter-aggregate bonding, an inclusion of a grain size term leaves the value of the intercept to account for the stability of the soil. In the transport equations, the intercept may represent inter-aggregate bonding.

The use of a grain size parameter in addition to the intercept value to represent soil erodibility thus has an advantage over erodibility indices which cater only for either grain size or aggregate stability. Moreover it allows the relationship between grain size and resistance to detachment by rainfall and runoff which, in this study is very similar, to be compared.

The exponent of the median grain size in the transport equation compares well with - 0.218 obtained by Poesen and Savat (1981). Although the exponents of both kinetic energy and slope angle are variable, the values obtained in this study and those of the workers cited above would seem to suggest the values listed in Table 15 as reasonable working ranges for the exponent of kinetic energy (a), slope (b), d_{50} (c) and d_{84} (e). Since these values were obtained empirically, they must be used with caution.

Table 15 Range of exponent values for kinetic energy (a), slope (b), d_{50} (c) and d_{84} (d) for different soil types

Soil Type	Splash detachment			Splash transport		
	a	c	d	b	c	d
All soils	1.15	- 0.43	- 0.34	1.05	- 0.22 to -0.34	- 0.27
Sand and loamy sand	0.80 - 1.10	-	-	0.70 - 1.00	-	-
Silt loam, silty clay, clay loam, and clay.	1.20 - 1.50	-	-	1.10 - 1.40	-	-

4.3 SUMMARY

Whenever the energy of raindrops is expended on a bare soil surface, splash detachment and transport become active. The results showed that the latter processes are significantly influenced by soil type, the intensity of rain, slope steepness and their first and second order interactions.

The standard sand and three soils tested differed significantly in the mean weight of soil detached and transported. For each soil there were significant increases in splash detachment and transport with rainfall intensity. Both splash parameters were significantly correlated with slope steepness.

As slope steepness increased, a greater percentage of detached clay and clay loam than sand and standard sand moved downslope. A soil with a lower detachability but a higher percentage downslope movement may result in a relatively high absolute transport.

The most important interactions that influenced splash detachment and transport were soil x intensity and slope x intensity respectively. The significant interactions indicate that the factors are not independent of each other, the simple effects of a factor varies according to the level of the other factors of the interaction term. These interactions have not been studied in previous research on splash erosion.

Power equations were established between splash activity and total kinetic energy, slope steepness, and grain size parameters (d_{50} and d_{84}). The exponents of kinetic energy and slope varied with soil type. However in combination with results reported by other workers, reasonable working ranges for the exponents are suggested. An inclusion of a grain size term (d_{50} or d_{84}) which is inversely related to both splash detachment and transport improved the predictive capabilities of the equations for all soils.

The results are further used to confirm those obtained by previous workers.

CHAPTER 5

HYDRAULICS OF OVERLAND FLOW WITH AND WITHOUT RAIN

In this chapter the hydraulic properties of overland flow, with and without rain are examined. The properties provide a fundamental understanding of flow characteristics relevant to the capacity of overland flow to detach and transport soil particles. These latter aspects are investigated in subsequent chapters. For the hydraulic analysis, flow velocity, depth and temperature were measured for three flow conditions, namely, flow without rain, flow with rain, and flow with rain and baseflow. The latter was used for only the standard sand surface and for the transport tests as explained earlier in Section 3.6.4. The measured values of velocity and depth were used in calculating Reynolds number, Froude number, Darcy Weisbach's friction factor, tractive force, stream power per unit boundary area, Manning's n and total runoff kinetic energy. Typical values of the parameters are tabulated.

The data obtained on the above parameters were analysed statistically using analysis of variance and the results are presented in this chapter to show the significance of the effects of slope steepness, flow rate, soil surface, and their interactions on flow hydraulics. In assessing the latter effects, several workers tend to use regression analysis. In order to compare their results with those obtained in this study, relationships are established between discharge and slope steepness and the above flow parameters using multiple regression analysis.

5.1 VELOCITY

As indicated in Section 3.5.4, flow velocity was measured by the oil-drop technique. For each soil plate, 32 readings were taken for detachment by overland flow with rain. A similar number of measurements were made for flow without rain and 56 for the only plate (standard sand-adhesive mix) used for the transport tests. These readings taken over distances of 30 cm were averaged to give mean velocity (mm s^{-1}) for each soil plate. The measurements for the transport tests permit the influence of an additional baseflow to flow with rain on velocity to be assessed for the standard sand surface.

The results of the velocity measurements for the detachment tests are presented in Appendix 11. These ranged from 21.10 to 143 and 30 to 138.40 for flow with and without rain respectively. For the latter, mean velocity (Table 18) for the various soil surfaces varied from 69.21 to 77.79 in an order of standard sand > clay loam > clay > sand. The differences in velocity were significant at 1.0 per cent level. Flow velocity also increased significantly ($P = 0.01$) as discharge increased with the velocity for the 2.8 l/min flow (94.13 mm s^{-1}) being twice that at the 1.0 l/min (46.47). Increasing slope steepness significantly increased velocity from 55.02 to 102.50 for a slope range of 3.5 to 14 per cent.

The values for flow with rain (Table 18) show the effect of impacting raindrops on flow velocity. In these tests, flow rates similar to those without rain were produced entirely by the simulated rain. In all cases flow velocities were reduced compared with those recorded without rain. Consideration of momentum exchange between the mass of impacting drops and the mass of water as surface flow would predict this retardation in velocity (Tödten , 1976; Yoon and Wenzel, 1971). The reduction was greater on the clay and clay loam surfaces (11.75 and 8.7 per cent) than the standard sand and sand (5.76 and 6.8 per cent).

With the exception of the 2.2 l/min flow, the percentage reduction in velocity tended to be the same for all flow rates. This accords with the observation made by Emmett (1978). Since the lowest intensities were accompanied by the lowest flow rates and vice versa, the overall effect of adding rainfall was to create a balance of the momentum exchange between runoff and rain so that the percentage effect was approximately the same for all intensities of rainfall (7 per cent).

Since the impact force of raindrops increases with decreasing slope steepness (Rowlison and Martin, 1971) velocity reduction would be expected for a constant intensity to be greater on lower slopes. The data confirm this with a mean percentage reduction of 14, 9, 4 and 6 for the 3.5, 7.0, 10.5 and 14 per cent slopes respectively. Similar reductions in flow velocity due to

TABLE 16 Analysis of variance of the effect of slope steepness, Soil surface and flow rate on flow velocity (flow without rain).

Source of variation	Sums of squares	Degrees of freedom	Mean squares	F
Slope	20467.77	3	6822.59	713.42***
Discharge	21638.42	3	7212.81	754.22***
Slope x Discharge	1118.46	9	124.27	12.99***
Soil surface	699.10	3	233.03	24.37***
Slope x Soil surface	912.06	9	101.34	10.60***
Discharge x Soil surface	107.19	9	11.91	1.25 NS
Slope x Discharge x Soil surface	258.21	27	9.56	
Total	45201.21	63		

*** significant at 0.1%

NS not significant at 5%

TABLE 17 Analysis of variance of the effect of slope steepness, Soil surface and flow rate on flow velocity (flow with rain).

Source of variation	Sums of squares	Degrees of freedom	Mean squares	F
Slope	21495.99	3	7165.33	570.94***
Discharge	16309.17	3	5436.39	433.18***
Slope x Discharge	1421.86	9	157.98	12.59***
Soil surface	1210.48	3	403.49	32.15***
Slope x Soil surface	1500.81	9	166.76	13.88***
Discharge x Soil surface	175.15	9	19.46	1.55 NS
Slope x Discharge x Soil surface	338.75	27	12.55	
Total	42452.21	63		

*** significant at 0.1%

NS not significant at 5%

TABLE 18 · The effect of soil surface, slope steepness and flow rate on velocity (mm s^{-1})

Factor level	Mean velocity (flow with rain)	Mean velocity (no rain)	% Decrease by rain
Soil surface			
Standard sand	73.3125 a*	77.7938 a	5.760
Sand	64.5063 b	69.2125 b	6.800
Clay loam	68.6188 c	75.1813 c	8.730
Clay	63.0813 d	71.4813 d	11.751
Flow rate (l/min)			
1.0	44.1313 a	46.4688 a	5.030
1.6	62.8438 b	67.1063 b	6.352
2.2	76.6063 c	85.9688 c	10.891
2.8	88.5750 d	94.1250 d	5.896
Slope (%)			
3.5	47.0875 a	55.0250 a	14.425
7.0	57.6625 b	63.7125 b	9.496
10.5	69.5250 c	72.4313 c	4.012
14.0	96.2438 d	102.4999 d	6.104

* The differences between values followed by dissimilar letters are significant.

LSD at 5% = 2.4549 for soil, discharge and slope means)
) flow with rain
LSD at 1% = 3.2264 for soil, discharge and slope means)

LSD at 5% = 2.1426 for soil, discharge and slope means)
) flow without rain
LSD at 1% = 2.8160 for soil, discharge and slope means)

raindrop impact effects have been reported by Yoon and Wenzel (1971), Shen and Li (1973), Glass and Smerdon (1967) and Smerdon (1964).

Flow velocity for the transport tests (Table 72) averaged 70.10, 84.28, 98.48 and 108.30 for the 1.0, 1.6, 2.2 and 2.8 l/min flows respectively. For the 3.5, 7.0, 10.5 and 14 per cent slopes, the values were 62.13, 74.08, 97.70, and 127.25 with the mean velocity for the single soil plate being 90.29. A comparison of these velocities with those for detachment tests on standard sand showed that the addition of 1.0 l/min baseflow to the flow with rain generally increased velocity by 23 per cent from 73.3 to 90.29. This is not surprising since all flow rates with rain were increased by the amount added as baseflow. The percentage increase was however greater at the lower than the higher flow rates being 48.75, 21.26, 17.09 and 12.20 for the 1.0, 1.6, 2.2 and 2.8 l/min flows respectively.

The importance of slope steepness, soil surface and flow rate as individual factors influencing velocity is shown by the results of an analysis of variance (Tables 16 and 17). This analysis also brings out the role of first order interactions, except discharge x soil surface. The significance of the factors ranked as discharge > slope > soil surface for flow without rain and slope > discharge > soil surface for flow with rain.

The major interaction for flow without rain was slope x discharge. This interaction showed that the velocity of a given flow increases as slope steepens with the proportionate increase being greater (34 per cent) at higher than (15 per cent) lower slopes. On the other hand velocity at each slope increased with increasing discharge. The proportionate increase however declined as discharge increased.

Flow velocity for each soil surface also increased with increasing slope steepness as a result of the significant slope x surface interaction. The increase was gradual, averaging 15 per cent as slope steepness increased from 3.5 through 7.0 to 10.5 per cent.

Thereafter a rapid increase in velocity (41 per cent) occurred as slope further increased to 14 per cent.

Similar observations were made for flow with rain. However in this case, the interactions ranked as slope x soil surface $>$ slope x discharge.

Through multiple regression analysis relationships were established between flow velocity as measured in this experiment, discharge per unit width and slope steepness. The power equations are presented in Tables 19 and 20.

The exponents relating velocity to discharge and slope for flow with rain ranged from 0.60 - 0.73 and 0.33 - 0.76 respectively. The corresponding values for flow without rain are 0.69 - 0.75 and 0.32 - 0.52. The equation obtained for all soils gave a mean value of 0.71 for the discharge exponent and 0.40 for slope, the higher exponent values being generally associated with the clay and clay loam surfaces. The slope and discharge exponents for the transport tests were also within these ranges presented above.

Compared to values reported by other workers (Table 21) the exponents for all soils are very close to those obtained by Lutz and Hargrove (1944) for shallow flows. The discharge exponents are greater than those obtained by Meyer (1965, 1975) and Savat (1980) on the assumption of turbulent flow. The slope exponent for the sand and standard sand surfaces is however the same as the 0.33 reported by the latter authors. The values for the clay and clay loam surfaces on the other hand were higher but lower than the laminar flow value of 1.0 suggested by Savat (1977).

In the presence of rain slope steepness explained a greater percentage (56 - 69) of the variations on the clay and clay loam surfaces. However, for flows without rain and for the sand surfaces in general, discharge accounted for a greater percentage (50 - 66) as indicated earlier by the analysis of variance. When the two factors were combined, the coefficient of determination (R^2) was significantly improved with a range between 0.91 and 0.98 for the various surfaces and 0.88 for the general relationship for all soils.

TABLE 19 Power equations relating flow velocity (V; m s^{-1}) to discharge (q; m^3 s^{-1} m^{-1}) and slope (S; sin S) for overland flow with rain. n = 16 for each soil

Soil-plate (detachment tests)	Equation	r^2	R^2	SEE	Eq. No
Standard sand	$V = e^{4.11} q^{0.68}$	0.61		1.24	69
	$V = e^{-1.71} S^{0.36}$	0.31		1.33	70
	$V = e^{5.04} q^{0.68} S^{0.36}$	-	0.92	1.14	71
Sand	$V = e^{3.19} q^{0.60}$	0.62		1.20	72
	$V = e^{-1.90} S^{0.33}$	0.30		1.33	73
	$V = e^{4.05} q^{0.60} S^{0.33}$	-	0.92	1.13	74
Clay loam	$V = e^{3.87} q^{0.67}$	0.36		1.41	75
	$V = e^{-1.20} S^{0.62}$	0.56		1.33	76
	$V = e^{5.45} q^{0.67} S^{0.62}$	-	0.92	1.13	77
Clay	$V = e^{4.35} q^{0.73}$	0.38		1.43	78
	$V = e^{-1.17} S^{0.66}$	0.57		1.35	79
	$V = e^{6.03} q^{0.73} S^{0.66}$	-	0.95	1.11	80

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TABLE 19 continued

Soil-plate (detachment tests)	Equation	r^2	R^2	SEE	Eq. No
All soils (n = 64)	$V = e^{4.08}\ q^{0.70}$	0.48		1.51	81
	$V = e^{-1.66}\ S^{0.45}$	0.23		1.53	82
	$V = e^{5.24}\ q^{0.70}\ S^{0.45}$	-	0.71	1.40	83
Soil plate for transport tests					
Standard sand	$V = e^{3.98}\ q^{0.67}$	0.35		1.25	84
	$V = e^{-0.60}\ S^{0.76}$	0.63		1.18	85
	$V = e^{5.75}\ q^{0.67}\ S^{0.76}$	-	0.98	1.04	86

TABLE 20 Power equations relating flow velocity (V; m s^{-1}) to discharge (q; m^3 s^{-1} m^{-1}) and slope (S; Sin S) for overland flow without rain. n = 16 for each soil

Soil-plate (detachment tests)	Equation	r^2	R^2	SEE	Eq. No
Standard sand	$V = e^{4.46}\ q^{0.71}$	0.66		1.22	87
	$V = e^{-1.77}\ S^{0.32}$	0.25		1.34	88
	$V = e^{5.22}\ q^{0.71}\ S^{0.32}$	-	0.91	1.11	89
Sand	$V = e^{4.15}\ q^{0.69}$	0.66		1.20	90
	$V = e^{-1.90}\ S^{0.32}$	0.26		1.33	91
	$V = e^{5.32}\ q^{0.69}\ S^{0.32}$	-	0.92	1.09	92
Clay loam	$V = e^{4.32}\ q^{0.70}$	0.50		1.31	93
	$V = e^{-1.47}\ S^{0.47}$	0.41		1.35	94
	$V = e^{5.88}\ q^{0.70}\ S^{0.47}$	-	0.91	1.13	95
Clay	$V = e^{4.74}\ q^{0.75}$	0.50		1.34	96
	$V = e^{-1.39}\ S^{0.52}$	0.44		1.37	97
	$V = e^{6.08}\ q^{0.75}\ S^{0.52}$	-	0.94	1.11	98
All soils (n = 64)	$V = e^{4.37}\ q^{0.71}$	0.56		1.28	99
	$V = e^{-1.66}\ S^{0.40}$	0.32		1.36	100
	$V = e^{5.47}\ q^{0.71}\ S^{0.40}$	-	0.88	1.14	101

TABLE 21 **Values for m and n in the relationship between flow velocity (V), discharge (Q) and slope (S) in the form $V \propto S^m Q^n$**

m	n	Sources	Remarks
0.33 - 0.66 (0.50)	0.60 - 0.73 (0.67)	(1)	Flow with rain
0.32 - 0.52 (0.42)	0.69 - 0.75 (0.72)	(1)	Flow without rain
0.76	0.67	(1)	Baseflow plus flow with rain
0.30	0.40	(2)	From continuity and Manning's equation and assuming turbulent flow, Meyer obtained for shallow infinitely wide channels, wide shallow parabolic channels, wide shallow triangular channels, for constant hydraulic roughness, rills on a 6 per cent slope exposed to raindrop impact at 6.4 cm h^{-1}.
0.35	0.31	(2)	
0.38	0.25	(2)	
0.33	0.33	(2)	
-	0.32	(2)	
0.333	0.417	(3)	Combining 3 equations - Nikurdase, Strickler and Manning for turbulent flow when
0.50	-	(3)	Re = 1000
0.80	-	(3)	Re = 500
1.00	-	(3)	Re = 250
0.369	0.659	(4)	Shallow flow in 26.25 cm wide concrete channel.

(1) Study; (2) After Meyer, 1965;1975 (3) Savat, 1977; (4) Lutz and Hargrove, 1944.

The significance of flow velocity in erosion studies is seen in its use as a criterion for the initiation of erosion. According to the graphs of Hjulström (1935) a flow of at least 200 mm s^{-1} will be required to entrain particles of the sizes found in the soils used in this study (Table 3). The lower flow velocities recorded in this study would not therefore be expected to erode the test soils. Nevertheless it is shown in Chapter 6 that rills can develop even at these low velocities.

Values of flow velocity are also important to the design of earth channels for runoff disposal and distribution of water for irrigation purposes. Velocities should be low enough to prevent scour but high enough to prevent sedimentation (Schwab et al. 1966). Whilst no definite optimum velocity can be prescribed, maximum permissible mean velocities based on the work of Fortier and Scobey (1926) are available from various sources (Schwab et al. 1966; Withers and Vipond, 1974). An average velocity of 600 - 900 mm s^{-1} is often sufficient to prevent sedimentation in shallow channels.

These average values and those listed in Table 22 for maximum permissible velocities are several orders of magnitude greater than those obtained in this study. Considering that the low velocity flows used in this study caused significant erosion (Chapter 6) there is a need for better guidelines for the selection of design velocities.

TABLE 22 Values of flow velocity from various sources

Flow velocity ($mm\ s^{-1}$)	Source	Remarks
		Using bare sand, clay loam and clay in flume studies with 50 - 140 mm h^{-1} flow with and without rain and 3.5 - 14 per cent slope the following mean velocities were obtained:
		bare soil and no rain
77.79	(1)	fine sand
69.21	(1)	sand
75.18	(1)	clay loam
71.48	(1)	clay
		bare soil with rain
73.31	(1)	fine sand
64.51	(1)	sand
68.62	(1)	clay loam
63.08	(1)	clay
46 - 94	(1)	1 - 2.8 l/min flow, no rain
44 - 88	(1)	1 - 2.8 l/min flow, with rain
55 - 102	(1)	3.5 - 14 per cent slope, no rain
47 - 96	(1)	3.5 - 14 per cent slope, with rain
46.20	(2)	Smooth bare clay loam in 14.25 m soil bin at 2.5 per cent slope with 44 mm h^{-1} simulated rain.
73.20	(2)	10 per cent slope
62.40	(2)	2.5 per cent slope and 88 mm h^{-1} simulated rain
41 - 64.9	(3)	Bare sand in flume, 5.7 per cent slope and 56.25 - 115 mm h^{-1} simulated rain
61.98 - 107.2	(3)	10 per cent slope
71 - 128.3	(3)	15 per cent slope
15 - 40	(4)	Bare loamy soil, 46 mm h^{-1} simulated rain, 9 per cent slope and interrill flow

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TABLE 22 Continued

Flow velocity (mm s^{-1})	Source	Remarks
450	(5)	Limiting velocities in earth channels. fine sand
525	(5)	sandy loam
1125	(5)	stiff clay
		from Schwab et al. (1966)
500	(6)	Maximum safe velocities in channels, light loose sand
750	(6)	sandy soil
1000	(6)	firm clay loam

(1) Study; (2) After Cooper and Neal, 1942;
(3) Kilinc and Richardson, 1973; (4) Young and Wiersma, 1973;
(5) Fortier and Scobey, 1926; (6) Hudson, 1971.

5.2 DEPTH

Flow depth was measured by a depth gauge as described in Section 3.5.4. The data obtained are presented in Appendix 20 with flow depth (mm) ranging between 0.40 and 1.55. The mean values for the detachment tests (Table 25) showed the depths for flow without rain to be significantly greater on the sand and clay surfaces than the clay loam and standard sand surfaces. Since velocity for a given flow was lower on the former surfaces, this trend would be expected from continuity of mass. Flow depth also varied significantly with flow rate increasing as discharge increased to a maximum of 0.92 for the 2.8 l/min flow without rain. Depth decreased for a given flow rate as slope steepness increased due to the resultant increases in velocity.

Raindrop impact increased depth for a given flow by retarding flow velocity. The percentage increase ranged from 8 to 14 for the surfaces studied with the upper limit associated with clay and clay loam. Depth for the 2.2 and 2.8 l/min flows increased by 13 per cent compared with 9 per cent for the lower rates. The percentage increase however declined as slope steepness increased, averaging 14 per cent for the 3.5 and 7.0 per cent slopes. These percentage values (grand mean of 11) compare very well with the 17 per cent reported by Parsons (1949) but are lower than the 50 per cent obtained by Emmett (1978) on slopes ranging from 0.33 to 7.75 per cent.

The mean depth for the transport tests (Table 72) average 1.02 for the one soil plate used. While depth increased with increasing flow rate, 0.89, 0.97, 1.07 and 1.15 mm for the 1.0, 1.6, 2.2, and 2.8 l/min flows respectively, it decreased as slope steepened, 1.34, 1.15, 0.87, and 0.73 mm for the 3.5, 7.0, 10.5, and 14 per cent slopes. The values of flow depth compare very well with those reported by other workers (Table 28).

The addition of baseflow generally increased depth by 27 per cent for flow with rain. The proportionate increase was slightly greater for depth than for flow velocity.

TABLE 23 Analysis of variance of the effect of slope steepness, soil surface and flow rate on flow depth (flow without rain).

Source of Variation	Sums of Squares	Degrees of freedom	Mean Squares	F
Slope	1.9437	3	0.6479	1619.75***
Discharge	0.4272	3	0.1424	323.64***
Slope x Discharge	0.0118	9	0.0013	2.95**
Soil surface	0.1257	3	0.0419	95.23***
Slope x Soil surface	0.0987	9	0.0110	25.00***
Discharge x Soil surface	0.0047	9	0.0005	1.14 NS
Slope x Discharge x Soil surface	0.0119	27	0.00044	
Total	2.6237	63		

*** significant at 0.1%

NS not significant at 5%

** significant at 1%

TABLE 24 Analysis of variance of the effect of slope steepness, soil surface and flow rate on flow depth (flow with rain).

Source of variation	Sums of Squares	Degrees of freedom	Mean Squares	F
Slope	3.1971	3	1.0657	710.47***
Discharge	0.7190	3	0.2397	159.80***
Slope x Discharge	0.0515	9	0.0057	3.80**
Soil surface	0.2672	3	0.0891	59.40***
Slope x Soil surface	0.3711	9	0.0412	27.47***
Discharge x Soil surface	0.0164	9	0.0018	1.20 NS
Slope x Discharge x Soil surface	0.0404	27	0.0015	
Total	4.6627	63		

*** significant at 0.1%

** significant at 1%

NS not significant at 5%

TABLE 25 The effect of soil surface, slope steepness and flow rate on flow depth (mm)

Factor level	Mean depth (flow with rain)	Mean depth (no rain)	% Increase by rain
Soil surface			
Standard sand	0.8031 a*	0.7400 a	8.527
Sand	0.8950 b	0.8256 b	8.402
Clay loam	0.9025 c	0.7944 c	13.608
Clay	0.9856 d	0.8606 d	14.525
Flow rate (l/min)			
1.0	0.7638 a	0.7031 a	8.633
1.6	0.8313 b	0.7575 b	9.743
2.2	0.9544 c	0.8425 c	13.282
2.8	1.0369 d	0.9175 d	13.014
Slope (%)			
3.5	1.2000 a	1.0200 a	17.647
7.0	0.9775 b	0.8800 b	11.080
10.5	0.8213 c	0.7781 c	5.552
14.0	0.5875 d	0.5425 d	8.295

* The differences between values followed by dissimilar letters are significant at 1% level.

LSD at 5% = 0.0268 for soil, discharge and slope means)
) flow with rain
LSD at 1% = 0.0353 for soil, discharge and slope means)

LSD at 5% = 0.0145 for soil, discharge and slope means)
) flow without rain
LSD at 1% = 0.0191 for soil, discharge and slope means)

The relative importance of the factors influencing flow depth is shown by the analysis of variance (Tables 23 and 24). The most significant of these is slope steepness which is followed by discharge and then by soil surface. Flow depth is further affected by slope x soil surface and slope x discharge interactions with the former being the most significant.

The slope x soil surface interaction showed depth for each surface to decrease as slope steepened. However the effect of each slope on depth varied significantly among the surfaces investigated. For example, while depth at 3.5 per cent slope for flow without rain ranked as clay > clay loam > sand > standard sand, at 14 per cent slope it was sand > clay > standard sand > clay loam. These variations are obscured when only main effects are investigated.

Power equations (Tables 26, 27) were established between discharge, slope steepness and flow depth in order to compare the exponents of the former two factors with theoretical values (Eq. 16) as well as those obtained by other workers. The exponents for discharge ranged from 0.25 to 0.34 and 0.25 to 0.37 for flow with and without rain respectively; and 0.42 for the transport tests. These values are comparable to the 0.27 - 0.37 and 0.36 to 0.43 obtained by Emmett (1970, 1978) for laminar flow over smooth and roughened surfaces respectively. The mean for flow without rain (0.27) was 18 per cent lower than the theoretical value of 0.33 (Eq. 16) while that for flow with rain (0.31) was 6 per cent lower.

The slope exponent varied between -0.31 and -0.66 for flow with rain and -0.33 and -0.49 for flow without rain. The corresponding means for the above range of values were -0.47 and -0.41.

Slope steepness was thus negatively correlated with flow depth and in combination with discharge, the two factors accounted for 77 to 98 per cent of the variations in depth.

TABLE 26 **Power equations relating flow depth (D; m) to discharge (q; $m^3\ s^{-1}\ m^{-1}$) and slope (S; sin S) for overland with rain**

Soil-plate (detachment tests)	Equation	r^2	R^2	SEE	Eq. No
Standard sand	$D = e^{-3.79}\ q^{0.34}$	0.28	-	1.28	102
	$D = e^{-8.06}\ S^{-0.35}$	0.55	-	1.18	103
	$D = e^{-4.69}\ q^{0.34}\ S^{-0.35}$	-	0.83	1.11	104
Sand	$D = e^{-3.69}\ q^{0.34}$	0.35	-	1.20	105
	$D = e^{-7.84}\ S^{-0.31}$	0.54	-	1.16	106
	$D = e^{-4.49}\ q^{0.34}\ S^{-0.31}$	-	0.89	1.08	107
Clay loam	$D = e^{-4.06}\ q^{0.30}$	0.11	-	1.40	108
	$D = e^{-8.58}\ S^{-0.59}$	0.78	-	1.18	109
	$D = e^{-5.58}\ q^{0.30}\ S^{-0.59}$	-	0.89	1.08	110
Clay	$D = e^{-4.46}\ q^{0.25}$	0.07	-	1.42	111
	$D = e^{-8.62}\ S^{-0.64}$	0.85	-	1.15	112
	$D = e^{-5.18}\ q^{0.25}\ S^{-0.64}$	-	0.92	1.11	113

/...

TABLE 26 Continued

Soil-plate (detachment tests)	Equation	r^2	R^2	SEE	Eq. No
All soils (n = 64)	$D = e^{-3.96} q^{0.31}$	0.15	-	1.33	114
	$D = e^{-8.28} S^{-0.47}$	0.64	-	1.20	115
	$D = e^{-5.18} q^{0.31} S^{-0.47}$	-	0.79	1.15	116
Soil-plate for sediment transport					
	$D = e^{-3.10} q^{0.42}$	0.21	-	1.22	117
Standard sand	$D = e^{-8.52} S^{-0.66}$	0.77	-	1.11	118
	$D = e^{-8.11} q^{0.42} S^{-0.66}$	-	0.98	1.03	119

* n = 16 for each soil.

TABLE 27 Power equations relating flow depth (D; m) to discharge (q; $m^3\ s^{-1}\ m^{-1}$) and slope (S; sin S) for overland without rain

Soil-plate (detachment tests)	Equation	r^2	R^2	SEE	Eq. No
Standard sand	$D = e^{-4.51}\ q^{0.27}$	0.21		1.23	120
	$D = e^{-8.07}\ S^{-0.33}$	0.56		1.16	121
	$D = e^{-5.21}\ q^{0.27}\ S^{-0.33}$	-	0.77	1.12	122
Sand	$D = e^{-4.35}\ q^{0.28}$	0.23		1.12	123
	$D = e^{-7.98}\ S^{-0.33}$	0.59		1.16	124
	$D = e^{-5.06}\ q^{0.28}\ S^{-0.33}$	-	0.82	1.10	125
Clay loam	$D = e^{-4.21}\ q^{0.37}$	0.13		1.30	126
	$D = e^{-7.98}\ S^{-0.33}$	0.71		1.18	127
	$D = e^{-5.06}\ q^{0.37}\ S^{-0.33}$	-	0.84	1.13	128
Clay	$D = e^{-4.66}\ q^{0.25}$	0.11		1.32	129
	$D = e^{-8.36}\ S^{-0.49}$	0.78		1.15	130
	$D = e^{-5.92}\ q^{0.25}\ S^{-0.49}$	-	0.89	1.10	131

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TABLE 27 Continued

Soil-plate (detachment tests)	Equation	r^2	R^2	SEE	Eq. No
All soils (n = 64)	$D = e^{-4.50}\, q^{0.27}$	0.15		1.28	132
	$D = e^{-8.22}\, S^{-0.41}$	0.62		1.18	133
	$D = e^{-5.61}\, q^{0.27}\, S^{-0.41}$	-	0.77	1.14	134

* n = 16 for each soil.

TABLE 28 Values of depths of overland flow

Flow depth (mm)	Source	Remarks
		Using bare sand, clay loam and clay in flume studies with 50 - 140 mm h^{-1} flow rate with and without rain and 3.5 - 14 per cent slope, the following mean depths were obtained:
0.74 - 0.86	(1)	bare soil, no rain
0.80 - 0.99	(1)	bare soil, with rain
0.70 - 0.92	(1)	flow without rain
0.76 - 1.04	(1)	flow with rain
0.54 - 1.02	(1)	14 - 3.5 per cent slope, no rain
0.59 - 1.20	(1)	14 - 3.5 per cent slope, with rain
0.98	(2)	bare clay loam, 2.5 per cent slope with 38.8 mm h^{-1} simulated rain
1.26	(2)	2.5 per cent slope, 83 mm h^{-1} rain
0.78 - 0.81	(2)	5 per cent slope, 38 - 44 mm h^{-1} rain
0.62 - 0.64	(2)	10 per cent slope, 38 - 43 mm h^{-1} rain
0.86	(3)	2.2 per cent slope, 60 mm h^{-1} simulated rain
0.58	(3)	5.4 per cent slope
0.46	(3)	12.7 per cent slope
0.08 - 0.15	(4)	Bare loamy soil, interrill flow, 46 mm h^{-1} rain and 9 per cent slope
2.26	(5)	Plate roughened with sand grains, 3.4×10^{-5} m^2 s^{-1} flow and 0.083 per cent slope
2.18	(5)	4.3×10^{-5} m^2 s^{-1} flow, 0.238 per cent slope
2.18	(5)	7.8×10^{-5} m^2 s^{-1} flow, 0.458 per cent slope
3.35	(5)	6.7×10^{-5} m^2 s^{-1} flow, 0.083 per cent slope

(1) Study; (2) After Parsons, 1949; (3) Savat, 1977; (4) Young and Wiersma, 1973; (5) Phelps, 1975.

5.3 REYNOLDS NUMBER (Re)

Using the measured values of depth and velocity, Reynolds number was calculated by Eq. 8. By recording the temperature (11 - 13°C) of flow during the experiments, it was possible to select the appropriate values of kinematic viscosity (Appendix 22).

The analysis of variance (Tables 29, 30) for the detachment tests showed discharge to be the main factor that caused variations in Reynolds number. The mean Re (Table 31) increased significantly ($P = 0.01$) as discharge increased with a range of 24.45 (1 l/min) to 65.93 (2.8 l/min). However, Reynolds number was fairly constant over the range of slopes and the different surfaces used in the tests and for flow with and without rain. Flow is laminar when Re is less than 500 and is fully turbulent at values above 2000 (Webber, 1971). On this basis, all the values in Table 31 along with those obtained for the transport tests (46.56 - 102.35; Table 72) suggest that the flow used in this study was laminar. Similar values (Table 32) were reported by Kilinc and Richardson (1973). For rain intensities of 31 - 115 mm h^{-1} on a sandy soil with a slope range of 5.7 to 40 per cent, the latter authors obtained Re of 0 - 130. Field studies of overland flow (Morgan, 1979) also reveal Re values between 1.0 and 50 on Cottenham sand.

When Re was expressed as a function of discharge using all the data for flow without rain, an exponent of 0.98 was obtained for discharge as indicated by the equation below:

$$Re = e^{13.46} \; q^{0.98} \quad (r^2 = 0.99) \qquad \text{Eq. 135}$$

Because of the links between slope and soil surface on the one hand and velocity and depth on the other and since $q = V\,d$ for overland flow, the high control by q is expected.

TABLE 29 Analysis of variance of the effect of slope steepness, soil surface and flow rate on Reynolds number (flow without rain)

Source of Variation	Sums of Squares	Degrees of freedom	Mean Squares	F
Slope	18.7872	3	6.2624	2.13 NS
Discharge	15412.0200	3	5137.3420	1749.73 ***
Slope x Discharge	18.2654	9	2.0295	0.69 NS
Soil surface	57.4794	3	19.1598	6.53 **
Slope x Soil surface	93.7798	9	10.4200	3.55 **
Discharge x Soil surface	23.7838	9	2.6426	0.900 NS
Slope x Discharge x Soil surface	79.2738	27	2.9361	
Total	15703.3894	63		

** significant at 1%

*** significant at 0.1%

NS not significant at 5%

TABLE 30 Analysis of variance of the effect of slope steepness, soil surface and flow rate on Reynolds number (flow with rain)

Source of Variation	Sums of Squares	Degrees of freedom	Mean Squares	F
Slope	18.8224	3	6.2741	3.51 *
Discharge	15768.0700	3	5256.0250	2940.25 ***
Slope x Discharge	44.6622	9	4.9625	2.78 NS
Soil surface	12.0305	3	4.0102	2.24 NS
Slope x Soil surface	52.6229	9	5.8470	3.27 **
Discharge x Soil surface	31.8551	9	3.5395	1.98 NS
Slope x Discharge x Soil surface	48.2655	27	1.7876	
Total	15976.3286	63		

* significant at 5%

** significant at 1%

*** significant at 0.1%

NS not significant

TABLE 31 The effect of soil surface, slope steepness and flow rate on Reynolds number

Factor level	Mean Reynolds number (flow with rain)	Mean Reynolds number (flow without rain)
Soil surface		
Standard sand	46.2638 a*	44.6644 a**
Sand	45.5650 a	44.7269 a
Clay loam	45.1150 a*	45.1944 a
Clay	45.9781 a	46.9988 b
Flow rate (l/min)		
1.0	24.4513 a	24.1819 a
1.6	38.3919 b	38.1544 b
2.2	54.1506 c	54.3375 c
2.8	65.9282 d	64.9106 d
Slope (%)		
3.5	45.2325 a	45.5306 a
7.0	46.2438 b	45.8594 a
10.5	45.1463 a	44.5013 b
14.0	46.2994 b	45.7931 a

** The difference between values followed by dissimilar letters are significant

* Differences are significant at 5%

LSD at 5% = 0.9265 for soil, discharge and slope means)
) flow with rain
LSD at 1% = 1.2177 for soil, discharge and slope means)

LSD at 5% = 1.1874 for soil, discharge and slope means)
) flow without rain
LSD at 1% = 1.5606 for soil, discharge and slope means)

TABLE 32 Values of Reynolds number for overland flow

Reynolds number	Source	Remarks
		Using bare sand, clay loam and clay in flume studies with 50 - 140 mm h^{-1} flow rate with and without rain and 3.5 - 14 per cent slope, the following mean values of Reynolds number were obtained:
45	(1)	bare soil with 3.5 - 14 per cent slope
24 - 65	(1)	flow with and without rain
18 - 43.4	(2)	Bare sand in flume, 5.7 per cent slope and 56.25 - 115 mm h^{-1} simulated rain
19.6 - 44.7	(2)	10 per cent slope
19.4 - 49	(2)	15 per cent slope
131	(3)	Bare clay loam, 2.5 per cent slope with 38.8 mm h^{-1} simulated rain
280	(3)	Bare clay loam, 2.5 per cent slope with 2.5 per cent slope, 83 mm h^{-1} rain
131 - 149	(3)	5 per cent slope, 38 - 44 mm h^{-1} rain
129 - 147	(3)	10 per cent slope, 38 - 43 mm h^{-1} rain
1.0 - 50	(4)	Overland flow on bare sand in the field
1.0 - 40	(5)	Overland flow on bare sandy silts in the field
36	(6)	Plate roughened with sand grains, 3.4 x 10^{-5} m^2 s^{-1} flow, 0.083 per cent slope
46	(6)	4.3 x 10^{-5} m^2 s^{-1} flow, 0.238 per cent slope
75	(6)	6.7 x 10^{-5} m^2 s^{-1} flow, 0.083 per cent slope
85	(6)	7.8 x 10^{-5} m^2 s^{-1} flow, 0.46 per cent slope

(1) Study; (2) After Kilinc and Richardson, 1973;
(3) Parsons, 1949; (4) Morgan, 1979; (5) Pearce, 1976; (6) Phelps, 1975.

5.4 FROUDE NUMBER (F)

Froude numbers (Appendix 28), calculated by Eq. 9 using the measured values of velocity and depth, varied from 0.18 - 1.82 and 0.32 - 1.79 for overland flow with and without rain respectively.

The mean values of Froude number for the detachment tests (Table 35) increased as flow rate increased. This implies that the increases in velocity with discharge are more important than the increases in depth. However apart from the 2.8 l/min flow without rain which was supercritical (1.04), the values of the remaining flows were all in the subcritical range. The mean values for the slopes showed that the supercritical regime was associated with only the 14 per cent slope. When the values of Froude number were averaged over slope steepness and discharge, the resulting means showed flow to be subcritical with a range of 0.70 - 0.86 and 0.79 - 0.94 for flow with and without rain.

Values of F reported for overland flow (Table 38) shows that in the field these range between 0.01 and 0.1 (Morgan, 1979) 0.05 and 0.20 (Emmett, 1970, 1978) and 0.05 and 0.9 (Pearce, 1976). These limited studies suggest that overland flow in the field is largely subcritical and that the simulated flow used in this study approximates to field conditions even though its F values are slightly higher.

However, the values obtained for the transport tests (Table 72) were, apart from those for the lowest flow rate (1 l/min), in the supercritical range for both the 10.5 and 14.0 per cent slopes. With F as high as 15, Savat (1977) finds most overland flow to be supercritical. Kilinc and Richardson (1973) made a similar observation in their flume studies with values ranging from 0.50 to 5.4. However, while the F values for the transport tests were equally split between supercritical and subcritical regimes, most of the values for the detachment tests belonged to the latter.

As shown by the development of rills in the detachment tests (Chapter 6) erosion by overland flow takes place with both

TABLE 33 Analysis of variance of the effect of slope steepness, soil surface and flow rate on Froude number (F) (flow without rain)

Source of variation	Sums of Squares	Degrees of freedom	Mean Squares	F
Slope	6.6920	3	2.2307	1239.28 ***
Discharge	1.9605	3	0.6535	363.06 ***
Slope x Discharge	0.1978	9	0.0220	12.22 ***
Soil surface	0.2288	3	0.0763	42.39 ***
Slope x Soil surface	0.2685	9	0.0298	16.55 ***
Discharge x Soil surface	0.0236	9	0.0026	1.44 NS
Slope x Discharge x Soil surface	0.0476	27	0.0018	
Total	9.4188	63		

*** significant at 0.1%

NS not significant

TABLE 34 Analysis of variance of the effect of slope steepness, soil surface and flow rate on Froude number (flow with rain)

Source of variation	Sums of Squares	Degrees of freedom	Mean Squares	F
Slope	6.2603	3	2.0868	564.00 ***
Discharge	1.2248	3	0.4083	110.35 ***
Slope x Discharge	0.2387	9	0.0265	7.16 **
Soil surface	0.2944	3	0.0981	26.51 ***
Slope x Soil surface	0.4594	9	0.0511	13.81 ***
Discharge x Soil surface	0.0361	9	0.0040	1.08 NS
Slope x Discharge x Soil surface	0.0989	27	0.0037	
Total	8.6136	63		

** significant at 1%

*** significant at 0.1%

NS not significant at 5%

TABLE 35 The effect of soil surface, slope steepness and flow rate on Froude number

Factor level	Mean Froude number (flow with rain)	Mean Froude number (flow without rain)	% Decrease by rain
Soil surface			
Standard sand	0.8644 a*	0.9381 a	7.856
Sand	0.7025 b	0.7881 b	10.862
Clay loam	0.7931 c	0.9019 c	12.063
Clay	0.7031 b	0.8238 d	14.652
Flow rate (l/min)			
1.0	0.5531 a	0.5963 a	7.245
1.6	0.7438 b	0.8188 b	9.160
2.2	0.8425 c	0.9950 c	15.327
2.8	0.9238 d	1.0419 d	11.335
Slope (%)			
3.5	0.4388 a	0.5487 a	20.029
7.0	0.5888 b	0.6813 b	13.577
10.5	0.7669 c	0.8250 c	7.042
14.0	1.2688 d	1.3969 d	9.170

* The differences between values followed by dissimilar letters are significant at 1%

LSD at 5% = 0.0422 for soil, discharge and slope means)
) flow with rain
LSD at 1% = 0.0554 for soil, discharge and slope means)

LSD at 5% = 0.0294 for soil, discharge and slope means)
) flow without rain
LSD at 1% = 0.0386 for soil, discharge and slope means)

subcritical and supercritical flow.

The critical Froude number of flow beyond which appreciable number of rills were formed was 0.55 for standard sand and sand and 0.68 for clay and clay loam. These figures are lower than those expected from the critical Froude number (Fr_c) expression

$$Fr_c > 1 + 0.0035\, D \qquad \text{Eq. 136a}$$

(in which D is median grain size in microns)
proposed by Boon and Savat (1981) for predicting rill formation.

In all cases rainfall reduced Froude number. Considering that F was calculated from flow depth and velocity, this is not surprising since, as reported earlier, rainfall retarded flow velocity with a resulting increase in depth.

The most important factor influencing Froude number is shown by the analysis of variance (Tables 33 and 34) to be slope steepness. Next in importance is discharge, and then soil surface. Froude number is also significantly affected by slope x soil surface and slope x discharge interactions. Compared to the main effects, these interactions are relatively small.

Nevertheless, the soil surface x slope interaction showed that the effect of soil surface on Froude number is enhanced as slope steepness increases. The proportionate increase was gradual for the slope range of 3.5 to 10.5 per cent, averaging 23 per cent. However, as flow changed from subcritical to supercritical (10.5 - 14 per cent slopes), the rate of increase in F became rapid, reaching a mean of 69 per cent.

The slope x discharge interaction further showed the effect of slope steepness on F to increase with increasing discharge. The proportionate increase was however greater at the lower flow rates. On the other hand, the influence of discharge became greater as slope steepened with the proportionate increase being more at the higher slopes.

Power equations relating F to discharge and slope steepness are presented in Tables 36 and 37. The exponents range from 0.43 - 0.63 and 0.48 - 1.09 for discharge and slope respectively. These exponents varied for the different surfaces but were generally greater for the clay and clay loam. As indicated earlier by the analysis of variance, a greater proportion of the variations in F was due to slope steepness.

TABLE 36 Power equations relating Froude number (F) to discharge (q; $m^3\ s^{-1}\ m^{-1}$), slope (S; sin S) for overland flow with rain

Soil-plate	Equation	r_1^2	r_2^2	R^2	SEE	Eq. No.
Standard sand	$F = e^{4.86}\ q^{0.51}$	0.28			1.38	136b
	$F = e^{1.16}\ S^{0.54}$	0.57			1.28	137
	$F = e^{6.25}\ q^{0.51}\ S^{0.54}$	0.28	0.57	0.85	1.16	138
Sand	$F = e^{3.89}\ q^{0.43}$	0.28			1.31	139
	$F = e^{0.85}\ S^{0.49}$	0.65			1.21	140
	$F = e^{5.15}\ q^{0.43}\ S^{0.49}$	0.28	0.65	0.93	1.09	141
Clay loam	$F = e^{4.78}\ q^{0.52}$	0.14			1.67	142
	$F = e^{1.97}\ S^{0.92}$	0.76			1.31	143
	$F = e^{7.12}\ q^{0.52}\ S^{0.92}$	0.14	0.76	0.90	1.19	144
Clay	$F = e^{5.44}\ q^{0.60}$	0.16			1.70	145
	$F = e^{1.99}\ S^{0.98}$	0.77			1.32	146
	$F = e^{7.94}\ q^{0.60}\ S^{0.98}$	0.16	0.77	0.93	1.16	147

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TABLE 36 continued

Soil-plate	Equation	r_1^2	r_2^2	R^2	SEE	Eq. No
All soils (n = 64)						
	$F = e^{4.74} q^{0.52}$	0.17			1.55	148
	$F = e^{1.49} S^{0.73}$	0.53			1.34	149
	$F = e^{6.61} q^{0.52} S^{0.79}$	0.17	0.53	0.70	1.24	150

TABLE 37 **Power equations relating Froude number (F) to discharge (q; $m^3\ s^{-1}\ m^{-1}$), slope (S; sin S), for overland flow without rain**

Soil-plate	Equation	r_1^2	r_2^2	R^2	SEE	Eq. No.
Standard sand	$F = e^{5.58}\ q^{0.58}$	0.35			1.35	151
	$F = e^{1.11}\ S^{0.48}$	0.46			1.32	152
	$F = e^{6.82}\ q^{0.58}\ S^{0.48}$	0.35	0.46	0.82		153
Sand	$F = e^{4.70}\ q^{0.50}$	0.34				154
	$F = e^{0.91}\ S^{0.45}$	0.48				155
	$F = e^{5.88}\ q^{0.50}\ S^{0.45}$	0.34	0.48	0.82		156
Clay loam	$F = e^{5.37}\ q^{0.56}$	0.22			1.51	157
	$F = e^{1.60}\ S^{0.71}$	0.64			1.32	158
	$F = e^{7.75}\ q^{0.56}\ S^{0.71}$	0.22	0.64	0.84		159
Clay	$F = e^{5.93}\ q^{0.63}$	0.24			1.54	160
	$F = e^{1.65}\ S^{0.77}$	0.66			1.33	161
	$F = e^{7.90}\ q^{0.63}\ S^{0.77}$	0.24	0.66	0.90	1.16	162

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TABLE 37 Continued

Soil-plate	Equation	r_1^2	r_2^2	R^2	SEE	Eq. No
All soils (n = 64)						
	$F = e^{5.48}\ q^{0.58}$	0.27			1.44	163
	$F = e^{1.33}\ S^{0.61}$	0.53			1.34	164
	$F = e^{7.14}\ q^{0.58}\ S^{0.61}$	0.27	0.53	0.80	1.21	165
Soil-plate for transport tests						
	$F = e^{4.39}\ q^{0.46}$	0.11			1.38	166
	$F = e^{1.53}\ S^{1.09}$	0.87			1.13	167
	$F = e^{6.92}\ q^{0.46}\ S^{1.09}$	0.11	0.87	0.98	1.04	168

TABLE 38 Values of Froude number for overland flow

Froude number	Source	Remarks
		Mean values for bare soil with 50 - 140 mm h^{-1} flow rate with and without rain and 3.5 - 14 per cent slopes are given below for study:
0.82 - 0.94	(1)	bare soil, no rain
0.70 - 0.86	(1)	bare soil, with rain
0.60 - 1.04	(1)	flow without rain
0.55 - 0.92	(1)	flow with rain
0.55 - 1.40	(1)	3.5 - 14 per cent slope, no rain
0.44 - 1.27	(1)	3.5 - 14 per cent slope, with rain
0.01 - 0.10	(2)	Overland flow on bare sand in the field
0.05 - 0.09	(3)	Overland flow on bare sandy silts in the field, 2 m^2 plot area
0.05 - 0.2	(4)	Field studies of overland flow
1.08 - 1.40	(5)	Bare sand in flume with 5.7 per cent slope and 56.25 - 115 mm h^{-1} simulated rain
1.18 - 1.77	(5)	10 per cent slope
1.44 - 2.31	(5)	15 per cent slope
1 - 15	(6)	Laboratory studies of overland flow 60 mm h^{-1} simulated rain

(1) Study; (2) Morgan, 1979; (3) Pearce, 1976;
(4) Emmett, 1970; (5) Kilinc and Richardson, 1973; (6) Savat, 1977.

5.5 FRICTION FACTOR (f)

Darcy-Weisbach's friction factor was calculated by substituting the measured values of depth and velocity in Eq. 23.

The data presented in Appendix 24 shows the friction factors for the detachment tests to vary between 0.60 and 14.88 for flow with rain and 0.62 and 5.33 for flow without rain. The range for the transport tests was 0.67 - 2.5. These values are comparable to the range 1.70 - 7.90 (flow with rain) and 0.43 - 3.86 (no rain) obtained by Kilinc and Richardson (1973) (Table 44) at a downslope distance of about 2 meters from the top end of their flume.

A consideration of the mean values (Table 41) indicated that f differed significantly for the surfaces and decreased in the order of clay > sand > clay loam > standard sand for flow without rain. Since friction factor increases with increasing surface roughness (Savat, 1980; Emmett, 1978) it can be inferred that the magnitude of the relative roughness of the soil-plates increased in the same order. This trend is confirmed in the next Section by the values of Manning's n.

The effect of increasing flow rate was to significantly reduce friction factor from 3.88 for 1 l/min to 1.2 for the 2.8 l/min flow without rain. This corresponds to a percentage reduction of 69. The increases in velocity with increasing discharge reported earlier would predict this trend.

The influence of slope steepness was however mixed for flow without rain. The friction factors for the 7 and 10.5 per cent slopes were significantly greater than those of the 3.5 and 14.0 per cent slopes. Since friction factor does not depend solely on slope steepness but also the depth of flow, such a variable response is possible especially where significant interactions as observed in this study exist between slope, discharge and soil surface.

Rainfall generally increased the friction factor. The percentage increase was greater on the clay (60 per cent) and clay loam (48 per cent) surfaces compared to the standard sand and sand

TABLE 39 Analysis of variance of the effect of slope steepness, soil surface and flow rate on Darcy-Weisbach's friction factor (flow without rain)

Source of Variation	Sums of Squares	Degrees of freedom	Mean Squares	F
Slope	20.3362	3	6.7788	150.31 ***
Discharge	72.6604	3	24.2201	537.03 ***
Slope x Discharge	7.4977	9	0.8331	18.47 ***
Soil surface	6.2543	3	2.0848	46.23
Slope x Soil surface	3.9002	9	0.4334	9.61 **
Discharge x Soil surface	2.8251	9	0.3139	6.96 **
Slope x Discharge x Soil surface	1.2179	27	0.0451	
Total	114.6918	63		

*** significant at 0.1%

** significant at 1%

TABLE 40 Analysis of variance of the effect of slope steepness, soil surface and flow rate on Darcy-Weisbach's friction factor (flow with rain)

Source of variation	Sums of Squares	Degrees of freedom	Mean Squares	F
Slope	47.0788	3	15.6929	12.86 ***
Discharge	123.3987	3	41.1329	33.70 ***
Slope x Discharge	26.8954	9	2.9884	2.45 *
Soil surface	35.8931	3	11.9644	9.80 **
Slope x Soil surface	44.2858	9	4.9207	4.03 **
Discharge x Soil surface	17.7195	9	1.9688	1.61 NS
Slope x Discharge x Soil surface	32.9511	27	1.2204	
Total	328.2224	63		

* significant at 5%

** significant at 1%

*** significant at 0.1%

NS not significant

TABLE 41 The effect of soil surface, slope steepness and flow rate on Darcy-Weisbach's friction factor (f)

Factor level	Mean f (flow with rain)	Mean f (flow without rain)	% Increase by rain
Soil surface			
Standard sand	1.9119 a*	1.6538 a	15.606
Sand	2.6388 b	2.2763 b	15.925
Clay loam	2.9394 b	1.9800 c	48.455
Clay	3.9956 d	2.4825 d	60.951
Flow rate (l/min)			
1.0	5.2063 a	3.8775 a	34.269
1.6	2.6181 b	1.9581 b	33.706
2.2	1.9538 c	1.3550 c	44.192
2.8	1.7075 c	1.2019 c	42.067
Slope (%)			
3.5	3.8131 a	2.0381 a	87.091
7.0	3.2894 a	2.5831 b	27.343
10.5	2.8831 b	2.5719 b	12.100
14.0	1.5000 c	1.1994 c	25.063

* The differences between values followed by dissimilar letters are significant

LSD at 5% = 0.7655 for soil, discharge and slope means)
) flow with rain
LSD at 1% = 1.0061 for soil, discharge and slope means)

LSD at 5% = 0.1472 for soil, discharge and slope means)
) flow without rain
LSD at 1% = 0.1934 for soil, discharge and slope means)

(both 16 per cent). On the other hand, f increased by 43 per cent for the 2.2 and 2.8 l/min flow and 34 per cent for the 1.0 and 1.6 l/min flow. Since each flow rate is equivalent to the intensity of rain applied, it is reasonable to expect the percentage increase to be similar for all intensities. This trend is evident when either the lower or higher flow rates are considered separately. However, the percentage increase was greater for higher than lower intensities.

For a constant discharge and soil surface, the increase in friction factor with rain generally declined as slope steepened with a maximum increase of 87 per cent on the 3.5 per cent slope. Similar trends in the increases of friction factor have been reported by Emmett (1970, 1978), Savat (1977), Yoon and Wenzel (1971) and Shen and Li (1973). The latter two authors show that the increase in values of the friction factor by falling rain is dependent on rainfall intensity with the higher intensities having the greater effect.

The mean friction factors for the transport tests showed that in the presence of an additional baseflow of 1 l/min, the f for flow with rain on the standard sand was reduced by 19.5 per cent from 1.91 to 1.54. Because of the increased discharge, the friction factors for all flow rates were also reduced averaging 2.07, 1.58, 1.33 and 1.18 for the 1.0, 1.6, 2.2 and 2.8 l/min flow.

The significance of soil surface, slope steepness, flow rate and their first order interactions in influencing friction factor is shown by the analysis of variance (Tables 39 and 40). The individual effects of the factors ranked as discharge $>$ slope steepness $>$ soil surface. The most important interaction for flow without rain was slope x discharge. Although significant, the slope x soil surface and discharge x soil surface interactions were relatively small. The relative significance of the interactions were even smaller in the case of flow with rain.

Relationships established between friction factor, discharge, Reynolds number and Froude number are presented in Tables 42 and 43.

TABLE 42 Power equations relating friction factor(f) to discharge ($m^3\ s^{-1}\ m^{-1}$), Reynolds number (Re) and Froude number (F) for overland flow without rain

Soil-plate	Equation	r^2	SEE	Eq. No
Standard sand	$f = e^{-11.65}\ q^{-1.15}$	0.66	1.37	169
	$f = e^{4.81}\ Re^{-1.19}$	0.70	1.35	170
	$f = e^{0.22}\ F^{-1.02}$	0.49	1.48	171
Sand	$f = e^{-10.85}\ q^{-1.11}$	0.72	1.30	172
	$f = e^{4.84}\ Re^{-1.11}$	0.70	1.32	173
	$f = e^{0.25}\ F^{-1.03}$	0.47	1.55	174
Clay loam	$f = e^{-11.20}\ q^{-1.12}$	0.53	1.50	175
	$f = e^{4.63}\ Re^{-1.10}$	0.50	1.52	176
	$f = e^{0.28}\ F^{-1.08}$	0.71	1.38	177
Clay	$f = e^{-11.78}\ q^{-1.26}$	0.60	1.50	178
	$f = e^{5.72}\ Re^{-1.32}$	0.67	1.44	179
	$f = e^{0.36}\ F^{-1.12}$	0.76	1.36	180
All soils	$f = e^{-10.88}\ q^{-1.15}$	0.58	1.46	181
	$f = e^{4.95}\ Re^{-1.17}$	0.58	1.46	182
	$f = e^{0.31}\ F^{-1.08}$	0.63	1.42	183

TABLE 43 Power equations relating friction factor (f) to discharge ($m^3\ s^{-1}\ m^{-1}$), Reynolds number (Re), and Froude number (F) for overland flow with rain

Soil-plate	Equation	r^2	SEE	Eq. No
Standard sand				
	$f = e^{-9.64}\ q^{-1.03}$	0.65	1.34	184
	$f = e^{4.33}\ Re^{-1.01}$	0.66	1.33	185
	$f = e^{0.32}\ F^{-0.93}$	0.50	1.42	186
Sand				
	$f = e^{-7.70}\ q^{-0.87}$	0.79	1.19	187
	$f = e^{4.17}\ Re^{-0.87}$	0.31	1.37	188
	$f = e^{0.63}\ F^{-0.66}$	0.72	1.22	189
Clay loam				
	$f = e^{-9.47}\ q^{-1.04}$	0.35	1.74	190
	$f = e^{4.90}\ Re^{-1.08}$	0.36	1.73	191
	$f = e^{0.41}\ F^{-1.15}$	0.86	1.30	192
Clay				
	$f = e^{-10.78}\ q^{-1.20}$	0.40	1.80	193
	$f = e^{5.84}\ Re^{-1.26}$	0.42	1.80	194
	$f = e^{0.50}\ F^{-1.19}$	0.88	1.29	195
All soils				
	$f = e^{-9.40}\ q^{-1.03}$	0.41	1.61	196
	$f = e^{4.82}\ Re^{-1.06}$	0.41	1.61	197
	$f = e^{0.42}\ F^{-1.12}$	0.74	1.34	198
Soil-plate for transport tests				
	$f = e^{-8.42}\ q^{-0.92}$	0.30	1.42	199
	$f = e^{4.42}\ Re^{-0.97}$	0.40	1.38	200
	$f = e^{0.34}\ F^{-1.18}$	0.94	1.11	201

Friction factor was negatively correlated with the above parameters. The inverse relationships reveal exponents ranging from -1.11 to -1.26, -1.10 to -1.32, and -1.02 to -1.12 for discharge, Reynolds number and Froude number respectively. In the presence of rain, these values are -0.87 to -1.29, -0.87 to -1.26, and -0.66 to -1.19. The exponents varied with soil surface but averaged about -1.0 as shown by the equations for all surfaces.

The values listed in Table 44 show that the parameter k in the relationship $f = k/Re$ always exceeds the theoretical value of 24 for laminar flow on smooth surfaces. The value of k increases with surface roughness. This is consistent with the observations of several workers (Savat, 1977, 1980; Phelps, 1975; Emmett, 1978). The k values ranged from 64.7 to 122.7 for the sand and standard sand and 102.5 to 343.8 for clay and clay loam. These are well within the range of typical values listed by Thornes (1980) where k varies from 30 - 120 for bare sand, and 100 - 5000 for eroded bare clay.

TABLE 44 Values of f and k in the relationship: f = k/Re for laminar overland flow

f	k	Source	Remarks
1.54 - 1.91	75.94 - 83.10	(1)	Standard sand surface, flow with rain
2.64	64.72	(1)	Sand
2.94	134.29	(1)	Clay loam
4.00	343.78	(1)	Clay
1.65	122.73	(1)	Standard sand surface, flow without rain
2.28	126.47	(1)	Sand
1.98	102.51	(1)	Clay loam
2.48	304.90	(1)	Clay
-	24 - 108	(2)	Concrete or Asphalt surface, from Thornes, 1980
-	30 - 120	(2)	Bare sand
-	90 - 400	(2)	Gravelled surface
-	100 - 5000	(2)	Eroded bare clay
5.21	-	(1)	50 mm h^{-1} flow with rain
2.62	-	(1)	80 mm h^{-1}
1.95	-	(1)	110 mm h^{-1}
1.71	-	(1)	140 mm h^{-1}
3.88	-	(1)	50 mm h^{-1} flow without rain
1.96	-	(1)	80 mm h^{-1}
1.36	-	(1)	110 mm h^{-1}
1.20	-	(1)	140 mm h^{-1}
3.00 - 3.86	-	(3)	Bare sand, 31 mm h^{-1}, flow without rain, 5.7 - 15 per cent slope
0.92 - 1.44	-	(3)	56 mm h^{-1}
0.61 - 0.86	-	(3)	91 mm h^{-1}
0.46 - 0.70	-	(3)	115 mm h^{-1}
6.00 - 7.91	-	(3)	31 mm h^{-1} flow with rain
3.62 - 3.83	-	(3)	56 mm h^{-1}
2.16 - 2.40	-	(3)	91 mm h^{-1}
1.72 - 1.95	-	(3)	115 mm h^{-1}

(1) Study; (2) Woohiser, 1975; (3) Kilinc and Richardson, 1973.

5.6 MANNING'S n

As indicated in Chapter 2, the modified version of Manning equation (Savat, 1977) for flows at low Reynolds number may be used in obtaining roughness values for overland flow. Since the Reynolds numbers for the simulated flows were all within the laminar range, n was calculated by substituting the measured values of flow velocity (m s^{-1}) and depth (m) into Eq. 23.

Manning's n for the detachment tests (Appendix 25) ranged from 0.05 - 0.21 for flow without rain and 0.05 - 0.43 for flow with rain. For transport tests, values of n varied from 0.09 - 0.17.

The mean values of Manning's n (Table 47) varied significantly for the factors studied as shown in Table 43. For flow without rain, n for the surfaces decreased in the order of clay, sand, clay loam, and standard sand. This trend shows the relative roughness of the simulated surfaces and is similar to that reported earlier for the friction factors. This is however expected since both Manning's n and friction factor are expressions of roughness.

The mean value of n for the 1 l/min flow was greater than those for the other three flow rates which did not differ significantly. The values averaged 0.10, 0.13, 0.13, 0.07, for the 3.5, 7.0, 10.5 and 14 per cent slopes respectively.

Because impacting raindrops increase flow depth by decreasing flow velocity, Manning's n which is calculated from these parameters increased under conditions of flow with rain. The grand mean increase was 33.87 per cent and was greater for the clay and clay loam surfaces, the 2.2 and 2.8 l/min flows and 3.5 and 7.0 per cent slopes.

The value of n for the soil plate used for the transport tests (Table 72) averaged 0.13. This shows an increase of 21.6 per cent over the value (0.107) obtained in the detachment tests for flow with rain on the equivalent soil plate. This suggests that the increase in depth due to the additional baseflow was more

TABLE 45 Analysis of variance of the effect of slope steepness, soil surface and flow rate on Manning's n (flow without rain)

Source of variation	Sums of Squares	Degrees of freedom	Mean Squares	F
Slope	0.0457	3	0.0152	253.33 ***
Discharge	0.0142	3	0.0047	78.33 ***
Slope x Discharge	0.0028	9	0.0003	5.00 **
Soil surface	0.0138	3	0.0046	76.67 ***
Slope x Soil surface	0.0081	9	0.0009	15.00 ***
Discharge x Soil surface	0.0010	9	0.0001	1.67 NS
Slope x Discharge x Soil surface	0.0017	27	0.00006	
Total	0.0873	63		

** significant 1%

*** significant 0.1%

NS not significant at 5%

TABLE 46 Analysis of variance of the effect of slope steepness, soil surface and flow rate on Manning's n (flow with rain)

Source of variation	Sums of Squares	Degrees of freedom	Mean Squares	F
Slope	0.0874	3	0.0291	41.57 ***
Discharge	0.0162	3	0.0054	7.71 **
Slope x Discharge	0.0136	9	0.0015	2.14 NS
Soil surface	0.0588	3	0.0196	28.00 ***
Slope x Soil surface	0.0686	9	0.0076	10.86 ***
Discharge x Soil surface	0.0077	9	0.0009	1.29 NS
Slope x Discharge x Soil surface	0.0179	27	0.0007	
Total	0.2702	63		

** significant at 1%

*** significant at 0.1%

NS not significant at 5%

TABLE 47 The effect of soil surface, slope steepness and flow rate on Manning's n

Factor level (detachment tests)	Mean n (flow with rain)	Mean n (flow without rain)	% Increase by rain
Soil surface			
Standard sand	0.1069 a*	0.0900 a	18.778
Sand	0.1456 b	0.1194 b	21.943
Clay loam	0.1481 b	0.1050 c	41.048
Clay	0.1925 c	0.1288 d	49.457
Flow rate (l/min)			
1.0	0.1756 a	0.1363 a	28.833
1.6	0.1369 b	0.1056 b	29.640
2.2	0.1381 b	0.0994 c	38.934
2.8	0.1425 b	0.1019 c	39.843
Slope (%)			
3.5	0.1756 a	0.1038 a	69.171
7.0	0.1750 a	0.1338 b	30.792
10.5	0.1569 b	0.1356 b	15.708
14.0	0.0856 c	0.0700 c	22.286

* The differences between values followed by dissimilar letters are significant.

LSD at 5% = 0.0183 for soil, discharge, and slope means)
) flow with rain
LSD at 1% = 0.0241 for soil, discharge, and slope means)

LSD at 5% = 0.0053 for soil, discharge, and slope means)
) flow without rain
LSD at 1% = 0.0070 for soil, discharge, and slope means)

important than velocity increases in influencing Manning's n.

Although, to a large extent, Manning's n and friction factors express the same phenomenon as indicated earlier, the analysis of variance (Tables 45 and 46) surprisingly shows slope steepness to be the major factor influencing the former and discharge for the latter (Section 5.5). A consideration of the exponents of depth in the equations used in deriving these roughness factors (1.7 for n compared to 1.0 for f) indicates Manning's n to be more sensitive to variations in depth. The greater control of slope steepness on flow depth (Section 5.2) is thus indirectly extended to the magnitude of Manning's n. Although significant, flow rate and soil surface did not affect n to the same extent as slope.

The effect of slope steepness on n however varies with the type of soil as a result of the significant slope x soil surface interaction. This interaction, being the most important, further shows the influence of soil surface on n to depend on slope steepness.

The choice of appropriate values for Manning's n for use in soil conservation design work has always exercised the minds of Engineers. As indicated in Chapter 2, most of the n values have been determined for channel flow and their validity for overland flow is doubtful. Because of this, and for ease of selection and comparison, the data obtained on Manning's n for overland flow are summarized for varying conditions in Table 48.

Compared to values recorded by other authors, the mean of Manning's n for conditions under rain (0.15) is 25 per cent lower than the lower range of values, 0.2 - 1.0 and 0.2 - 1.7 reported by Emmett (1970) and Morgan (1980); but 7.5 times greater than the value of 0.02 commonly used for bare soil in channel design. (Schwab et al. 1966; Hudson, 1971).

For the flow range studied Manning's n increased as flow depth increased (Table 48) apparently due to increases in the effective area of contact between the flow and roughness elements. On the other hand, n decreased with increasing flow velocity as predicted by Eq. 23.

TABLE 48 Values for Manning's n under conditions of flow with and without rain

	With rain	No rain	Source
Bare sand	0.13	0.11	(1)
Bare clay and clay loam	0.17	0.12	(1)
Bare soil	0.15	0.11	(1)
Bare soil to poor grass cover	0.20 - 1.0	-	(2)
	0.20 - 1.7	-	(3)
	0.35	-	(4)
Ploughed, harrowed field	0.049	-	(5)
Cultivated field	0.049	-	(5)
Cereals	0.075	-	(5)
Sorghum	0.04 - 0.11	-	(6)
Dense grass cover	0.21 - 0.62	-	(7)
Fair grass cover	0.31 - 0.51	-	(7)
Poor grass cover	0.25 - 0.28	-	(7)
1 - 1.6 l/min flow	0.16	0.12	(1)
2.2 - 2.8 l/min flow	0.14	0.10	(1)
3.5 - 7 per cent slope	0.18	0.12	(1)
10.5 - 14 per cent slope	0.12	0.10	(1)
Flow depth (mm)			
0.50	0.07 (88.3)*	0.08 (92.5)	(1)
0.80	0.15 (67.8)	0.13 (85.2)	(1)
1.10	0.17 (63.4)	0.11 (64.8)	(1)
1.40	0.24 (46.4)	0.13 (62.3)	(1)

(1) Study; (2) Emmett, 1970; (3) Morgan, 1980;
(4) Pearce, 1976; (5) Voetberg, 1970; (6) Petryk and Bosmajian, 1973;
(7) Ree, Wimberly and Crow, 1977.

* Flow velocity (mm s^{-1})

Because of the close association between discharge and depth and velocity which are used in calculating n; and for the greater control of slope on depth as indicated earlier, regression analysis involving n and discharge and slope steepness was avoided to prevent counting the effects of factors twice.

5.7 TRACTIVE FORCE

Tractive force was calculated from Eq.24 by substituting the measured values of flow depth. The data presented in Appendix 17 show tractive force (N m^{-2}) for the detachment tests to range from 0.47 - 1.66 and 0.46 - 1.96 for flow without and with rain respectively. The values for the transport tests (Table 72) varied from 0.72 - 2.0.

Examination of the mean values presented in Table 51a indicated that variations in soil surface caused significant differences in tractive force. The values of Manning's n showed the surfaces to rank as clay > clay loam > sand > standard sand. The values of tractive force followed the same trend with a range of 1.03 - 1.15 for flow without rain and 1.11 - 1.28 for flow with rain. Tractive force thus increased with increasing surface roughness. Since the frictional resistance exerted by these surfaces on the flowing water is equal to tractive force and increases with increasing roughness, this is not surprising.

There was also a general increase in tractive force as flow rate increased. Maximum values of 1.40 and 1.26 were recorded for the 2.8 l/min flow with rain and without rain respectively. The corresponding minimum values for the 1 l/min flow were 1.02 and 0.95. The data also showed the trend of increasing tractive force with increasing slope steepness.

It is also clear from Table 51a that rainfall increased tractive force, the increase being greater on the clay and clay loam, at the two higher flow rates and for the 3.5 and 7.0 per cent slopes. The grand percentage mean increase of 10 compares very well with the value of 15 obtained by Smerdon (1964) for shallow channel flow (30 - 120 mm depth) impacted by high rainfall intensities (312.5 - 1250 mm h^{-1}).

The mean values of tractive force for the transport tests were 1.21, 1.32, 1.46, and 1.56 for the 1.0, 1.6, 2.2, and 2.8 l/min flows; and 0.80, 1.37, 1.59, and 1.77 for the 3.5, 7.0, 10.5 and 14 per cent slopes respectively. These were generally

TABLE 49 Analysis of variance of the effect of slope steepness, soil surface and flow rate on tractive stress (without rain)

Source of Variation	Sums of Squares	Degrees of freedom	Mean Squares	F
Slope	6.1434	3	2.0478	3413.00 ***
Discharge	0.8747	3	0.2916	486.00 ***
Slope x Discharge	0.1180	9	0.0131	21.83 ***
Soil surface	0.1620	3	0.0540	90.00 ***
Slope x Soil surface	0.0866	9	0.0096	16.00 ***
Discharge x Soil surface	0.0071	9	0.0008	1.33 NS
Slope x Discharge x Soil surface	0.0168	27	0.0006	
Total	7.4086	63		

*** significant at 0.1%

NS not significant

TABLE 50 Analysis of variance of the effect of slope steepness, soil surface and flow rate on tractive stress (with rain)

Source of Variation	Sums of Squares	Degrees of freedom	Mean Squares	F
Slope	5.9303	3	1.9768	859.48 ***
Discharge	1.3627	3	0.4542	197.48 ***
Slope x Discharge	0.1442	9	0.0160	6.96 **
Soil surface	0.2732	3	0.0911	39.61 ***
Slope x Soil surface	0.3877	9	0.0431	18.74 ***
Discharge x Soil surface	0.0217	9	0.0024	1.04 NS
Slope x Discharge x Soil surface	0.0623	27	0.0023	
Total	8.1821	63		

** significant at 1%

*** significant at 0.1%

NS not significant at 5%

TABLE 51a The effect of soil surface, slope steepness and flow rate on tractive stress (τ_o; N m^{-2})

Factor level (detachment tests)	Mean τ_o (flow with rain)	Mean τ_o (no rain)	% Increase by rain
Surface roughness			
Standard sand	1.1131 a	1.0342 a	7.629
Sand	1.2550 b	1.1475 b	9.368
Clay loam	1.1819 c	1.0688 c	10.582
Clay	1.2800 d	1.1506 d	11.246
Flow rate (l/min)			
1.0	1.0213 a	0.9506 a	7.437
1.6	1.1213 b	1.0350 b	8.338
2.2	1.2894 c	1.1581 c	11.338
2.8	1.3981 d	1.2573 d	11.199
Slope (%)			
3.5	0.7225 a	0.6119 a	18.075
7.0	1.1769 b	1.0581 b	11.2277
10.5	1.4931 c	1.4038 c	6.361
14.0	1.4375 d	1.3273 d	8.303

* The differences between values followed by dissimilar letters are significant at 1%

LSD at 5% = 0.0332 for soil, discharge and slope means)
) flow with rain
LSD at 1% = 0.0437 for soil, discharge and slope means)

LSD at 5% = 0.0170 for soil, discharge and slope means)
) flow without rain
LSD at 1% = 0.0223 for soil, discharge and slope means)

TABLE 51b Values of tractive force

	τ_o with rain	τ_o no rain	Source
Fine sand to fine sandy loam	1.11	1.03	(1)
	0.81	0.72	(2)
	-	1.29	(3)
Sand to sandy loam	1.26	1.15	(1)
	0.72	0.77	(2)
	-	1.77	(3)
Clay loam	1.18	1.07	(1)
Loam	1.17	1.10	(2)
Firm loam	-	3.59	(3)
Silty clay loam	1.02	0.95	(2)
Clay	1.28	1.15	(1)
Stiff clay	-	12.45	(3)
Black clay	1.17	1.10	(2)
Bare sand, 31 mm h^{-1} flow with rain, 5.7 per cent slope	0.51	-	(4)
10 per cent slope	1.06	-	(4)
15 per cent slope	1.20	-	(4)
56 mm h^{-1} flow with rain			
5.7 per cent slope	0.88	-	(4)
10 per cent slope	1.83	-	(4)
15 per cent slope	2.15	-	(4)
91 mm h^{-1} flow with rain			
5.7 per cent slope	1.15	-	(4)
10 per cent slope	2.19	-	(4)
15 per cent slope	2.46	-	(4)
115 mm h^{-1} flow with rain			
5.7 per cent slope	1.51	-	(4)
10 per cent slope	2.43	-	(4)
15 per cent slope	2.96	-	(4)
50 mm h^{-1} flow with and without rain	1.02	0.95	(1)
80	1.12	1.04	(1)
110	1.29	1.16	(1)
140	1.40	1.26	(1)

/...

TABLE 51b continued

	τ_o with rain	τ_o no rain	Source
29 mm h^{-1} rain with			
2 $cm^2\ s^{-1}$ base flow	0.58	-	(5)
3.36 $cm^2\ s^{-1}$ base flow	0.54 - 0.74	-	(5)
8.60 $cm^2\ s^{-1}$ base flow	0.680	-	(5)
3.36 $cm^2\ s^{-1}$ flow without rain	-	0.66 - 0.76	(5)
8.60 $cm^2\ s^{-1}$ flow without rain	-	0.56 - 0.68	(5)

(1) Study; (2) After Smerdon, 1964; (3) Lane, 1955;
(4) Kilinc and Richardson, 1973; (5) Foster and Huggins, 1977.

higher than the values obtained for flow with rain in the detachment tests where no baseflow was provided. With an average of 1.39, the tractive force for the transport tests was 25 per cent higher.

The analysis of variance (Tables 49 and 50) showed slope steepness to be the most important factor influencing tractive force. This is however expected considering that slope enters directly into the calculation of tractive force. The next important factor was discharge which was then followed by soil surface.

Although relatively small, the slope x discharge and slope x soil surface interaction for flow without rain showed the effect of slope steepness to vary with discharge, increasing as discharge increased. The effect of discharge on tractive force also increased as slope steepened from 3.5 to 10.5 per cent with the increase being proportionately greater at the lower slopes. After the 10.5 per cent slope there was a slight decrease in the effect of discharge on tractive force.

Power equations (Tables 52 and 53) relating tractive force to discharge, slope steepness and flow velocity were established to permit comparisons to be made with similar equations derived theoretically. The discharge and slope exponents for flow with rain averaged 0.31 and 0.54 respectively. The corresponding values for flow without rain were 0.27 and 0.61. These are comparable to the discharge and slope exponents of 0.33 and 0.67 respectively obtained by Foster and Huggins (1977) for overland flow by combining Eqs. 12, 14 and 24. The velocity exponents, ranging from 0.41 - 1.04 and 0.55 - 0.76 for flow with and without rain respectively are however lower than the value of 2 obtained for turbulent flow by combining Eqs. 17 and 24 and used by Meyer and Wischmeier (1969).

For a given flow to detach and transport soil particles its tractive force must exceed a critical value which the soil cannot withstand. These critical values are very important in evaluating stability in open channel design. Smerdon (1964) measured critical tractive force for soils ranging from fine sandy

TABLE 52 Power equations relating tractive stress ($N\ m^{-2}$) to discharge ($m^3\ s^{-1}\ m^{-1}$), slope (S; $\sin S$), and velocity ($m\ s^{-1}$) for flow with rain

Soil-plate	Equation	r^2	R^2	SEE	Eq. No.
Standard sand					
	$\tau_o = e^{3.4}\ q^{0.34}$	0.12		1.44	202
	$\tau_o = e^{1.74}\ S^{0.66}$	0.81		1.18	203
	$\tau_o = e^{2.15}\ V^{0.80}$	0.49		1.32	204
	$\tau_o = e^{5.11}\ q^{0.34}\ S^{0.66}$		0.93	1.11	205
Sand					
	$\tau_o = e^{3.51}\ q^{0.34}$	0.11		1.46	206
	$\tau_o = e^{1.96}\ S^{0.70}$	0.86		1.16	207
	$\tau_o = e^{3.06}\ V^{1.04}$	0.61		1.29	208
	$\tau_o = e^{5.31}\ q^{0.34}\ S^{0.70}$	-	0.97	1.08	209
Clay loam					
	$\tau_o = e^{3.11}\ q^{0.30}$	0.18		1.28	210
	$\tau_o = e^{1.20}\ S^{0.42}$	0.64		1.18	211
	$\tau_o = e^{1.44}\ V^{0.47}$	0.55		1.20	212
	$\tau_o = e^{4.18}\ q^{0.30}\ S^{0.42}$		0.82	1.12	213

/...

TABLE 52 Continued

Soil-plate	Equation	r^2	R^2	SEE	Eq. No.
Clay					
	$\tau_o = e^{2.74}\ 0.25$	0.17		1.25	214
	$\tau_o = e^{1.18}\ s^{0.37}$	0.67		1.15	215
	$\tau_o = e^{1.40}\ v^{0.41}$	0.62		1.16	216
	$\tau_o = e^{3.70}\ q^{0.25}\ s^{0.37}$	-	0.84	1.10	217
All soils (n = 64)					
	$\tau_o = e^{3.19}\ q^{0.31}$	0.13		1.37	218
	$\tau_o = e^{1.52}\ s^{0.54}$	0.70		1.20	219
	$\tau_o = e^{1.02}\ v^{0.31}$	0.21		1.33	220
	$\tau_o = e^{4.58}\ q^{0.31}\ s^{0.54}$		0.83	1.15	221
Soil-plate for transport tests					
	$\tau_o = e^{4.37}\ q^{0.47}$	0.47		1.11	222
	$\tau_o = e^{1.27}\ s^{0.36}$	0.49		1.11	223
	$\tau_o = e^{1.65}\ v^{0.51}$	0.91		1.05	224
	$\tau_o = e^{5.21}\ q^{0.42}\ s^{0.36}$	-	0.96	1.03	225

TABLE 53 Power equations relating tractive stress (τ_o; N m^{-2}) to discharge (q; m^3 s^{-1} m^{-1}), slope (S; sin S) and velocity (V; m s^{-1}) for flow without rain

Soil-plate	Equation	r^2	R^2	SEE	Eq. No.
Standard sand	$\tau_o = e^{2.82} q^{0.27}$	0.07		1.46	226
	$\tau_o = e^{1.73} S^{0.69}$	0.85		1.16	227
	$\tau_o = e^{1.76} V^{0.69}$	0.36		1.37	228
	$\tau_o = e^{4.59} q^{0.27} S^{0.69}$	-	0.92	1.10	229
Sand	$\tau_o = e^{2.97} q^{0.28}$	0.08		1.45	230
	$\tau_o = e^{1.81} S^{0.68}$	0.87		1.15	231
	$\tau_o = e^{2.13} V^{0.76}$	0.42		1.34	232
	$\tau_o = e^{4.71} q^{0.28} S^{0.68}$	-	0.95	1.10	233
Clay loam	$\tau_o = e^{2.85} q^{0.29}$	0.12		1.35	234
	$\tau_o = e^{1.38} S^{0.53}$	0.76		1.17	235
	$\tau_o = e^{1.56} V^{0.58}$	0.48		1.26	236
	$\tau_o = e^{4.71} q^{0.29} S^{0.53}$	-	0.88	1.12	237

/...

TABLE 53 Continued

Soil-plate	Equation	r^2	R^2	SEE	Eq. No.
Clay					
	$\tau_o = e^{2.53}\ q^{0.25}$	0.10		1.35	238
	$\tau_o = e^{1.44}\ S^{0.52}$	0.81		1.14	239
	$\tau_o = e^{1.59}\ V^{0.55}$	0.55		1.23	240
	$\tau_o = e^{3.81}\ q^{0.25}\ S^{0.52}$	-	0.91	1.10	241
All soils (n = 64)					
	$\tau_o = e^{2.67}\ q^{0.27}$	0.08		1.40	242
	$\tau_o = e^{1.62}\ S^{0.61}$	0.78		1.17	243 a
	$\tau_o = e^{1.02}\ V^{0.31}$	0.21		1.33	243 b
	$\tau_o = e^{4.33}\ q^{0.27}\ S^{0.61}$	-	0.86	1.13	243 c

loam to black clay and obtained values varying from 0.72 to 1.00. Since the tractive force values obtained in this study are higher than these critical figures, soils that fall within this range like those used for these experiments can be detached and transported by the simulated flow. Compared to the maximum permissible values computed by Lane (1955) (Table 51b) those reported in this study are lower. Considering that even at these lower values significant rilling occurred on the test soils (Chapter 6) a greater caution should be exercised in the selection of critical tractive force values for designing erodible channels.

5.8 STREAM POWER PER UNIT BOUNDARY AREA (P_s)

The rate at which the flow performs work on the flow bed is expressed by stream power per unit boundary area (J s^{-1} m^{-2}). The latter was calculated from Eq. 25 using the measured values of flow velocity and the calculated values of tractive force.

The data are presented in Appendix 18 and Table 72 for the detachment and transport tests respectively. These were used in establishing relationships between the detachment and transport capacities of the flow and flow power.

The mean values for the detachment tests (Table 54) ranged from 0.05 - 0.13 for the 1.0 - 2.8 l/min flow and 0.03 - 0.14 for the 3.5 - 14 per cent slope. The values for the transport tests averaged 0.13.

Since Eq. 25 shows $P_s \propto q$ and s, flow power would be expected to be influenced by the variables from which it was calculated. Any further analysis involving P_s and q and s will result in double counting the effects of the influencing variables. This was avoided by carrying out no statistical analysis.

5.8.1 Total runoff kinetic energy (RE)

Total runoff energy was calculated by multiplying the values obtained for stream power (P_s) by the duration of the run in seconds to yield values in units of energy as shown below:

For a 20-minute run (1200 s) and P_s = 0.10 J s^{-1} m^{-2}, total runoff energy is given by

$$RE = 0.10 \times J \times \frac{1}{\cancel{s}} \times \frac{1}{m^2} \times 1200\cancel{s}$$

$$= 120 \text{ J m}^{-2}$$

The values of runoff energy are presented in Appendix 19. Total runoff energy increased with increasing discharge and slope steepness with mean values (Table 54b) ranging from 55.3 - 149 J m^{-2} for the 1.0 - 2.8 l/min flow without rain and

TABLE 54a Mean values of stream power per unit boundary area (P_s; J s^{-1} m^{-2})

Factor level	Flow with rain	No rain
Soil surface		
Standard sand	0.0894	0.0862
Sand	0.0877	0.0852
Clay loam	0.0868	0.0865
Clay	0.0866	0.0892
Flow rate (l/min)		
1.0	0.0470	0.0461
1.6	0.0736	0.0726
2.2	0.1034	0.1043
2.8	0.1266	0.1243
Slope (%)		
3.5	0.0341	0.0343
7.0	0.0694	0.0688
10.5	0.1060	0.1045
14.0	0.1411	0.1394

TABLE 54b Values for total runoff kinetic energy (RE)

RE ($J\ m^{-2}$)	Source	Remarks
55.3 - 87.0 (443.6 - 768.3*)	(1)	1.0 - 1.6 l/min flow, no rain
125.1 - 149.0 (1109.3 - 1397.8)	(1)	2.2 - 2.8 l/min flow, no rain
56.4 - 88.3	(1)	1.0 - 1.6 l/min flow, with rain
124.1 - 151.9	(1)	2.2 - 2.8 l/min flow, with rain
343 (3623)	(2)	Overland flow for 30 storms in the field
0.5 - 84.5 (13.5 - 855)	(3)	Overland flow in the field for 1 - 80 mm h^{-1} rain
41.2 - 82.5	(1)	Mean for 3.5 - 7.0 per cent slope with flow, no rain
125.4 - 167.3	(1)	10.5 - 14.0 per cent slope
40.9 - 83	(1)	Mean for 3.5 - 7.0 per cent slope, flow with rain
127.2 - 169.3	(1)	10.5 - 14.0 per cent slope
223 - 486	(1)	2 - 3.8 l/min flow with rain

(1) Study; (2) Morgan, 1978; (3) Pearce, 1976.

* Total kinetic energy of rain ($J\ m^{-2}$)

56.4 - 151.9 for flow with rain. The corresponding ranges for the 3.5 - 14 per cent slope were 41.2 - 167.3 and 40.9 - 169.3.

The values for the 1 - 2.8 l/min flow compare with 443.56, 768.28, 1109.32 and 1397 being the total kinetic energy (J m^{-2}) of the 50, 80, 110 and 140 mm h^{-1} rain. These values indicate that about 11.5 per cent of the rainfall energy contributes the overland flow energy. This is very close to the 9 per cent reported by Morgan (1978) for runoff in the field.

For a run duration of 45 minutes and an additional baseflow of 1 l/min, the total runoff energy for the transport tests (222.95 - 486) was greater than those reported above for the detachment tests.

Because only a few studies have examined runoff energy, typical values are very scarce in the literature. The limited values listed in Table 55 with those from this study however show that total runoff kinetic energy is several orders of magnitude lower than those of rainfall.

5.9 SUMMARY

Although the hydraulics of overland flow are closely related to the detachment and transport of soil particles in the flow, very few studies have examined these relationships. In order to fill this gap, the hydraulic properties of overland flow over roughened soil plates were measured.

1) The results showed that flow velocities were generally small. Mean values of velocity for 1 - 2.8 l/min flow varied from 46.47 - 94.13 mm s^{-1} for flow without rain and 44.13 - 88.58 mm s^{-1} for flow with rain.

2) The most important factors that individually influenced the velocity of flow with and without rain were slope steepness and discharge respectively.

3) The most significant interaction that affected flow velocity was slope steepness x soil surface. The effects of factor

interactions on flow parameters have not been made explicit in earlier studies.

4) On the average raindrop impact reduced flow velocity by 7 per cent with the percentage reduction being greater at the lower slopes. This trend confirms the observations made by earlier workers.

5) Considering that even the low velocity flows used in this study caused significant erosion there is a need for better guidelines for the selection of design velocities which currently average 600 - 900 mm s^{-1} for earth channels.

6) Flow depths were also generally small with mean values for the 1 - 2.8 l/min flow ranging from 0.70 - 0.92 mm for flow without rain and 0.76 - 1.04 mm for flow with rain.

7) Raindrop impact increased flow depth by 11 per cent.

8) The major factor that individually influenced flow depth was slope steepness; and slope x soil surface was the most significant interaction.

9) With mean values of Reynolds number ranging from 24 - 64, flow was predominantly laminar.

10) The mean values of Froude number (0.60 - 1.04) showed that flow can be either supercritical or subcritical. However, flow was predominantly subcritical laminar. Similar flow regime has been reported for overland flow in the field. The simulated flow used in this study thus approximates field conditions.

11) The threshold Froude number of flow beyond which appreciable number of rills were formed was 0.55 for standard sand and sand and 0.68 for clay and clay loam.

12) The individual effects of the factors on Froude number ranked as slope steepness > discharge > soil surface.

13) The Froude number of flow was also significantly affected by slope x soil surface and slope x discharge interactions.

14) Rainfall reduced Froude number by 8.6 per cent.

15) Friction factors were generally high with values averaging 3.88 for the 1 l/min flow without rain and 5.21 for flow with rain. The corresponding values for the 2.8 l/min flow were 1.20 and 1.71.

16) Rainfall increased friction factor by 28 per cent confirming the observations of other workers. The proportionate increase was greater at the higher intensities and at the lower slopes.

17) The value of k in the relationship, $f = k/Re$, always exceeded the theoretical value of 24 for laminar flow over smooth surfaces.

18) The major interaction that influenced friction factor was slope x discharge.

19) Manning's n was about 7.5 times greater than the value of 0.02 commonly used for erodible channel design and about 25 per cent lower than the lower range value of 0.2 reported for field conditions.

20) Impacting raindrops increased the value of Manning's n by 33.87 per cent.

21) Tractive force increased with increasing discharge and slope steepness with values ranging from 0.95 - 1.26 N m^{-2} for the 1.0 - 2.8 l/min flow and 0.60 - 1.33 N m^{-2} for the 3.5 - 14 per cent slope.

22) Raindrop impact increased tractive force for flow without rain by 10 per cent.

23) Although relatively small, the slope x discharge and slope x soil surface interactions significantly affected tractive force.

24) The earlier remarks made on the selection of critical velocities for channel design also apply to tractive force. In most cases tractive force was greater than the critical value for most agricultural soils but lower than the maximum permissible values used in erodible channel design.

25) Total runoff energy was several orders of magnitude smaller than that of rain.

26) About 11.5 per cent of the rainfall energy contributes the overland flow energy.

27) Typical values of the above flow parameters obtained under varying conditions have been tabulated.

28) Power equations established between the above flow parameters and discharge and slope steepness show that in most cases the exponents of the latter two variables are similar to those derived theoretically for overland flow. The exponents also compare very well with those obtained by other workers from similar experiments.

CHAPTER 6

DETACHMENT CAPACITY OF OVERLAND FLOW

This Chapter examines the detachment capacity of overland flow. Its measurement is outlined in Chapter 3 and Table 2 shows the levels of the factors studied. Two series of tests consisting of 256 runs each were carried out for detachment by flow with and without rain. It must be emphasized that in the case of flow with rain no baseflow was provided and detachment was by the combined action of rainfall and the flow it produced.

The results presented in Sections 6.1 and 6.5 comprise the types of erosion that occurred during the tests; the factors that influence the process; the relative contribution to total detachment by overland flow and splash; and the relationships between detachment and the influencing factors. These results are discussed in Section 6.6 which is followed by an examination of the hydraulics of overland flow detachment in Section 6.7 and a summary of the Chapter in Section 6.8.

6.1 EXPERIMENTAL OBSERVATIONS

i) Detachment by overland flow without rain occurred predominantly by rilling. At the start of each run, the flow caused an initial flush of detached particles from the entire surface of the eroding bed immediately after which seemingly randomly distributed flow lines were formed. Whilst these covered a major part of the surface of the standard sand and sand, only a few were clearly visible on the clay and clay loam. Concentration of runoff in these flow lines initiated rilling. The rills started as random formation of nicks at some points along the flow lines. Flow directed into these focal points deepened and intensified soil failure which tended to advance upslope. In the case of the sand and standard sand, the latter movement covered the 10 cm length of the soil bed within a few seconds from the start of a run and consequently caused higher rates of detachment early in a run. For the clay and clay loam however, the upslope movement of the rill head was relatively slower indicating a greater resistance to detachment by flow. Once they were formed, detachment was

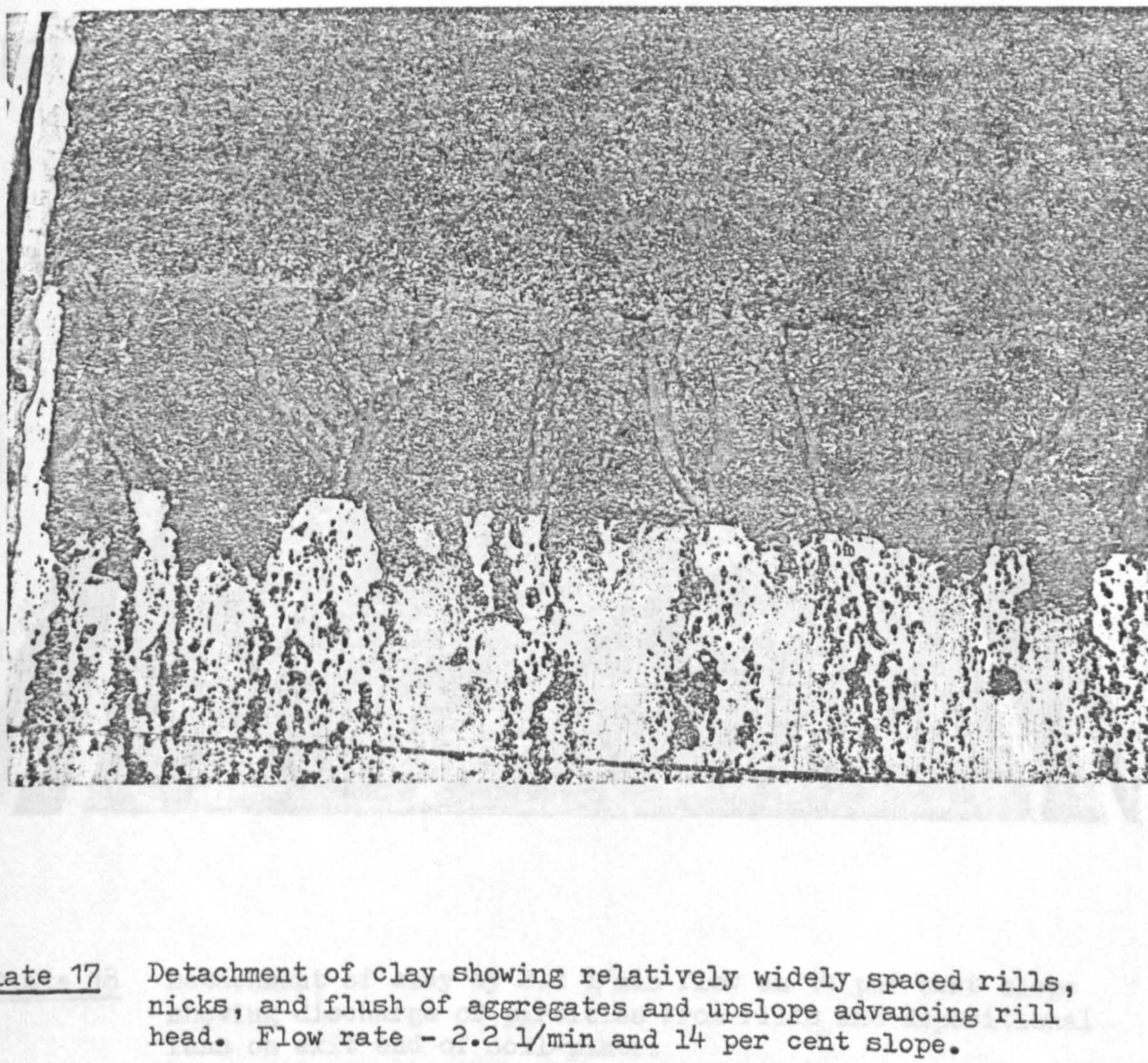


Plate 17 Detachment of clay showing relatively widely spaced rills, nicks, and flush of aggregates and upslope advancing rill head. Flow rate - 2.2 l/min and 14 per cent slope.

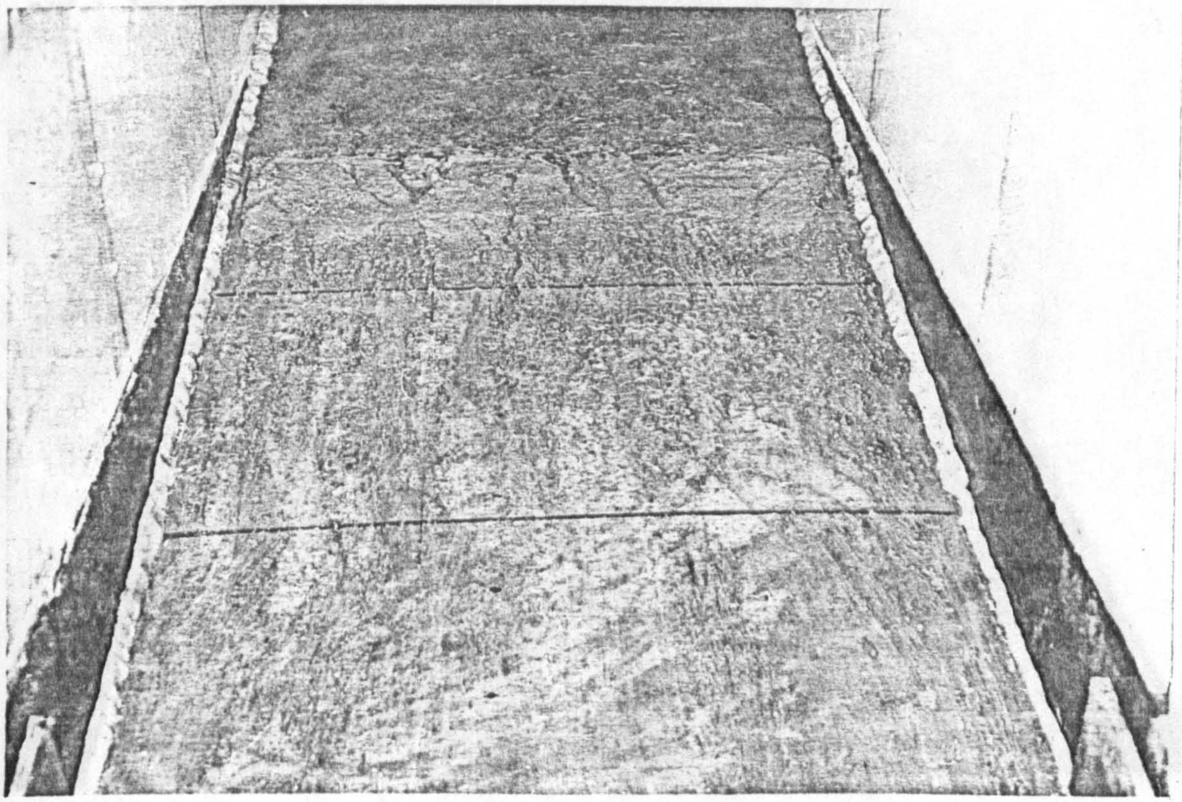


Plate 18 Detachment of clay by 2.2 l/min flow on 14 per cent slope showing discharge of particles from rills and depositional fans on exit end of soil-plate.

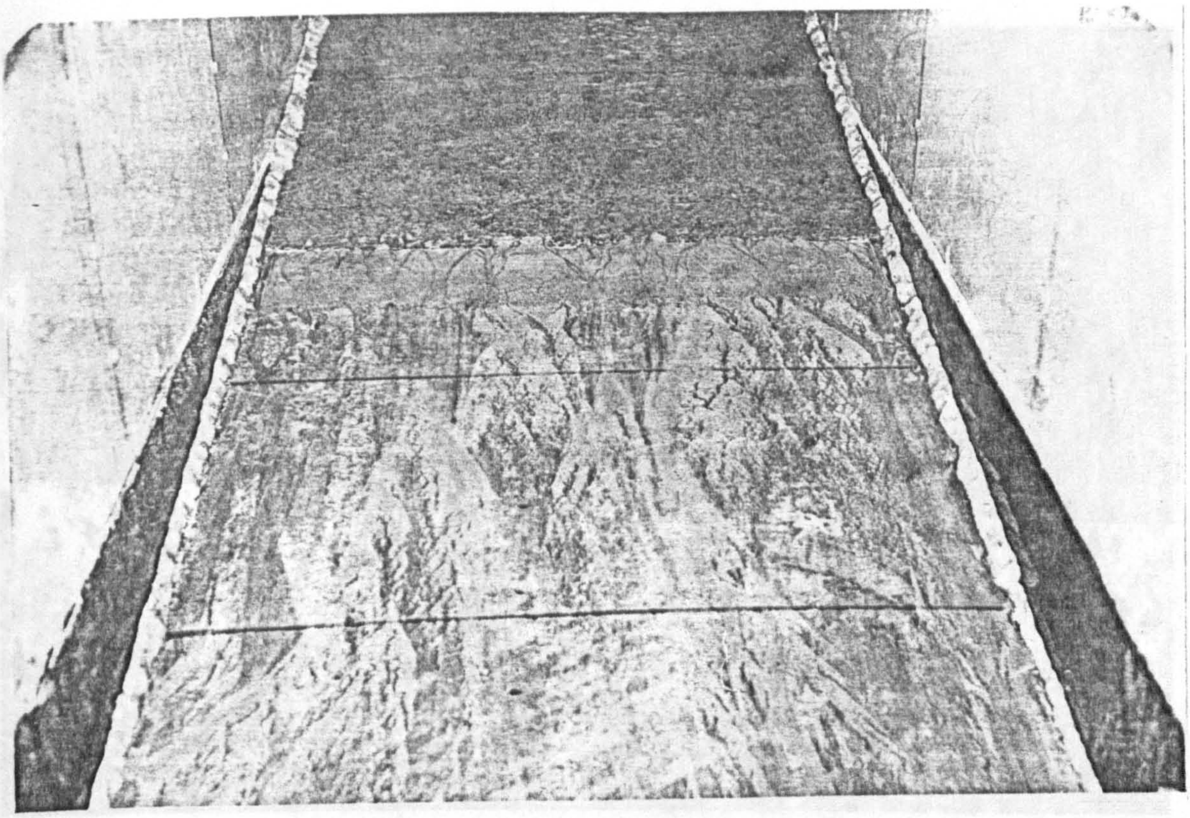


Plate 19 Detachment of sand by 2.2 l/min flow on 14 per cent slope showing rill distribution, discharge of particles from rills and depositional fans on exit end of soil plate.

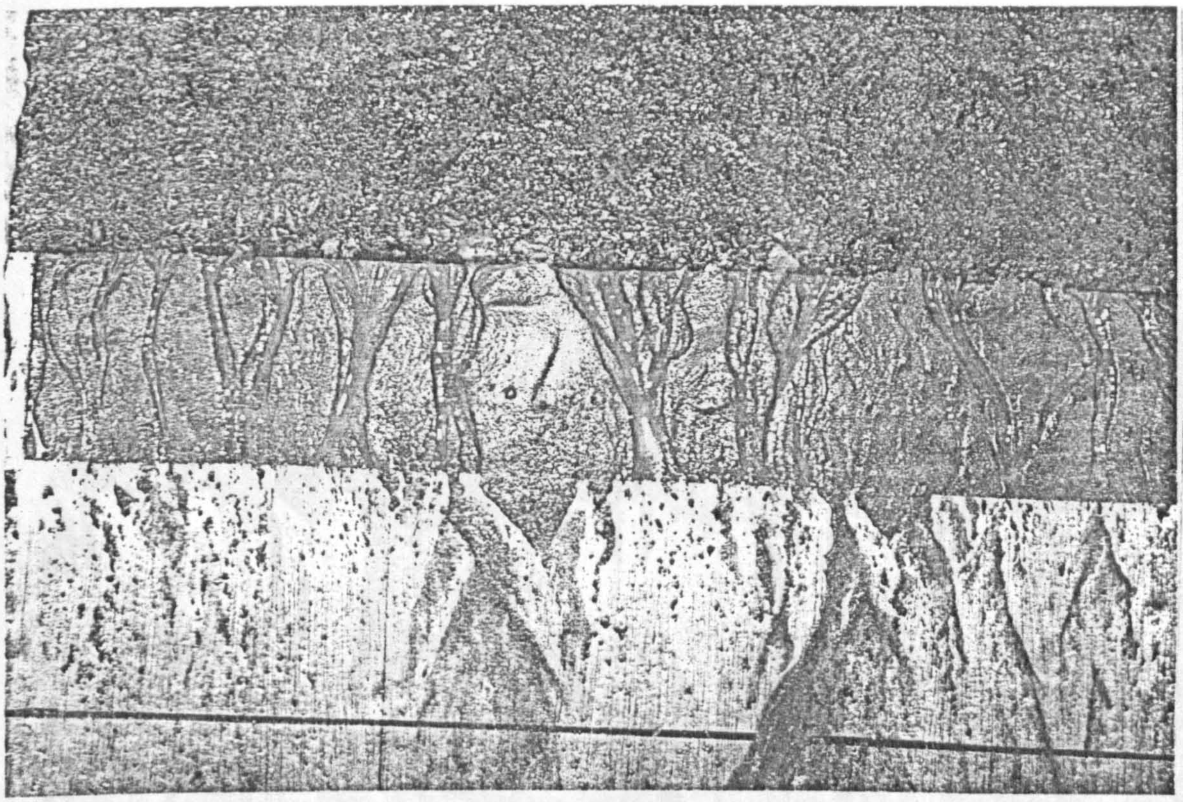


Plate 20 Detachment of sand by 2.2 l/min flow on 14 per cent slope showing closely spaced rill network.

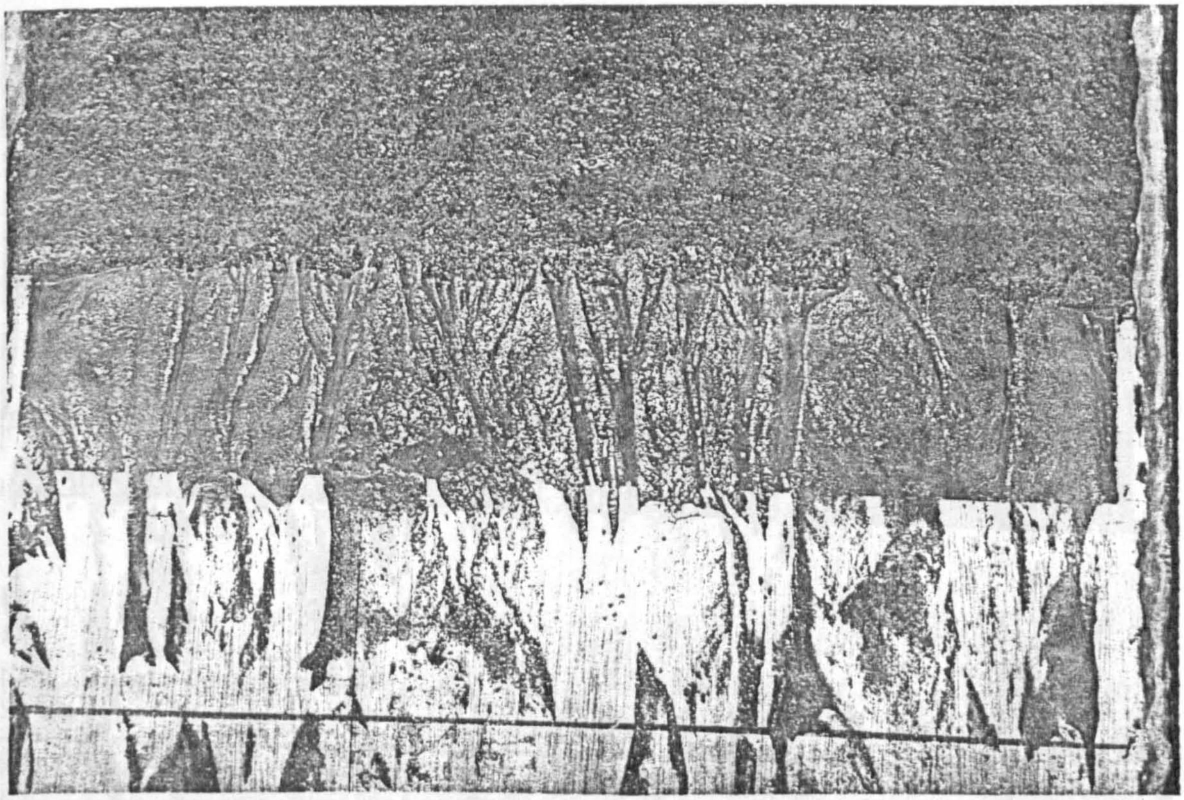


Plate 21 Detachment of sand by 2.2 l/min flow on 7 per cent slope showing rill network.

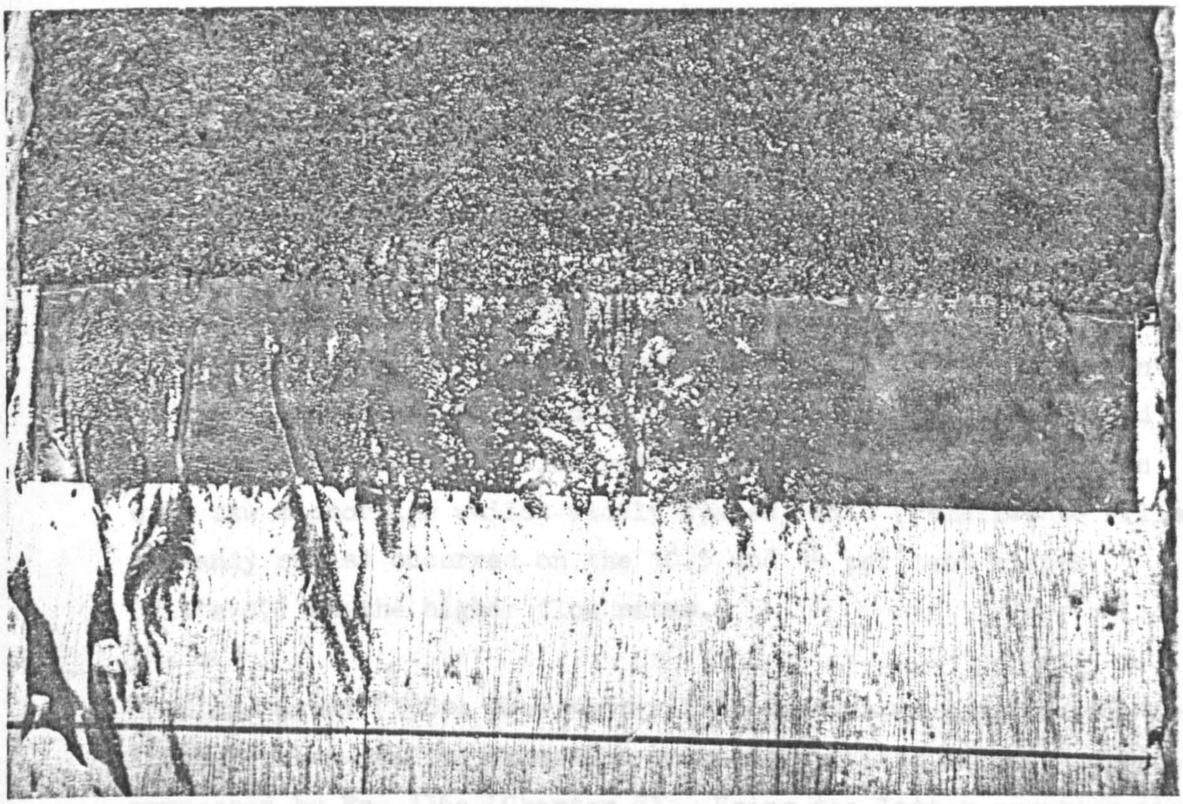


Plate 22 Detachment of sand by 1 l/min flow on 7 per cent slope showing few rills.

mainly from the rills and the detached particles rolled and saltated downslope along the path of the concentrated flow and tended to form depositional fans on the smooth end of the soil plate. After the initial flush of particles, detachment by sheet flow in the interrill areas consisted mainly of intermittent rolling of particles over short distances within the soil tray. Some of these however, rolled out of the tray.

The appearance of the eroding bed during and after a run depended on soil type, flow rate and slope steepness. For the sand and standard sand, rilling occurred on all slopes for all the flow rates studied. For a constant slope, the intensity and number of rills were influenced by the rate of flow. On the sand and standard sand, the 2.2 and 2.8 l/min flows guttered the entire surface of the soil bed (7 - 14 per cent slopes) with closely spaced rills (Plates 20, 21 and 22). For the clay and clay loam, the initial flush of particles was the major cause of detachment on the lower slopes (3.5 and 7.0 per cent). As slope steepened, detachment by the lower flow rates increased with the formation of a few microrills whilst widely spaced rills (relative to rills on sandy soils) occurred on the 10.5 and 14 per cent slopes (Plate 17) at the higher flow rates.

Boon and Savat (1981) show that rill formation is possible if the Froude number of flow exceeds a critical particle Froude number expressed by Eq. 136a (Chapter 5). Using the latter equation the respective critical values for the standard sand, sand, clay loam, and clay were 4.26, 3.14, 2.05, and 1.70. Since the measured values of the flows Froude number (0.60 - 1.04) were less than the above critical values, rill formation could not have been possible. The experimental observations however show that even at values less than the critical particle Froude number, rills can be formed.

ii) Detachment by overland flow with rain was distinctly different from that of flow without rain. At the start of a run, raindrop impact was the major detaching agent. Particles were ejected in both downslope and upslope directions while side splashes adhered to the wall of the extension frame of the flume. With the accumulation of runoff, flow moved over the soil bed and increased the rate at which soil particles left the soil-tray indicating an increased detachment rate.

On the sand and standard sand, several closely spaced rills were formed. As the flow detached particles in the rills, interrill detachment was by the splash action of raindrops. Evidence is that craters formed by the impacting drops in the interrill areas were distinctly visible especially on the white standard sand. As the run progressed and the sides of the rills were continuously worn down by impacting raindrops, contiguous rills merged to form broader and shallower channels than those for flow without rain. This action was so efficient that at the end of the run, the surface of the eroding bed on the lower slopes was almost level giving the appearance of sheet removal of soil. At the higher slopes, however, the outlines of the broad channels were still visible. Also, the surface of these soils seemed compacted with the Cottenham sand showing evidence of surface armouring by coarser fractions.

For the clay and clay loam, the few rills that were formed were immediately obliterated by impacting raindrops. Detachment of the aggregates was mainly by raindrops while the disturbed flow washed the particles out of the soil tray. Movement of particles occurred over the whole surface of the eroding bed and comprised projectiles of ejected particles which subsequently fell back into the flow; and intermittent raindrop impact-aided rolling and saltation of detached particles by flow. At the end of the run, the initial granular and porous appearance of the original sample was reduced to a paved level surface. Since no surface seal was observed in the absence of rain (i, above), compaction by raindrop impact was considered to be the major cause.

Samples collected during the runs showed that sediment concentration for all soils was least during the first 3 minutes. After this, a steady rate of runoff was obtained and sediment concentration increased up to the 15th minute after which it became erratic, increasing in some cases and decreasing in others.

Because of the deposition of the detached particles on the exit end of the soil-plate, explaining differences in sediment concentration was difficult since they could be due to either crust formation resulting in temporal variability in detachment rate or spatial changes in depositional pattern.

6.2 FACTORS INFLUENCING DETACHMENT BY OVERLAND FLOW

The data for detachment by overland flow with and without rain are summarized in Appendices 29 and 30. Each value is an average of 4 readings. However all 256 observations were used in the statistical analysis of the data.

The mean weight of soil detached (Table 57) differed significantly ($P = 0.01$) with the various soil types. The order of detachability for both flow with and without rain was standard sand > sand > clay loam > clay. There were also significant increases in detachment as slope steepness and flow rate increased. For the latter, the increase in detachment was gradual. However for a slope change of 3.5 to 14 per cent, detachment increased 2.57 times for flow with rain and 9 times for flow without. Raindrop impact significantly increased detachment, the increase being greater for clay and clay loam; and for the 3.5 and 7.0 per cent slopes.

For detachment by flow without rain, the analysis of variance showed soil type to be the most influencing factor (Table 55). This was followed by slope steepness, and then by discharge. The corresponding order for flow with rain was intensity, slope steepness, and soil type (Table 56). It is further shown that the first and second order interactions of these factors significantly influence detachment by flow. On a relative basis, the second order interaction is small and the importance of the first order interactions can be placed in an increasing order of slope x soil, slope x discharge, and discharge x soil for flow without rain. For flow with rain, they rank as slope x soil, discharge x soil, and slope x discharge.

The slope x soil interaction implies that for a given flow, the effect of slope varies with the type of soil or that the influence of soil type also depends on slope steepness. As slope steepened, each soil

TABLE 55

Analysis of Variance of the Effect of Slope, Discharge and Soil Type on Detachment by Overland Flow Without Raindrop Impact

Source of Variation	Sums of Squares	Degrees of freedom	Mean Squares	F
Slope	156.4787	3	52.1596	7559.36***
Replication	0.0072	3	0.0024	0.35 NS
Discharge	44.7225	3	14.9075	2160.51***
Slope x Discharge	13.9901	9	1.5545	225.29***
Soil	208.1345	3	69.3782	10054.81***
Slope x Soil	126.3965	9	14.0441	2035.38***
Discharge x Soil	11.7810	9	1.3090	189.71***
Slope x Discharge x Soil	5.9187	27	0.2192	31.77***
Residual	1.3051	189	0.0069	
Total	568.7343	255		

*** significant at 0.1% NS not significant at 5%

TABLE 56

Analysis of Variance of the Effect of Slope, Discharge and Soil Type on Detachment by Overland Flow With Raindrop Impact

Source of Variation	Sums of Squares	Degrees of freedom	Mean Squares	F
Slope	318.9828	3	106.3275	14767.71***
Replication	0.0621	3	0.0207	2.88 NS
Discharge	345.4368	3	115.1456	15992.44***
Slope x Discharge	30.6107	9	3.4012	472.39***
Soil	284.9516	3	94.9839	13192.21***
Slope x Soil	85.7246	9	9.5250	1322.92***
Discharge x Soil	35.0863	9	3.8985	541.46***
Slope x Discharge x Soil	9.1576	27	0.3392	47.11***
Residual	1.3525	189	0.0072	
Total	1111.3650	255		

*** Significant at 0.1%   NS Not significant at 5%

TABLE 57

The Mean Weight of Soil Detached (n = 256) by Overland Flow with (Q_{rodet}) and without (Q_{odet}) Raindrop Impact.

Factor level	Mean Q_{odet} kg m^{-2}	Mean Q_{rodet} kg m^{-2}	No of times**
Soil			
Standard sand	2.5247 a*	4.8625 a	1.93
Sand	1.2290 b	3.4861 b	2.84
Clay loam	0.4135 c	2.5905 c	6.26
Clay	0.2530 d	2.0832 d	8.23
Discharge (l/min)			
1.0	0.6047 a	1.5730 a	2.60
1.6	0.8201 b	2.9300 b	3.57
2.2	1.3101 c	3.7883	2.89
2.8	1.6754 d	4.7310 d	2.82
Slope (%)			
3.5	0.2470 a	1.9017 a	7.70
7.0	0.5489 b	2.6330 b	4.80
10.5	1.3525 c	3.6073 c	2.67
14.0	2.2619 d	4.8803 d	2.20

* The differences between values followed by dissimilar letters are significant at 1% level.

** Number of times Q_{rodet} is greater than Q_{odet}.

LSD at 5% = 0.0288 for soil, discharge and slope means)
) flow without rain
LSD at 1% = 0.0378 for soil, discharge and slope means)

LSD at 5% = 0.0293 for soil, discharge and slope means)
) flow with rain
LSD at 1% = 0.0385 for soil, discharge and slope means)

had an increasing effect on detachment, the proportionate increase being greater for sand and standard sand than for clay and clay loam. The differences between soils, on the other hand, showed the influence of each slope on detachment to vary significantly among the soil types ($P = 0.01$). With the exception of the 3.5 per cent slope at which the differences between the clay and clay loam for flow without rain were not significant, detachability ranked as standard sand, sand, clay loam, and clay in a decreasing order of response.

The slope x discharge interaction revealed significant increases in detachment for all slopes as discharge increased. The magnitude of the response was greater at the lower than higher slopes. As slope steepness increased, the detachment capacity of flow both with and without rain was also enhanced. The increase was proportionately more for the 1.0 and 1.6 l/min than the 2.2 and 2.8 l/min flows.

Examination of the soil x discharge interaction indicated that, for flow without rain, detachability increases more for the clay and clay loam than for the standard sand and sand as discharge increases. In the presence of rain however, the response of the soils did not differ much. The detachment capacity of each flow rate also varied significantly ($P = 0.01$) with the soil type. The only exception being the 1.6 l/min flow without rain for the clay and clay loam.

6.3 CONTRIBUTION TO TOTAL DETACHMENT BY OVERLAND FLOW AND SPLASH

By determining the amount of material detached by overland flow with and without rain, it was possible to calculate the relative contributions to total detachment by overland flow and by splash as follows:

Q_{rodet} = total detachment by combined flow and raindrop impact (kg m^{-2})

Q_{odet} = detachment by overland flow without rain (kg m^{-2})

$$Q_{det} = Q_{rodet} - Q_{odet} \quad (\text{kg m}^{-2}) \qquad \text{Eq. 244a}$$

$$\text{Per cent contribution by splash} = \frac{Q_{det} \times 100}{Q_{rodet}} \quad \text{and} \qquad \text{Eq. 244}$$

$$\text{Per cent contribution by overland flow} = \frac{Q_{odet}}{Q_{rodet}} \times 100 \qquad \text{Eq. 245}$$

$$= 100 - \%\ \text{contribution by splash}$$

Computed in this way, the contribution to total detachment by rainfall-runoff interaction is lumped with that by splash (Q_{det}).

TABLE 58

The Contribution to Total Detachment (Q_{rodet}) by Overland Flow (Q_{odet}) and Splash (Q_{det}).

Soil	Slope	Q_{rodet}	Q_{odet}	% of Q_{rodet}	No.of times*	Q_{det}	% Q_{rodet}
	%	kg m^{-2}	kg m^{-2}	%		kg m^{-2}	%
	3.5	2.416	0.420	17.38	5.75	1.996	82.62
Standard sand	7.0	3.889	1.189	30.57	3.27	2.700	69.43
	10.5	5.440	3.216	59.12	1.69	2.224	40.88
	14.0	7.705	5.275	68.46	1.46	2.430	31.54
	3.5	1.849	0.322	17.41	5.74	1.527	82.59
Sand	7.0	2.675	0.527	19.70	5.08	2.148	80.30
	10.5	4.093	1.518	37.09	2.698	2.575	62.91
	14.0	5.328	2.299	43.15	2.32	3.029	56.85
	3.5	1.838	0.136	7.40	13.51	1.702	92.60
	7.0	2.183	0.316	14.48	6.91	1.867	85.52
Clay loam	10.5	2.750	0.460	16.73	5.98	2.29	83.27
	14.0	3.597	0.743	20.66	4.84	2.85	79.34
	3.5	1.504	0.111	7.38	13.55	1.393	92.62
Clay	7.0	1.785	0.165	9.24	10.82	1.620	90.76
	10.5	2.146	0.216	10.07	9.94	1.930	89.93
	14.0	2.898	0.480	16.56	6.04	2.418	83.44

* Number of times Q_{rodet} is greater than Q_{odet}.

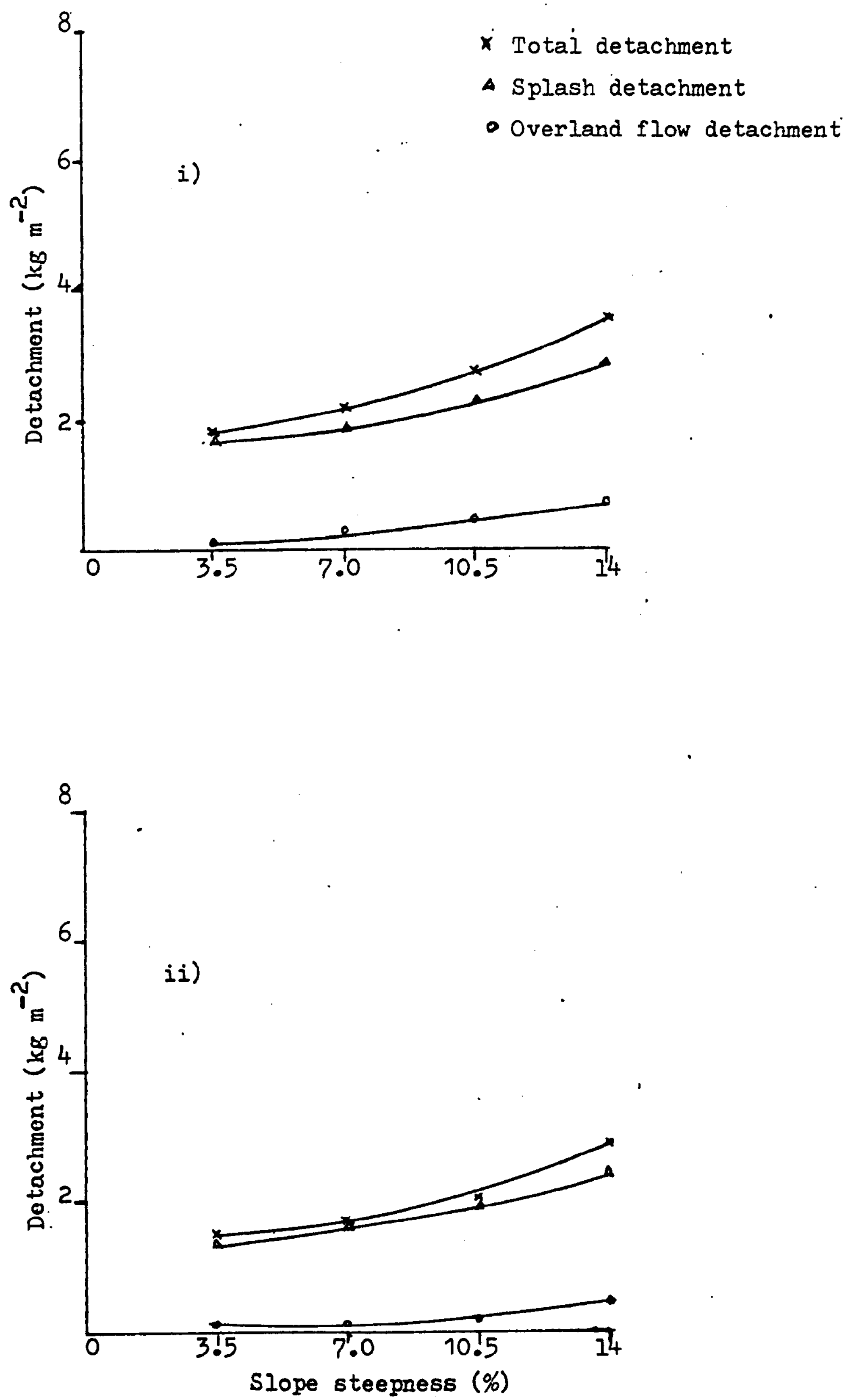


Fig. 2a Contribution to total detachment by splash and overland flow

i) clay loam
ii) clay.

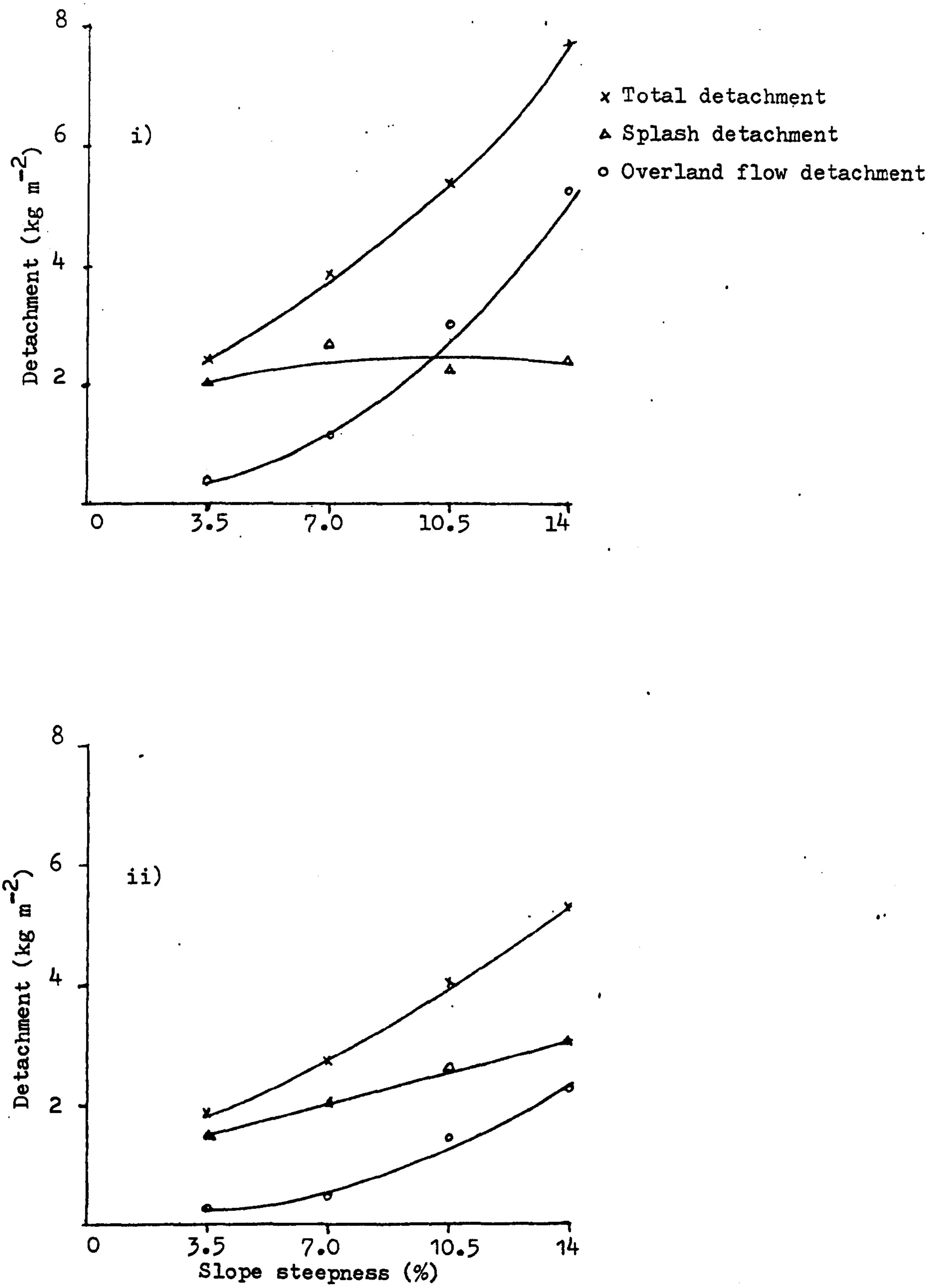
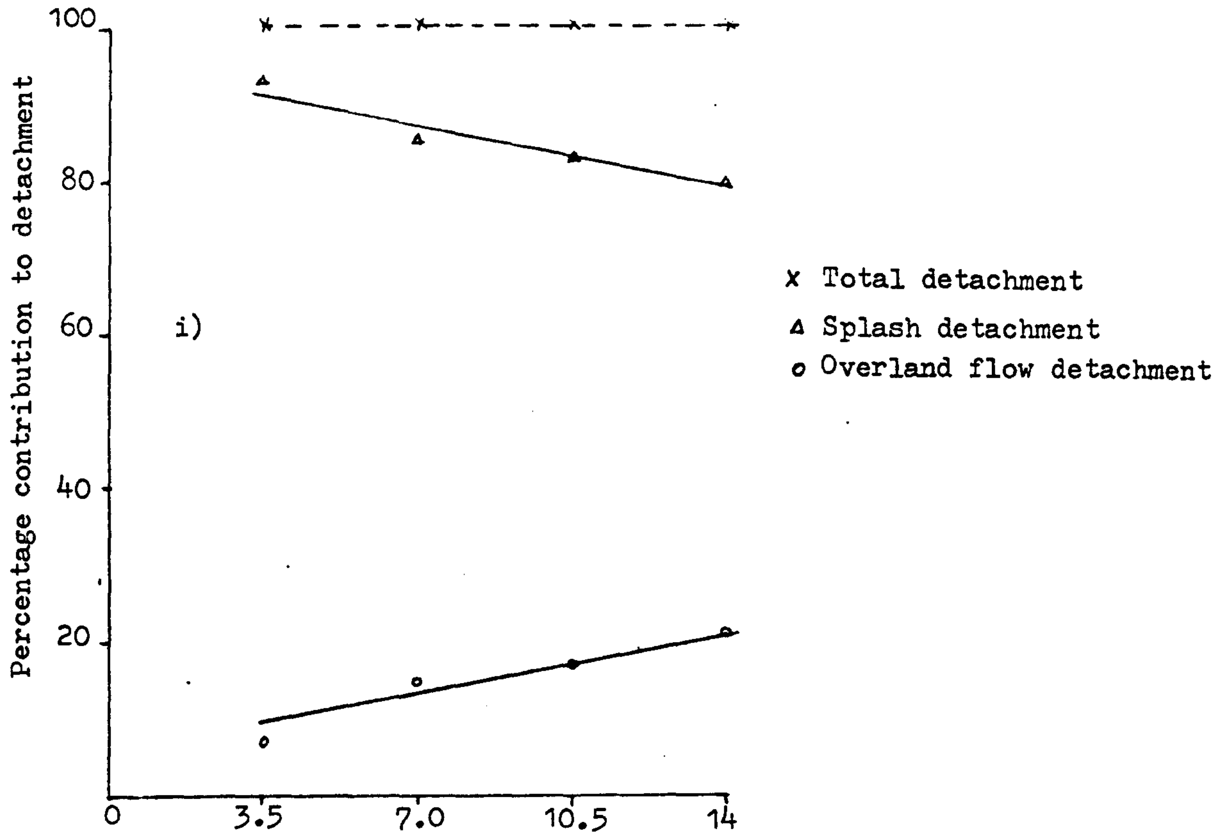


Fig. 2b Contribution to total detachment by splash and overland flow

i) Standard sand
ii) Cottenham sand.



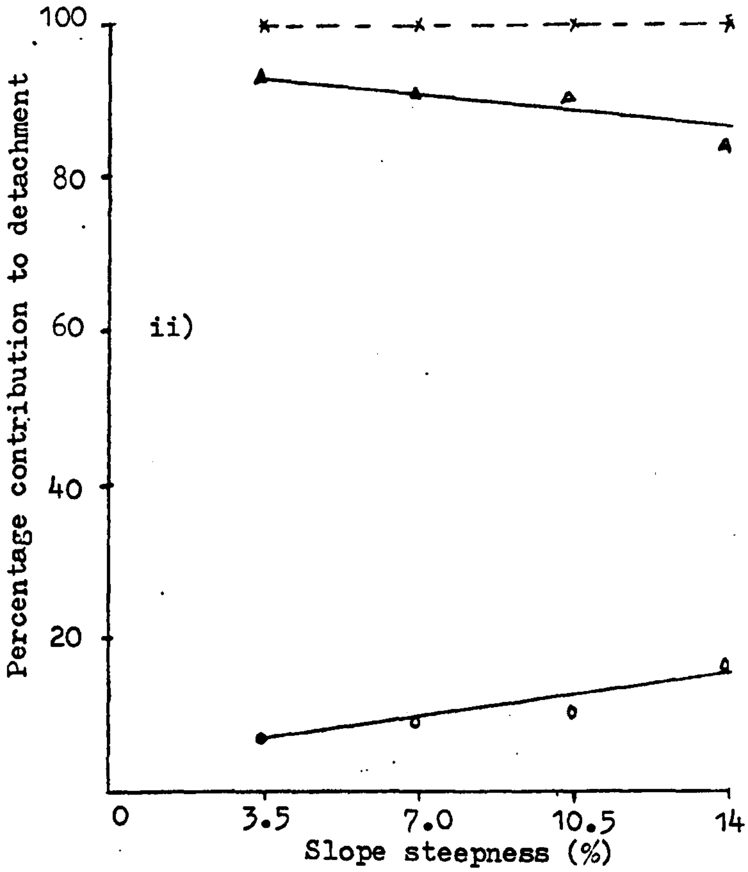
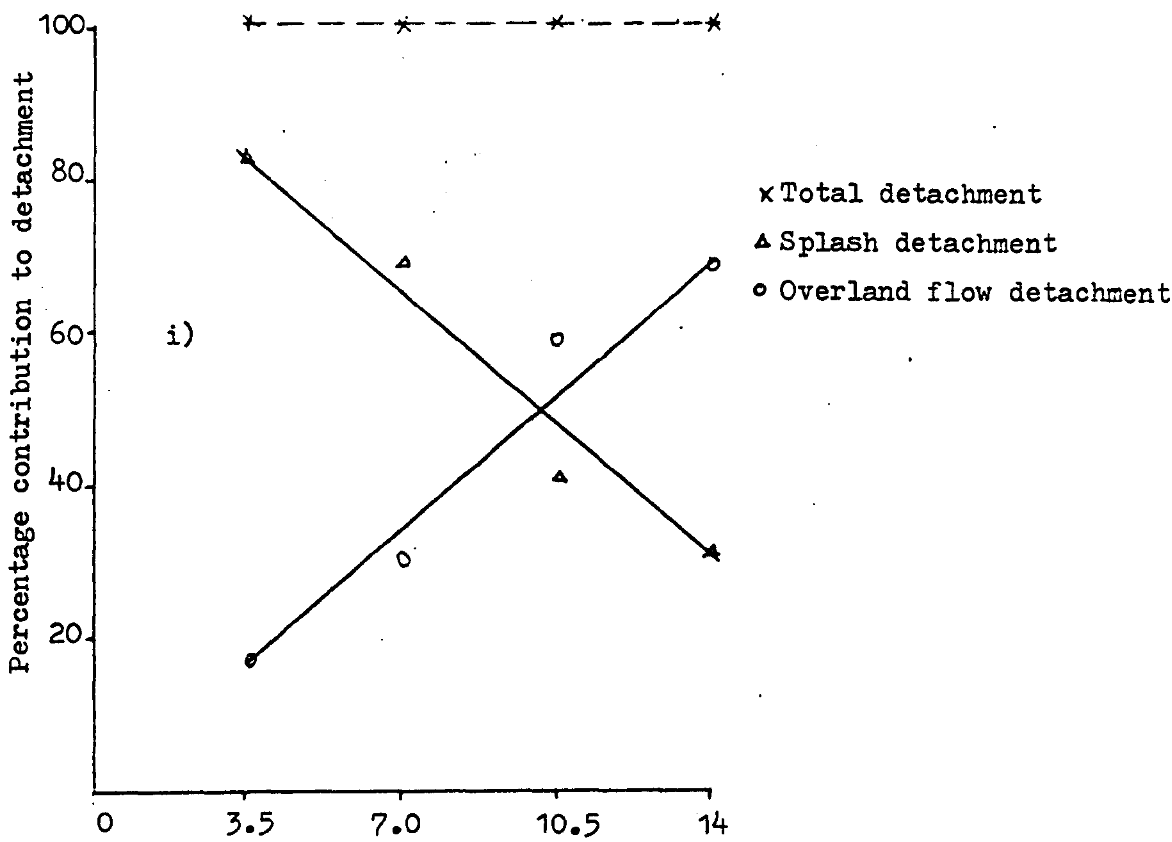


Fig. 3a. Relative contribution to total detachment by splash and overland flow

i) clay loam

ii) clay.



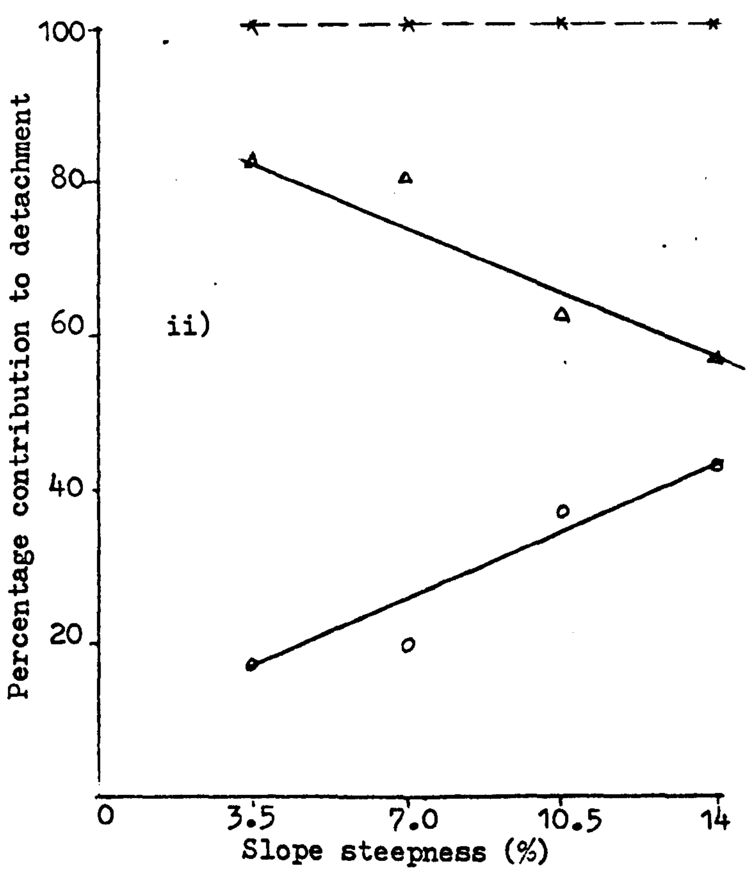


Fig.3b Relative contribution to total detachment by splash and overland flow

i) Standard sand
ii) Cottenham sand

The results obtained are presented in Table 58 and summarized in Figs 2a and 2b. At lower slopes the bulk of detachment on all soils was by splash while overland flow detached a small amount. As slope increased, splash detachment increased but rather gradually. In contrast, the increase in overland flow detachment was rapid. For a slope steepness change from 3.5 to 14.0 per cent, splash detachment for standard sand, sand, clay loam and clay increased by 1.21, 1.98, 1.66, and 1.74 respectively. The corresponding increase in overland flow detachment was 12.56, 7.14, 5.46, and 4.32. The effect of soil type on this increase is thus clearly evident but more so in the case of detachment by overland flow.

The percentage contributions to total detachment by splash and overland flow and their performance under increasing slope steepness are presented in Figs 3a and 3b. The results showed that on the 3.5 per cent slope, the percentage contribution to total detachment by splash was 83 for sand and standard sand; and 93 for clay and clay loam. With increase in slope steepness, the percentage contribution by splash declined reaching, for the 14 per cent slope, 32, 57, 79, and 83 on the standard sand, sand, clay loam and clay respectively. Thus the percentage contributions by overland flow increase steadily with increasing slope with the respective values for standard sand, sand, clay loam and clay ranging between 17 - 68, 17 - 43, 7 - 20, and 7 - 17 for a slope steepness range of 3.5 - 14.0 per cent.

6.4 RELATIONSHIPS FOR DETACHMENT BY OVERLAND FLOW WITHOUT RAIN

The data for detachment by overland flow without rain were examined for correlations with the variables studied. The results (Table 59) indicated a highly significant positive (P = 0.001) correlation between overland flow detachment, slope steepness, discharge and flow power. This implies an increase in detachment with increasing levels of these factors. Conversely, an increase in grain size causes a decrease in detachment since the two are negatively correlated (P = 0.001).

Power equations relating detachment to the variables are presented in Table 60. The exponents of the variables differ for each soil

TABLE 59

Coefficient of correlation: Overland Flow Detachment (Q_{odet}; kg m^{-2}) versus Discharge (q; $m^3\ s^{-1}\ m^{-1}$), slope (S; sin S), Grain size (d_{50}, d_{84}; mm), and Flow Power (qs; l m^{-1} min^{-1})

Soil+		discharge	slope			
Standard sand						
	Q_{odet}	0.35*	0.92			
Sand						
	Q_{odet}	0.47	0.82			
Clay loam	Q_{odet}	0.79	0.54			
Clay	Q_{odet}	0.61	0.65			
All soils (n = 256)				d_{50}	d_{84}	qs
	Q_{odet}	0.41	0.54	-	-	-
		0.41	0.54	- 0.67		
		0.41	0.52	-	- 0.66	
		-	-	- 0.67	-	0.68
		-	-	-	- 0.66	0.68

+ n = 64 for each soil

* All the values in the table (correlation coefficients) are significant at 0.1%

TABLE 60 Power equations relating overland flow detachment (Q_{odet}; kg m^{-2}), to discharge (q; m^3 s^{-1} m^{-1}), slope (S; sin S), grain size (d_{50}, d_{84}; mm), and flow power (qs; l m^{-1} min^{-1}). n = 64 for each soil; n = 256 for all soils.

Soil	Equation	r_1^2	r_2^2	R^2	SEE	Eq. No
Standard sand						
	$Q_{odet} = e^{10.58}\ q^{1.02}$	0.12			2.87	246
	$Q_{odet} = e^{5.47}\ S^{1.96}$	0.84			1.56	247
	$Q_{odet} = e^{15.48}\ q^{1.01}\ S^{1.96}$	0.12	0.84	0.96	1.23	248
Sand						
	$Q_{odet} = e^{11.56}\ q^{1.19}$	0.22			2.36	249
	$Q_{odet} = e^{3.68}\ S^{1.52}$	0.68			1.73	250
	$Q_{odet} = e^{15.44}\ q^{1.19}\ S^{1.52}$	0.22	0.68	0.90	1.35	251
Clay loam						
	$Q_{odet} = e^{19.32}\ q^{2.09}$	0.63			1.87	252
	$Q_{odet} = e^{1.29}\ S^{1.05}$	0.29			2.38	253
	$Q_{odet} = e^{22.01}\ q^{2.09}\ S^{1.05}$	0.63	0.29	0.92	1.35	254

/...

TABLE 60 continued

Soil	Equation	r_1^2	r_2^2		R^2	SEE	Eq. No
Clay							
	$Q_{odet} = e^{15.79}\, q^{1.79}$	0.42				2.27	255
	$Q_{odet} = e^{1.26}\, S^{1.23}$	0.37				2.35	256
	$Q_{odet} = e^{18.95}\, q^{1.79}\, S^{1.23}$	0.42	0.37		0.79	1.66	257
All soils		r_1^2	r_2^2	r_3^2	R^2	SEE	Eq. No
	$Q_{odet} = e^{17.85}\, q^{1.50}\, S^{1.44}$	0.17	0.29		0.46	2.79	258
	$Q_{odet} = e^{16.37}\, q^{1.50}\, S^{1.44} d_{50}^{-1.54}$	0.17	0.29	0.45	0.91	1.52	259
	$Q_{odet} = e^{17.38}\, q^{1.50}\, S^{1.44} d_{84}^{-1.14}$	0.17	0.27	0.44	0.90	1.52	260
	$Q_{odet} = e^{0.04} (qs)^{1.41}\, d_{50}^{-1.51}$	0.46	0.45		0.91	1.59	261
	$Q_{odet} = e^{0.99} (qs)^{1.41}\, d_{84}^{-1.12}$	0.46	0.44		0.90	1.62	262

type with the discharge exponent ranging from 1.02 - 1.19 and 1.79 - 2.09 for standard sand and sand; and clay and clay loam respectively. The corresponding ranges for slope are 1.52 - 1.96 and 1.05 - 1.23. Thus, as already observed from the analysis of variance, an increase in slope steepness causes a greater proportionate increase in the detachment of standard sand and sand than of clay and clay loam. The converse is however true with discharge.

Slope steepness alone accounted for 64 - 84 and 29 - 37 per cent of the variations in detachment on the sandy and clayey soils respectively. In combination with discharge, the respective coefficients of determination, R^2, ranged from 90 - 96 and 79 - 92.

In order to introduce a grain size term into the relationships, the data for all the soils were bulked and analysed. The resulting R^2 value for slope steepness and discharge was reduced to about half the value of that for the individual soils. However, an inclusion of either d_{50} or d_{84} significantly improved the coefficient of determination from 0.46 to 0.90, detachment decreasing as - 1.14 and - 1.54 power of d_{84} and d_{50} respectively. A combination of flow power, with an exponent of 1.41, and grain size also performed equally well; and together they explained 90 per cent of the variations in soil detachment. This is however expected since flow power is proportional to discharge times slope steepness.

6.5 RELATIONSHIPS FOR DETACHMENT BY OVERLAND FLOW WITH RAIN

Relationships similar to those presented in the preceding Section were also established for detachment by overland flow with rain. In addition to slope steepness, discharge, and grain size, correlations between detachment and both rain intensity and kinetic energy were examined.

There was a highly significant correlation (P = 0.001) between detachment and all the parameters (Table 61). Apart from the negative coefficient of correlation (r) for grain size, the variables were positively correlated with detachment. The r values for discharge increased and those for slope decreased with soil type

TABLE 61 Coefficient of correlation: detachment by overland flow with rain (Q_{rodet}; kg m^{-2}) versus discharge (q; m^3 s^{-1} m^{-1}), slope (S; sin S), rain intensity (I; mm h^{-1}), total kinetic energy of rain (KE; J m^{-2}), and flow power (qs; l m^{-1} min^{-1}) n = 64 for each soil; n = 256 for all soils.

Soil		discharge	slope	intensity	kinetic energy
Standard sand					
	Q_{rodet}	0.66*	0.71	-	-
		-	0.71	0.66	
			0.71	-	0.66
Sand					
	Q_{rodet}	0.73	0.65	-	-
		-	0.65	0.73	
		-	0.65	-	0.73
Clay loam					
	Q_{rodet}	0.82	0.51		
		-	0.51	0.82	-
		-	0.51	-	0.82
Clay	Q_{rodet}	0.86	0.42		
		-	0.42	0.86	-
		-	0.42	-	0.86

All soils	q	S	I	KE	d_{50}	d_{84}	qs
Q_{rodet}	0.67	0.52	-	-	-	-	-
	0.67	0.52	-	-	- 0.42	-	-
	0.67	0.52	-	-	-	- 0.41	-
	-	0.53	0.67	-	- 0.42	-	-
	-	0.53	0.67	-	-	- 0.41	-
	-	0.53	-	0.67	- 0.42	-	-
		0.53	-	0.67	-	- 0.41	-
	-	-	-	-	- 0.42	-	0.81
	-	-	-	-	-	- 0.41	0.84

* All the values are significant at 0.1%

in the order of standard sand, sand, clay loam, and clay.

The discharge exponent (Table 62) was about 1.2 for standard sand and sand; and ranged from 0.97 to 1.13 for clay and clay loam. Thus, the values for the sandy soils were about the same as those for detachment by flow without rain while the clay and clay loam exponents were halved. The slope exponent was also significantly reduced in the presence of rain with a range of 0.78 - 0.93 and 0.41 - 0.45 for the sand and standard sand; and clay and clay loam respectively.

Considering the variations in the soils used, the discharge, kinetic energy and rain intensity exponents are quite stable and can be reasonably approximated to 1.0, a value obtained when data for all the soils were analysed together.

The coefficient of determination indicated that 92 - 96 per cent of the variations in detachment was accounted for by differences in slope steepness and either discharge, intensity or kinetic energy of rain. The percentage was however reduced to 72 when the data for all the soils were bulked and analysed. Nevertheless, an inclusion of a grain size term (d_{50} or d_{84}) again increased the R^2 from 0.72 to 0.90 with detachment decreasing as - 0.47 and - 0.33 power of d_{50} and d_{84} respectively. With an exponent of 0.81, flow power together with grain size explained about 85 per cent of the variations in detachment by flow with rain.

6.6 DISCUSSION

As stated earlier, overland flow also has the capacity to detach soil particles. Since minor concentrations of flow (< 2 mm) were observed as a result of the roughness elements on the soil plates used, overland flow as simulated in this text is viewed as comprising sheet as well as incipient channel flow. In reality, this is the pattern of flow often observed in the field (Emmett, 1970; Dunne, 1978; Morgan, 1979). Whether incipient channel flow should be classified as overland flow or channel flow is a question to be resolved by further research (Morgan, 1980).

TABLE 62 Power equations relating detachment by overland flow with rain (Q_{rodet}; kg m^{-2}) to discharge (q; m^3 s^{-1} m^{-1}), Slope (S; sin S), rain intensity (I; mm h^{-1}), total kinetic energy of rain (KE; J m^{-2}), and grain size (d_{50}, d_{84}; mm). n = 64 for each soil; n = 256 for all soils.

Soil	Equation	r_1^2	r_2^2	R^2	SEE	Eq. No
Standard sand	$Q_{rodet} = e^{12.84}\ q^{1.16}$	0.43	-	-	1.68	263
	$Q_{rodet} = e^{3.78}\ S^{0.93}$	0.51	-	-	1.61	264
	$Q_{rodet} = e^{15.24}\ q^{1.16}\ S^{0.93}$	0.43	0.51	0.94	1.18	265
	$Q_{rodet} = e^{-1.23}\ I^{1.12}\ S^{0.93}$	0.43	0.51	0.94	1.18	266
	$Q_{rodet} = e^{-3.17}\ KE^{1.03}\ S^{0.93}$	0.43	0.51	0.94	1.18	267
Sand	$Q_{rodet} = e^{12.85}\ q^{1.19}$	0.54	-	-	1.54	268
	$Q_{rodet} = e^{3.07}\ S^{0.78}$	0.42	-	-	1.62	269
	$Q_{rodet} = e^{14.85}\ q^{1.19}\ S^{0.78}$	0.54	0.42	0.96	1.14	270
	$Q_{rodet} = e^{-2.10}\ I^{-1.15}\ S^{0.78}$	0.54	0.42	0.96	1.13	271
	$Q_{rodet} = e^{-4.14}\ KE^{1.06}\ S^{0.78}$	0.54	0.42	0.96	1.13	272

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TABLE 62 (continued - 2)

Soil	Equation	r_1^2	r_2^2	R^2	SEE	Eq No
Clay loam	$Q_{rodet} = e^{10.49}\ q^{0.97}$	0.68	-	-	1.30	273
	$Q_{rodet} = e^{1.99}\ S^{0.45}$	0.26	-	-	1.48	274
	$Q_{rodet} = e^{11.63}\ q^{0.97}\ S^{0.45}$	0.68	0.26	0.94	1.12	275
	$Q_{rodet} = e^{-2.23}\ I^{0.94}\ S^{0.45}$	0.68	0.26	0.94	1.12	276
	$Q_{rodet} = e^{-3.86}\ KE^{0.87}\ S^{0.45}$	0.68	0.26	0.94	1.12	277
Clay	$Q_{rodet} = e^{11.79}\ q^{1.13}$	0.74	-	-	1.30	278
	$Q_{rodet} = e^{1.67}\ S^{0.41}$	0.18	-	-	1.60	279
	$Q_{rodet} = e^{12.89}\ q^{1.13}\ S^{0.41}$	0.74	0.18	0.92	1.16	280
	$Q_{rodet} = e^{-3.24}\ I^{1.10}\ S^{0.41}$	0.74	0.18	0.92	1.16	281
	$Q_{rodet} = e^{-5.12}\ KE^{1.01}\ S^{0.41}$	0.74	0.18	0.92	1.16	282

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TABLE 62 (continued - 3)

Soil	Equation	r_1^2	r_2^2	r_3^2	R^2	SEE	Eq. No
All soils	$Q_{rodet} = e^{13.76}\ q^{1.12}\ S^{0.64}$	0.45	0.27		0.72	1.40	283
	$Q_{rodet} = e^{13.40}\ q^{1.12}\ S^{0.66}\ d_{50}^{-0.47}$	0.45	0.27	0.18	0.90	1.23	284
	$Q_{rodet} = e^{13.55}\ q^{1.12}\ S^{0.63}\ d_{84}^{-0.33}$	0.45	0.26	0.17	0.88	1.25	285
	$Q_{rodet} = e^{-2.27}\ I^{1.09}\ S^{0.64}$	0.45	0.27		0.72	1.40	286
	$Q_{rodet} = e^{-2.62}\ I^{1.09}\ S^{0.66}\ d_{50}^{-0.47}$	0.44	0.28	0.18	0.90	1.23	287
	$Q_{rodet} = e^{-2.35}\ I^{1.09}\ S^{0.63}\ d_{84}^{-0.33}$	0.45	0.26	0.17	0.88	1.25	288
	$Q_{rodet} = e^{-4.20}\ KE^{1.01}\ S^{0.64}$	0.45	0.27		0.72	1.04	289
	$Q_{rodet} = e^{-4.51}\ KE^{1.0}\ S^{0.66}\ d_{50}^{-0.47}$	0.44	0.28	0.18	0.90	1.23	290
	$Q_{rodet} = e^{-4.27}\ KE^{1.0}\ S^{0.63}\ d_{84}^{-0.33}$	0.45	0.26	0.17	0.88	1.25	291
	$Q_{rodet} = e^{2.07}\ (qs)^{0.82}\ d_{50}^{-0.47}$	0.67	0.18		0.85	1.29	292
	$Q_{rodet} = e^{1.80}\ (qs)^{0.81}\ d_{84}^{-0.33}$	0.66	0.17		0.83	1.30	293

Where rills are formed, soil particles are detached both from the rill and interrill areas by flow (Foster and Meyer, 1975; Meyer et al. 1975). However because interrill flow is often accompanied by small flow rates, depths and shear stresses, its detachment capacity is often regarded as negligible (David and Beer, 1975; Foster and Meyer, 1975; Rowlison and Martin, 1971; Morgan and Morgan, 1981). The results of this study, however, indicate that in the presence of minor flow concentrations, the tractive forces exerted by overland flow (0.95 - 1.26 N m^{-2}) can exceed the critical values, 0.72 - 1.0 N m^{-2} (Smerdon, 1964), for most agricultural soils. The result is the formation of rills and a significant contribution to detachment (Plates 17 - 22). In its role as a contributor to sediment production in drainage basins, the capacity of overland flow to detach soil particles should not be underestimated. Depending on flow rate, slope steepness, soil type, raindrop impact and their interactions, the detachment capacity of overland flow may even outstrip that by splash. Yet, because hardly any work has been done on the separate evaluation of the detachment capacity of overland flow, the effects of these factors have also not been explicitly assessed.

6.6.1 Factors influencing detachment by overland flow with and without rain.

Flow rate

The magnitude of the hydrodynamic forces such as drag, lift and viscous forces exerted by flow on the soil surface significantly influences how much material is detached (Carson and Kirkby, 1972; Graf, 1971). The average hydraulic conditions of overland flow as measured in this study revealed increases in flow velocity, tractive force, stream power and total runoff energy as flow rate increased. It is therefore not surprising that detachment capacity increased with increasing flow rate.

The detachment capacity of the flow is further influenced by the interaction of discharge with slope steepness and soil type. The implication is that discharge is not independent in its effect on detaching soil particles. As slope steepness increases, the capacity of the flow to detach particles increases, this increase being proportionately greater for the lower flow rates. Similarly, as soils vary in type, so also does the detachment capacity of flow. However, in some cases, the detachment capacity of a given flow rate may be the same for different soils as observed for the 1.6 l/min flow on clay and clay loam.

The effect of raindrop impact was to about treble the capacity of flow to detach soil particles. This increase may be accounted for by the following observations.

1) Raindrop impact increased the tractive force of overland flow by an average of 9.6 per cent (Chapter 5) and by imparting energy to the flow while disturbing its surface may have increased the intensity of turbulence as observed by Yoon and Wenzel, 1971; and Shen and Li, 1973).

2) In addition to the amount of soil detached from the rills by flow, raindrops directly dislodged particles from the interrill areas and the sides of the rills.

3) Because of the effect in (2) the area contributing to detachment by the combined flow and rain was greater relative to the small area covered by the rills alone especially on the clay and clay loam. This accords with the observation made by Morgan (1977) on the effectiveness of sheetwash in contrast to rill erosion on Cottenham sand in the field.

Soil type

As a result of variations in soil type, the amount of soil detached differed significantly in the order of standard sand > sand > clay loam > clay. According to Ellison and Ellison (1947) the amount of soil detached is a function not only of the energy of flow but also the detachability of the soil. Both Shield's (1936) and Hjulström's (1935) diagrams show that loose fine sand is the least resistant to entrainment. It is thus reasonable to assume the detachability of the soils to increase in the same order as presented above. The differential detachability of the soils has important implications on the pattern of erosion that may occur. As observed by Ellison and

Ellison (1947) in the field, rills formed on soils that are of low detachability tend to be considerable distances apart while the converse is true of highly detachable soils. This pattern is portrayed by Plates 20 and 17 for Cottenham sand and clay respectively.

It is further shown that the effect of soil type on detachment varies with slope steepness and flow rate. This is implicit in the significant interactions of the latter two factors with soil type, an effect that is clearly demonstrated in Plates 21 and 22.

Slope steepness

On account of the increases in flow velocity, tractive force, stream power and total kinetic energy of flow due to increasing slope steepness, the detachment of soil particles was also enhanced in sympathy. This is in agreement with the observations of Woodruff (1947) and Ellison (1947). The slope effect is however influenced by the type of soil and flow rate, a fact borne out by the significant soil x slope and slope x discharge interactions.

Compared to flow without rain, raindrop impact significantly increased the amount of soil detached on each slope. As indicated earlier, impacting raindrops added to detachment by dislodging particles from the interrill areas. Since the normal component of the impact force increases as the cosine of the slope angle (Rowlison and Martin, 1971) the increase due to raindrop impact was significantly greater on the 3.5 and 7.0 than the 10.5 and 14.0 per cent slopes.

6.6.2 Relationships for detachment rate by overland flow

In establishing predictive equations for the detachment capacity of overland flow, attention was first paid to those parameters that can be readily measured or reliably evaluated, as suggested by Meyer (1981). Among these are slope steepness and discharge which, as shown by the results, are significantly correlated with the flow's capacity to detach soil particles. Since slope steepness and runoff management play a major role in controlling erosion, their inclusion in models provides a useful base for evaluating the effectiveness of conservation practices. Two sets of relationships for flow with and without rain were obtained.

The equations for flow without rain show that the magnitude of the exponents relating detachment capacity to slope steepness and discharge are significantly influenced by soil type. This reflects the significant interactions between the three factors. The detachment of clay and clay loam is more sensitive to increases in discharge than to increases in slope steepness and the converse is true of standard sand and sand. For this reason slope steepness explained a greater percentage of the variations in the detachment of the sandy soils whilst for the clayey soils discharge was the main variable.

The intercept values of the equations are usually taken to represent the detachability of the soil. On this basis, the equations incorporating discharge and slope steepness show the clayey soils to be more detachable than the sandy soils. This is the exact reverse of the ranking order shown by the mean detachment values and the equations for flow with rain. The reasons for this reverse trend, which questions the real meaning of the intercept values, were not immediately obvious.

Most of the equations for the individual soils relating detachment capacity to discharge and slope are very satisfactory (R^2 = 90 - 96) for predictive purposes. On the other hand, the general equation for all soils, obtained from 256 observations, with R^2 of 0.46, did not perform so well. However, an inclusion of a grain size term significantly improved its predictive capabilities (R^2 = 0.90). The assumed linear relationship shows detachment capacity of overland to be very sensitive to grain size, increasing as particle size decreases. This indicates the way in which particle size generally affects detachment and fits the trend shown by the Shield's (1936) diagram for uniform grain sizes greater than 0.25 mm. The linear relationship does not however cater for the influence of particle cohesiveness, which increases as particle size decreases with a resulting decline in detachment rate. Also, it does not account for the effects of surface armouring by coarser fractions, cover crops and mulches which may protect finer particles and thereby reduce the rate at which they are detached. Moreover, for small slope steepnesses and lengths, detachment increases as particle size increases (Meyer and Monke, 1965; Bubenzer et al. 1966). All these effects must be recognized in interpreting results.

The equations which incorporate flow power and grain size are also satisfactory for predicting detachment by flow. Such relationships, as noted by Kirkby (1980), are convenient, simple and provide a link to expressions for bed materials movement based on stream power per unit area.

In addition to slope steepness and discharge, detachment capacity of flow with rain was expressed in terms of total kinetic energy and intensity of rain. The exponents for the latter three parameters tended to center around 1.0. In spite of the variations in the soils used, the exponents are quite stable and detachment capacity can be reasonably approximated as proportional to either discharge, or total kinetic energy or intensity of rain. This makes the exponent independent of soil type and the time period over which detachment is measured (Morgan and Morgan, 1981). Apart from being mathematically convenient, it fulfils an important requirement in establishing parameter values for general use in detachment capacity equations. Such an expression also permits the isolation and assessment of the temporal variations in the detachability of the soil in contrast to lumping them with gross rainfall or flow parameters, as noted by Foster and Meyer (1975).

Detachment by flow with rain is however less sensitive to grain size. This is not surprising since raindrops can dislodge a wide range of soil particles (Ellison, 1944; Gabriels and Moldenhauer, 1978; Alberts et al., 1980). The high coefficient of determination for the equations also promises a satisfactory estimation of detachment by flow with rain.

Comparisons of the exponents in the equations for flow with and without rain indicate that higher values are related to situations where detachment is mainly by rilling (flow without rain) while a relatively even removal of soil as observed for flow with rain yields lower values. The higher values may be due to the flashy nature of sediment discharge from the rills. With each intermittent slump of rill sides, an event which is very sensitive to increases in discharge and slope steepness, there was a tremendous increase in the amount of soil detached. Nevertheless, the discharge exponent for both types of flow was similar for the sandy soils. The higher intercept values of the equations for the sandy soils however indicate that sand and standard sand are more detachable than the clay and clay loam. Because of this, even small flows can form rills over the entire surface of the former soils. Detachment without rain may in this case be almost as uniform as that by flow with rain.

Meyer and Wischmeier (1969) quote 0.666 for the exponent of both discharge and slope steepness in their equation for detachment by runoff without rain. In comparison, the 1.50 and 1.44 obtained here for the discharge and slope exponents for all soils are quite high. Their slope exponent is however the same as the 0.66 obtained in the general equation for flow with rain.

The exponents of flow power compare with the value of 2.0 suggested by Kirkby (1980) for rill flow detachment. The equations involving flow power basically represent the relationship between detachment and slope length, a surrogate for runoff and slope steepness. On this premise, the value 1.4 for flow without rain is the same as reported by Zingg (1940), Musgrave (1947) and Kirkby (1969) for soil loss on field plots up to 15 per cent slope steepness. Values (-3.8 to 2.0) derived experimentally for other conditions and from which reasonable judgements on the appropriate value of the flow power exponent can be made have been listed by Morgan (1980)

6.6.3 Relative contribution to total detachment by raindrop impact and overland flow.

If the choice of soil conservation strategies is to be based on which process limits erosion, then the relative importance of the process under given conditions must be known (Morgan, 1980; Meyer, 1981). Earlier studies indicate that raindrop impact is the major detaching agent (Ellison, 1947; Young and Wiersma, 1973). However on steeper slopes runoff water with its greater energy takes over as the main detaching agent (Woodruff, 1947; Meyer, 1981). The slope steepness at which this changing role takes place is not known, yet, because of its influence on the erosion limiting process, the success or failure of practices designed to control erosion may depend on it.

The results of this study indicate that the relative contribution to detachment by overland flow and splash is influenced by the type of soil and slope steepness. Over the range of slope steepnesses studied, raindrop impact was the principal detaching agent on the Cottenham sand (Fig 2b ii), clay loam (Fig 2a i), and clay (Fig 2a ii). This was true with the standard sand up to a slope steepness of about 10 per cent (Fig 2b i). Thereafter the bulk of detachment was by overland flow.

As slope steepens, the percentage contribution to detachment decreases for splash and increases for overland flow. Because of this behaviour, the percentage contribution curves slope upward and downward for overland flow and splash respectively (Figs 3a and 3b). This suggests a cross-over point which, in this study corresponds to a threshold slope steepness at which the two processes contribute equally to detachment. Beyond this point, overland flow becomes the dominant detaching agent. Fig 3b i thus gives a critical slope of about 10 per cent for standard sand. Assuming that the curves can be reasonably extrapolated, the critical slope for the Cottenham sand will be 17.15 per cent. The values of 39.73, and 60.90 per cent for clay loam and clay respectively are interesting for comparative purposes but, considering the range of slopes studied, such an extrapolation is unreasonable and is not recommended. The cross-over slopes depend on soil type (Figs 3a and 3b) and appear to decrease in the order of clay > clay loam > sand > standard sand.

6.7 HYDRAULICS OF DETACHMENT BY FLOW WITH AND WITHOUT RAIN

The detachment capacity of overland flow is related, among other things, to its hydraulic characteristics. Prominent among these are flow velocity and tractive force. Because of an inherent resistance of the soil due to particle weight, friction and cohesive forces (Carson and Kirkby, 1972; Vanoni, 1975), both flow velocity and tractive force must attain a threshold value before detachment commences (Hjulström, 1935; Shield, 1936). Although several aspects of the hydraulics of overland flow have been examined (Horton, 1970; Savat, 1977, 1980; Yoon and Wenzel, 1971; Robertson et al. 1966; Emmett, 1970, 1978), less attention has been paid to relating flow parameters to its capacity to detach soil particles (Foster and Meyer, 1975).

In order to characterize the detachment capacity of overland flow by its hydraulic properties, the detachment data were used in establishing relationships with the following flow parameters: velocity (V; m s^{-1}), depth (D; m), Reynolds number (Re), Froude number (F), Darcy-Weisbach's friction factor (f), tractive force (To; N m^{-2}), stream power per unit boundary area (Ps; J s^{-1} m^{-2}), runoff energy (RE; J m^{-2}) and slope steepness (S; sin S).

The equations for detachment by flow without rain (Table 63) showed that flow depth and friction factor are inversely related to detachment. For a given flow, increasing flow depth and friction factor result in reductions in flow velocity and therefore in flow power as momentum is transferred from flow to soil particles without entrainment and within the flow from one water 'particle' to another. Although the r^2 for depth was too low for predictive purposes, the results show a greater proportionate decrease in detachment of sand and standard sand with increasing depth (exponents of - 2 to - 2.65) than for clay and clay loam (- 0.58 to - 1.35). The latter two soils were however more sensitive to changes in friction factor (exponents of - 1.35 and - 1.39 compared with - 0.85 and - 0.54). In subcritical flows, where a laminar sublayer develops, a greater force is required to lift and entrain particles that are completely submerged in the layer (Statham, 1977; Allen, 1970). A decrease in flow velocity due to depth increases that may cause the sublayer to thicken will thus

TABLE 63 Power equations relating overland flow detachment (Q_{odet}; kg m^{-2}) to flow parameters

Soil	Equation	r_1^2	r_2^2	R^2	SEE	Eq. No
Clay loam	$Q_{odet} = e^{5.08}\ V^{2.43}$	0.83			1.53	294
	$Q_{odet} = e^{-5.53}\ D^{-0.58}$	0.03			2.76	295
	$Q_{odet} = e^{-9.20}\ Re^{2.09}$	0.61			1.91	296
	$Q_{odet} = e^{-1.01}\ F^{1.78}$	0.65			1.83	297
	$Q_{odet} = e^{-0.70}\ f^{-1.35}$	0.57			1.90	298
	$Q_{odet} = e^{-1.43}\ To^{2.34}$	0.54			2.01	299
	$Q_{odet} = e^{2.61}\ P_s^{\ 1.34}$	0.80			2.46	300
	$Q_{odet} = e^{-6.89}\ RE^{1.34}$	0.80			2.46	301
	$Q_{odet} = e^{-6.56}\ Re^{2.10}\ S^{1.09}$	0.61	0.29	0.90	1.35	302
Clay	$Q_{odet} = e^{4.36}\ V^{2.30}$	0.79			2.49	303
	$Q_{odet} = e^{-11.52}\ D^{-1.35}$	0.14			2.72	304
	$Q_{odet} = e^{-8.76}\ Re^{1.80}$	0.44			2.24	305
	$Q_{odet} = e^{-1.33}\ F^{1.85}$	0.73			1.75	306
	$Q_{odet} = e^{-0.92}\ f^{-1.39}$	0.68			1.84	307

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TABLE 63 (continued - 2)

Soil	Equation	r_1^2	r_2^2	R^2	SEE	Eq. No
Clay (continued)	$Q_{odet} = e^{-2.15}\ To^{2.48}$	0.50			2.14	308
	$Q_{odet} = e^{1.72}\ P_s^{\ 1.38}$	0.75			1.71	309
	$Q_{odet} = e^{-8.06}\ RE^{1.38}$	0.75			1.71	310
	$Q_{odet} = e^{-6.02}\ Re^{1.80}\ S^{1.25}$	0.43	0.37	0.80	1.61	311
Standard sand	$Q_{odet} = e^{6.92}\ V^{2.48}$	0.56			2.11	312
	$Q_{odet} = e^{-18.76}\ D^{-2.65}$	0.29			2.58	313
	$Q_{odet} = e^{-3.41}\ Re^{1.03}$	0.12			2.87	314
	$Q_{odet} = e^{0.79}\ F^{2.55}$	0.72			1.82	315
	$Q_{odet} = e^{0.64}\ f^{-0.54}$	0.07			2.98	316
	$Q_{odet} = e^{0.54}\ To^{2.68}$	0.88			1.49	317
	$Q_{odet} = e^{4.76}\ P_s^{\ 1.63}$	0.90			1.37	318
	$Q_{odet} = e^{-6.80}\ RE^{1.63}$	0.90			1.37	319
	$Q_{odet} = e^{1.43}\ Re^{1.04}\ S^{1.95}$	0.14	0.84	0.98	1.22	320

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TABLE 63 (continued - 3)

Soil	Equation	r_1^2	r_2^2	R^2	SEE	Eq. No
Sand	$Q_{odet} = e^{6.53} V^{2.48}$	0.71			1.69	321
	$Q_{odet} = e^{-14.53} D^{-2.01}$	0.22			2.36	322
	$Q_{odet} = e^{-4.36} Re^{1.11}$	0.19			2.40	323
	$Q_{odet} = e^{0.14} F^{0.78}$	0.47			2.04	324
	$Q_{odet} = e^{0.37} f^{-0.85}$	0.19			2.40	325
	$Q_{odet} = e^{-0.38} To^{2.20}$	0.75			1.62	326
	$Q_{odet} = e^{3.52} P_s^{1.41}$	0.89			1.39	327
	$Q_{odet} = e^{-6.48} RE^{1.41}$	0.90			1.37	328
	$Q_{odet} = e^{-0.73} Re^{1.12} S^{1.52}$	0.21	0.68	0.89	1.38	329
All soils (n = 256)	$Q_{odet} = e^{6.07} V^{2.42}$	0.45			2.81	330
	$Q_{odet} = e^{-14.07} D^{-1.65}$	0.13			3.69	331
	$Q_{odet} = e^{-6.05} Re^{1.51}$	0.15			3.63	332
	$Q_{odet} = e^{-0.23} F^{1.74}$	0.47			2.76	333
	$Q_{odet} = e^{-0.06} f^{-1.04}$	0.27			3.29	334
	$Q_{odet} = e^{-0.86} To^{2.42}$	0.28			3.29	335
	$Q_{odet} = e^{3.05} P_s^{1.44}$	0.45			2.81	336
	$Q_{odet} = e^{-7.16} RE^{1.44}$	0.45			2.81	337
	$Q_{odet} = e^{-1.67} Re^{1.51} S^{1.45}$	0.17	0.29	0.46	2.81	338

have a greater effect on the entrainment of submerged heavier particles (standard sand and sand) than lighter aggregates (clay and clay loam). On the other hand, although increasing friction factor also increases flow depth by decreasing velocity, the effects of the latter may be more important in the detachment of clay and clay loam particles. Because of their cohesiveness the critical velocities required to detach them are greater than those for the sandy soils. The effect of velocity reductions due to increasing friction factor is therefore more noticeable on these former soils.

The equations for the variables other than flow depth and friction factor, show a positive relationship with detachment. Although the performance of the flow parameters varied in all cases with soil type, 75 to 90 per cent of the differences in detachment was accounted for by variations in either stream power or total runoff energy; and the R^2 for Re and slope steepness ranged from 0.80 - 0.98. These high values show that any of the above equations are suitable for predicting the detachment capacity of flow.

The coefficient of determination for flow velocity, tractive force and Froude number ranged from 0.56 to 0.88 for standard sand, 0.47 - 0.75 for sand, 0.54 - 0.83 for clay loam, and 0.50 - 0.79 for clay.

The exponents of the parameters also varied with soil type. Detachment capacity increased as the 2.30 - 2.48 power of flow velocity. This range compares well with a value of 2.0 assumed by Meyer and Wischmeier (1968).

Attempts to relate the flow's detachment capacity to its tractive force have been made by Meyer and Wischmeier (1969), Foster and Meyer (1975) and Partheniades (1965) who quote tractive force exponents of 1.0, 1.5 and 1.9 respectively. These values are lower than the 2.2 - 2.68 obtained in this study. Flow power and total kinetic energy of flow are also highly correlated with detachment capacity. For each soil the exponent is similar for both parameters being 1.34, 1.38, 1.41 and 1.63 for clay loam, clay, sand and standard sand respectively. Kirkby (1980) however suggests a value of 2.0 for flow power in rill-flow detachment.

As Reynolds and Froude numbers increase, laminar subcritical flow approaches supercritical turbulent regime resulting in significant increases in detachment capacity. Even in the former regime, flow remains rough where surface roughness elements protrude above its surface (Carson and Kirkby, 1972; Thornes, 1980).

While most of the equations for individual soils are satisfactory for predicting detachment capacity, those for all soils combined are rather poor.

The equations for flow with rain are presented in Table 64. Compared to flow without rain, the detachment capacity of the combined flow and rain was less sensitive to the flow parameters. This is indicated by the relatively lower values of the exponents. Flow parameters that accounted for 74 - 96 per cent of the variations in detachment capacity include V, F, To, Ps, RE and (Re and S) for standard sand and sand; and V, Ps, RE, f and (Re and S) for clay and clay loam.

The values of the exponents for the flow parameters were quite similar for the clay and clay loam. The velocity exponent was 0.98, 1.84, and 2.09 for the clayey soils, standard sand and sand respectively. The latter is similar to the value used by Meyer and Wischmeier (1969). Where direct detachment by drop impact predominates over that by flow, as indicated earlier for clay and clay loam, detachment capacity will be less sensitive to increases in flow velocity and this explains the lower exponent. On the other hand, the contribution to detachment by flow is highly significant on the sandy soils. The proportionate increase in detachment is therefore greater as flow velocity increases.

The tractive force exponents ranging between 1.17 and 1.53 are well within the values quoted by Foster and Meyer (1975) and Meyer and Wischmeier (1969) but lower than the 1.9 obtained by Partheniades (1965). Detachment capacity was directly proportional to flow power and total kinetic energy of overland flow for the sandy soils but varied as the 0.62 power for the clayey soils. The predictive capabilities of the equations for all soils were better than those for flow without rain. However, because of the low R^2 values, they are still not adequate.

TABLE 64 Power equations relating detachment by overland flow with rain to flow parameters

Soil	Equation	r_1^2	r_2^2	R^2	SEE	Eq. No
Standard sand	$Q_{rodet} = e^{6.28}\ V^{1.84}$	0.84			1.31	339
	$Q_{rodet} = e^{-2.37}\ D^{-0.53}$	0.04			1.96	340
	$Q_{rodet} = e^{-2.91}\ Re^{1.14}$	0.45			1.67	341
	$Q_{rodet} = e^{1.75}\ F^{1.63}$	0.80			1.36	342
	$Q_{rodet} = e^{1.82}\ f^{-0.82}$	0.35			1.74	343
	$Q_{rodet} = e^{1.33}\ To^{1.53}$	0.75			1.41	344
	$Q_{rodet} = e^{3.96}\ P_s^{1.00}$	0.84			1.32	345
	$Q_{rodet} = e^{-3.13}\ RE^{1.00}$	0.84			1.32	346
	$Q_{rodet} = e^{-0.48}\ Re^{1.12}\ S^{0.92}$	0.45	0.51	0.96	1.17	347
Sand	$Q_{rodet} = e^{6.90}\ V^{2.09}$	0.97			1.11	348
	$Q_{rodet} = e^{-0.88}\ D^{-0.28}$	0.01			1.88	349
	$Q_{rodet} = e^{-3.63}\ RE^{1.25}$	0.53			1.54	350
	$Q_{rodet} = e^{1.83}\ F^{1.87}$	0.90			1.22	351
	$Q_{rodet} = e^{2.11}\ f^{-1.15}$	0.48			1.63	352
	$Q_{rodet} = e^{0.87}\ To^{1.29}$	0.66			1.45	353

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TABLE 64 (continued - 2)

Soil	Equation	r_1^2	r_2^2	R^2	SEE	Eq. No
Sand (continued)	$Q_{rodet} = e^{3.44} P_s^{0.90}$	0.88			1.24	354
	$Q_{rodet} = e^{-2.94} RE^{0.90}$	0.88			1.24	355
	$Q_{rodet} = e^{-1.58} Re^{1.22} S^{0.76}$	0.53	0.42	0.95	1.14	356
Clay loam	$Q_{rodet} = e^{3.55} V^{0.97}$	0.85			1.20	357
	$Q_{rodet} = e^{-1.20} D^{-0.29}$	0.05			1.56	358
	$Q_{rodet} = e^{-2.91} Re^{1.00}$	0.69			1.29	359
	$Q_{rodet} = e^{1.10} F^{0.66}$	0.63			1.32	360
	$Q_{rodet} = e^{1.35} f^{-0.59}$	0.77			1.24	361
	$Q_{rodet} = e^{0.70} T^{1.17}$	0.49			1.24	362
	$Q_{rodet} = e^{2.47} P_s^{0.61}$	0.79			1.23	363
	$Q_{rodet} = e^{-1.82} RE^{0.61}$	0.79			1.23	364
	$Q_{rodet} = e^{-1.76} Re^{0.99} S^{0.43}$	0.69	0.26	0.95	1.13	365

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TABLE 64 (continued - 3)

Soil	Equation	r_1^2	r_2^2	R^2	SEE	Eq. No
Clay	$Q_{rodet} = e^{3.44}\ V^{0.99}$	0.78			1.27	366
	$Q_{rodet} = e^{-1.31}\ D^{-0.28}$	0.04			1.65	367
	$Q_{rodet} = e^{-3.70}\ Re^{1.15}$	0.74			1.30	368
	$Q_{rodet} = e^{0.95}\ F^{0.66}$	0.57			1.40	369
	$Q_{rodet} = e^{1.29}\ f^{-0.61}$	0.78			1.27	370
	$Q_{rodet} = e^{0.31}\ To^{1.37}$	0.42			1.48	371
	$Q_{rodet} = e^{2.27}\ P_s^{\ 0.63}$	0.69			1.33	372
	$Q_{rodet} = e^{-2.20}\ RE^{0.63}$	0.69			1.33	373
	$Q_{rodet} = e^{-2.32}\ Re^{1.14}\ S^{0.41}$	0.74	0.18	0.92	1.16	374
All Soils	$Q_{rodet} = e^{3.62}\ V^{1.47}$	0.51			1.56	375
	$Q_{rodet} = e^{-2.40}\ D^{-0.48}$	0.05			1.87	376
	$Q_{rodet} = e^{-3.29}\ Re^{1.14}$	0.45			1.61	377
	$Q_{rodet} = e^{1.38}\ F^{1.20}$	0.60			1.50	378
	$Q_{rodet} = e^{1.63}\ f^{-0.78}$	0.55			1.54	379
	$Q_{rodet} = e^{0.82}\ To^{1.34}$	0.37			1.67	380
	$Q_{rodet} = e^{3.56}\ P_s^{\ 0.79}$	0.51			1.56	381
	$Q_{rodet} = e^{-2.04}\ RE^{0.79}$	0.51			1.56	382
	$Q_{rodet} = e^{-1.63}\ Re^{1.12}\ S^{0.63}$	0.45	0.27	0.72	1.41	383

6.8 SUMMARY

From the above results the contribution to our knowledge on the detachment capacity of overland flow can be summarized as follows:

1) In the presence of minor flow concentrations such as on rough surfaces, the capacity of overland flow to detach soil particles can be considerable.

2) For flow without rain, detachment was mainly by rilling, the intensity of rilling being influenced by soil type, slope steepness, flow rate and their interactions.

3) Detachment by flow with rain consisted of a relatively even removal of soil particles from the entire surface of the test soil thereby rendering the latter surfaces relatively level. Raindrop impact thus appears to inhibit rill formation by shallow flows especially on small slope steepnesses.

4) The factors influencing detachment by flow with rain rank in an order of importance as soil type, slope steepness and discharge. The corresponding order for flow with rain was intensity, slope steepness and soil type.

5) The magnitude of the effect of each of the three variables on detachment depends on the level of the other variables, with the slope x soil interaction being the most important affecting detachment by flow with and without rain.

6) The relative detachabilities of the soils in the absence of rain were 0.49, 0.16 and 0.10 compared with standard sand (1.0) for sand, clay loam, and clay respectively. With rain, detachability increased with the corresponding values being 0.72, 0.53 and 0.43.

7) On the average, the addition of rainfall increased the detachment capacity of flow three fold.

8) Detachment by flow with rain is less sensitive to particle size than that by flow without rain.

9) Over the range of slope steepnesses studied, raindrop impact was the principal detaching agent on the Cottenham sand, clay loam and

clay. This was also true with the standard sand up to a slope steepness of about 10 per cent. Thereafter, the bulk of detachment was by overland flow.

10) As slope steepens, the percentage contribution to detachment decreases for splash and increases for overland flow.

11) There is a threshold slope at which both splash and overland flow contribute equally to detachment. At slopes lower than the critical slope, splash is the main detaching agent shilst detachment by flow predominates at steeper slopes.

12) The critical slope is soil specific and appears to decrease in the order of clay > clay loam > sand > standard sand. The respective critical slopes for these soils are 60.90, 39.73, 17.15 and 10.0 per cent. The first three values were obtained by extrapolation which is not recommended.

13) There was a significant correlation between detachment capacity and flow parameters, the most important being with flow velocity, stream power per unit boundary area, total runoff, kinetic energy and Reynolds number. Detachment was negatively correlated with flow depth and friction factor.

14) For flow without rain, detachment increased as the 2.42, 1.44, and 1.51 of velocity, streampower and total kinetic energy of flow, and Reynolds number. The corresponding values for flow with rain were 1.47, 0.79, and 1.12.

15) The most important flow parameter that singly predicted detachment capacity of flow with rain was velocity. In the absence of rain, flow velocity, and flow power and total kinetic energy were the most important on the clay and clay loam, and the sand and standard sand respectively.

16) For predictive purposes power equations were established through multiple regression analysis between detachment capacity and discharge and slope steepness. In the case of flow without rain, the exponent for discharge and slope steepness ranged between 1.0 and 1.19 and 1.52 and 1.96 for the standard sand and sand. The corresponding values for clay and clay loam were 1.79 - 2.09 and 1.05 - 1.23. The R^2 for the equations ranged from 0.79 to 0.96.

17) In addition to discharge and slope steepness, relationships were established between detachment capacity and rain intensity and total kinetic energy of rain for overland flow with rain. In all cases the exponent of discharge, kinetic energy and intensity centered around 1.0. The slope exponent however varied from 0.78 to 0.93 and 0.41 to 0.46 for sand and standard sand; and clay and clay loam respectively. The R^2 of the equations was very high, 0.92 - 0.96.

18) The following general equations for all soils incorporating discharge, slope steepness, flow power and grain size were obtained for detachment capacity:

<u>Flow without rain</u>	R^2	Eq. No
$Q_{odet} = e^{16.37}\ q^{1.50}\ S^{1.44}\ d_{50}^{-1.54}$	0.91	384
$Q_{odet} = e^{0.04}\ (qs)^{1.41}\ d_{50}^{-1.54}$	0.91	385
<u>Flow with rain</u>		
$Q_{rodet} = e^{13.40}\ q^{1.12}\ S^{0.66}\ d_{50}^{-0.47}$	0.90	386
$Q_{rodet} = e^{1.80}\ (qs)^{0.82}\ d_{50}^{-0.47}$	0.85	387

19) In using the equations presented in this Chapter for predicting detachment rates, several modelling strategies can be adopted.

i) For the Meyer-Wischmeier (1969) approach, the appropriate equation for a particular soil incorporating discharge and slope steepness can be selected and used for overland flow without rain such as in irrigated fields. However, for rain-fed conditions, the equations for flow with rain should be used.

ii) Equations 384 and 386 are applicable where the Carson and Kirkby (1972) and Meyer and Monke (1965) types of model are adopted.

iii) For the flow power approach (Kirkby, 1980), Equations 385 and 387 are recommended. Where detachment on a particular soil is of interest, e.g. experimental fields, the flow power equation for the individual soils may be used.

iv) Alternatively the runoff energy approach may be used. In such situations, the runoff energy equations for the individual soils with r^2 greater than 0.80 can be used.

20) The use of equations that incorporate rainfall effects is recommended since in reality detachment is by the combined action of flow and rain.

21) Until validated for field conditions, the suggested working equations may be used only as first approximation in predicting detachment rates.

Vol 3

CHAPTER 7

TRANSPORT CAPACITY OF OVERLAND FLOW WITH RAIN AND SEDIMENT YIELD

The results of the sediment transport capacity experiments (Chapter 3) are presented in this Chapter under the headings of experimental observations; factors affecting transport capacity; factors affecting sediment yield; and relationships for transport capacity and sediment yield. These aspects comprise Sections 7.1 to 7.4. The results are discussed in Section 7.5 and a summary is presented in Section 7.6. As indicated earlier, the sediment transport tests comprised only runs with combined flow and rain and all the 256 runs were carried out on the same soil-plate.

7.1 EXPERIMENTAL OBSERVATIONS

Sediment introduced into the flow by gravity tended to pile up beneath the dispenser (Plates 23, 27 and 30). This was because sediment was protected against the direct impact of raindrops by the dispenser and sediment pick-up by the base flow could not match the sediment feed rate. The result was a build up of flow which overtopped the deposits or gushed through them at weak points discharging flushes of sediment into the test area (Plate 24). Once in the latter area, impacting raindrops splashed the particles about and distributed them more uniformly over the entire soil-plate (Plates 25, 30 and 31).

Movement of the clayey and sandy soils consisted predominantly of rolling of aggregates and saltation of particles respectively, processes which are associated with bed-load transportation. Occasionally, particles rolled in clusters whilst others, especially the clay and clay loam, were lifted into the flow and floated along as suspended load. Impacting raindrops played a significant role in these modes of transportation which increased with every burst of rain. It must be remembered that the rainfall simulator (Chapter 3) provided rain in successive bursts, each separated by a few seconds time lag. The role of raindrops in aiding the rolling of particles, coupled with direct splash transport was especially important on lower slopes and for small flow rates.

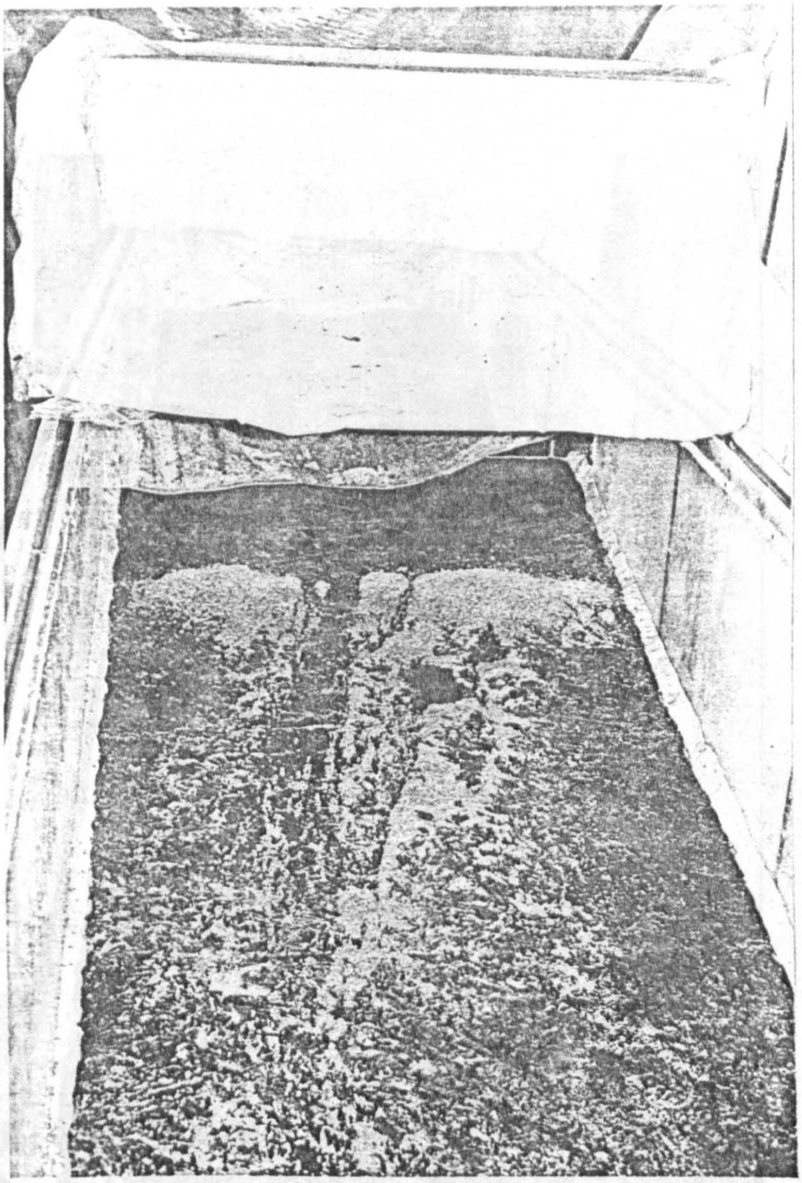

Plate 23 Transport of clay at 50 mm h^{-1} rain intensity and 14 per cent slope showing
pile of clay particles underneath sediment dispenser,
a break through clay pile resulting in a flush of clay aggregates by flow and
sediment dispenser covered with polythene sheet to prevent wetting of soil.

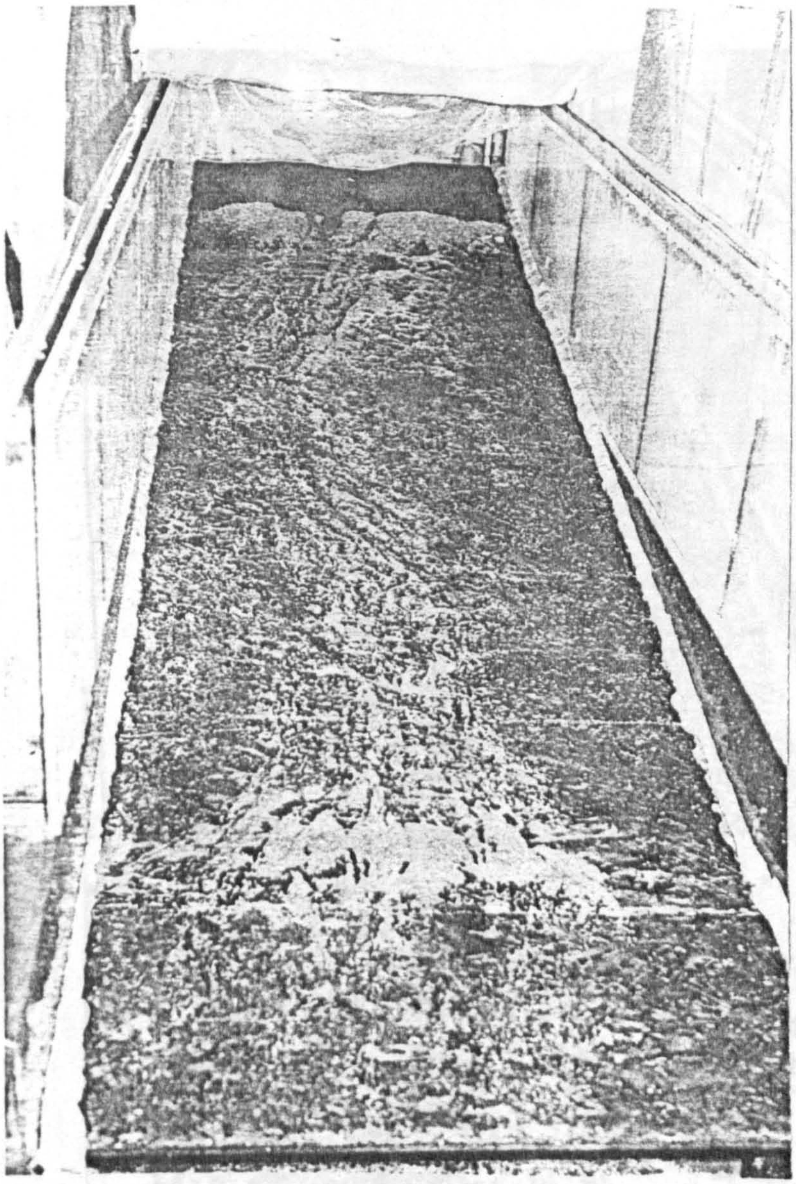

Plate 24 Transport of clay at 50 mm h^{-1} and 14 per cent slope showing flush of clay particles into test area by flow.

Plate 25 Transport of clay at 50 mm h^{-1} and 14 per cent slope showing distribution of clay aggregates over soil-plate, deposition of clay and splashed aggregates stuck on extension frame.

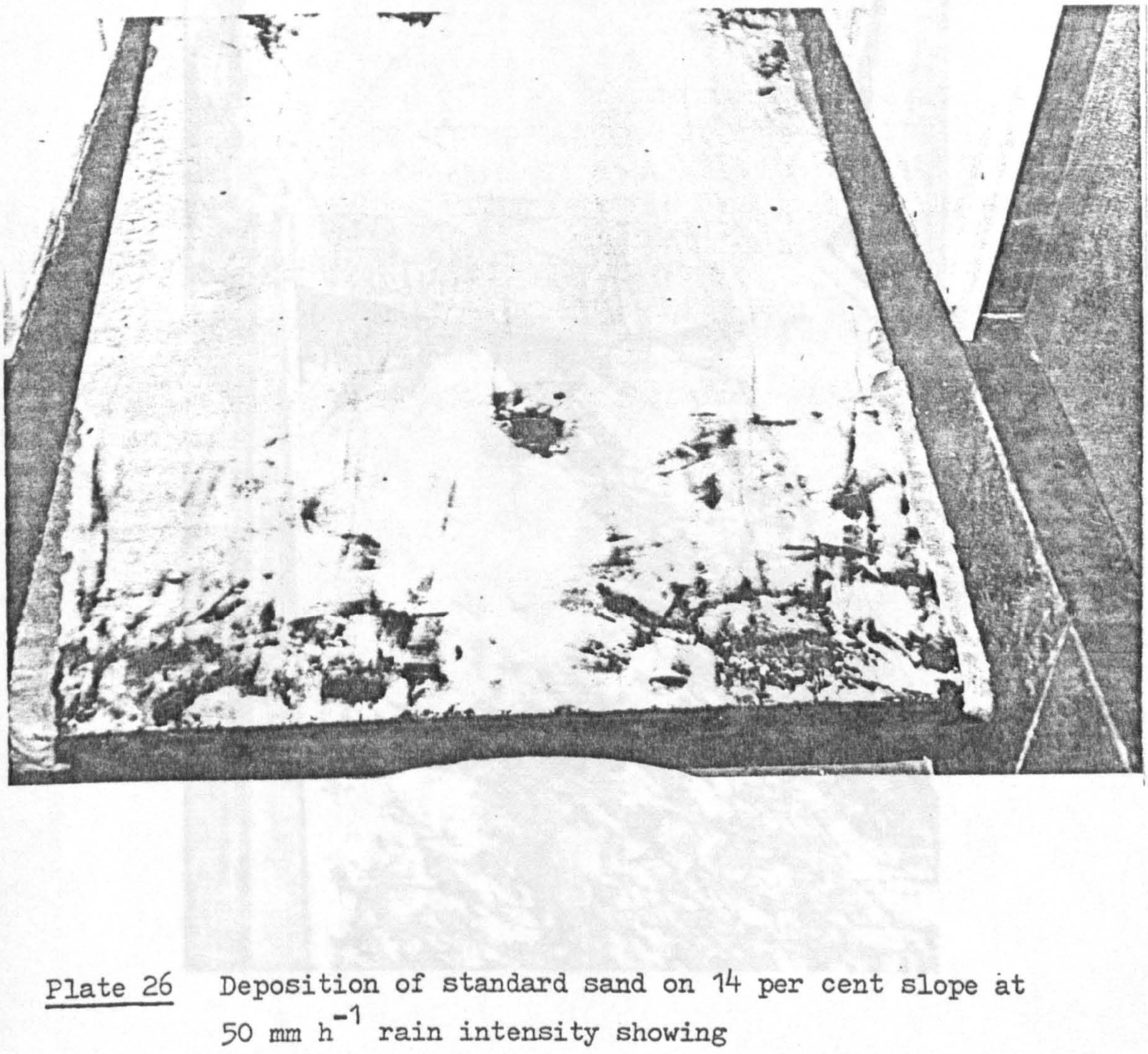

Plate 26 Deposition of standard sand on 14 per cent slope at 50 mm h^{-1} rain intensity showing
complete cover exit end of soil-plate,
flow lines and microrills,
porridge-like consistency of deposited particles and
original roughness elements swamped by sand particles.

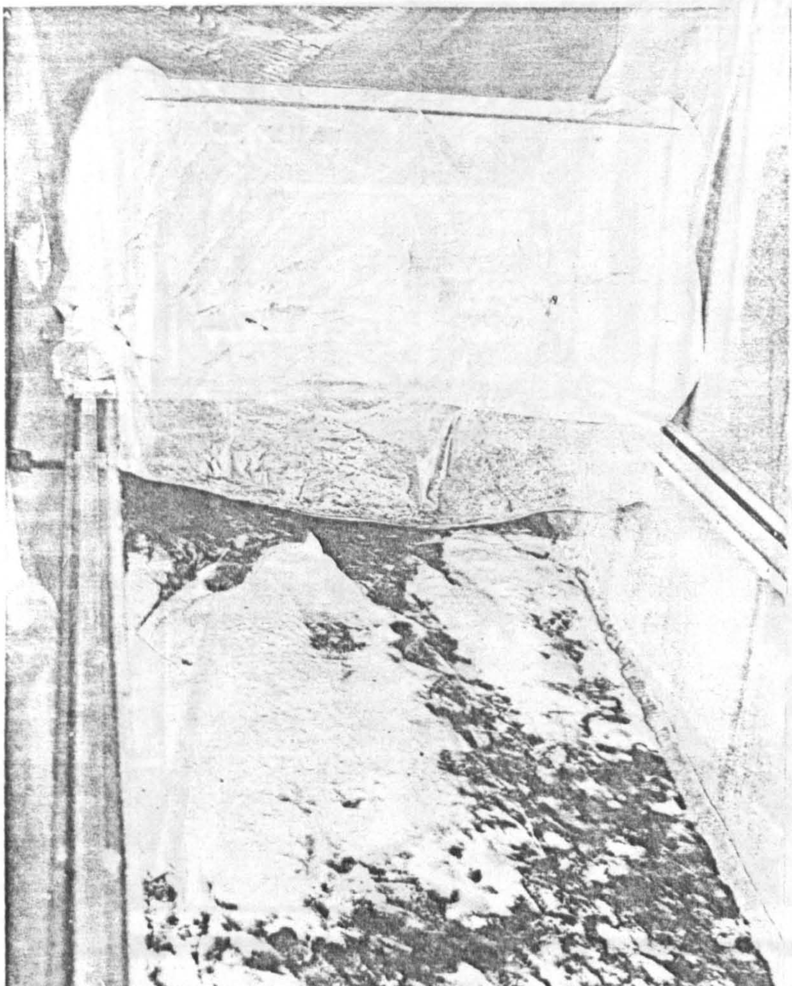

Plate 27 Input of standard sand into flow at 50 mm h^{-1} and 14 per cent slope showing deposition of sediment underneath dispenser, a break in deposited material by flow and a single "stalagmite".

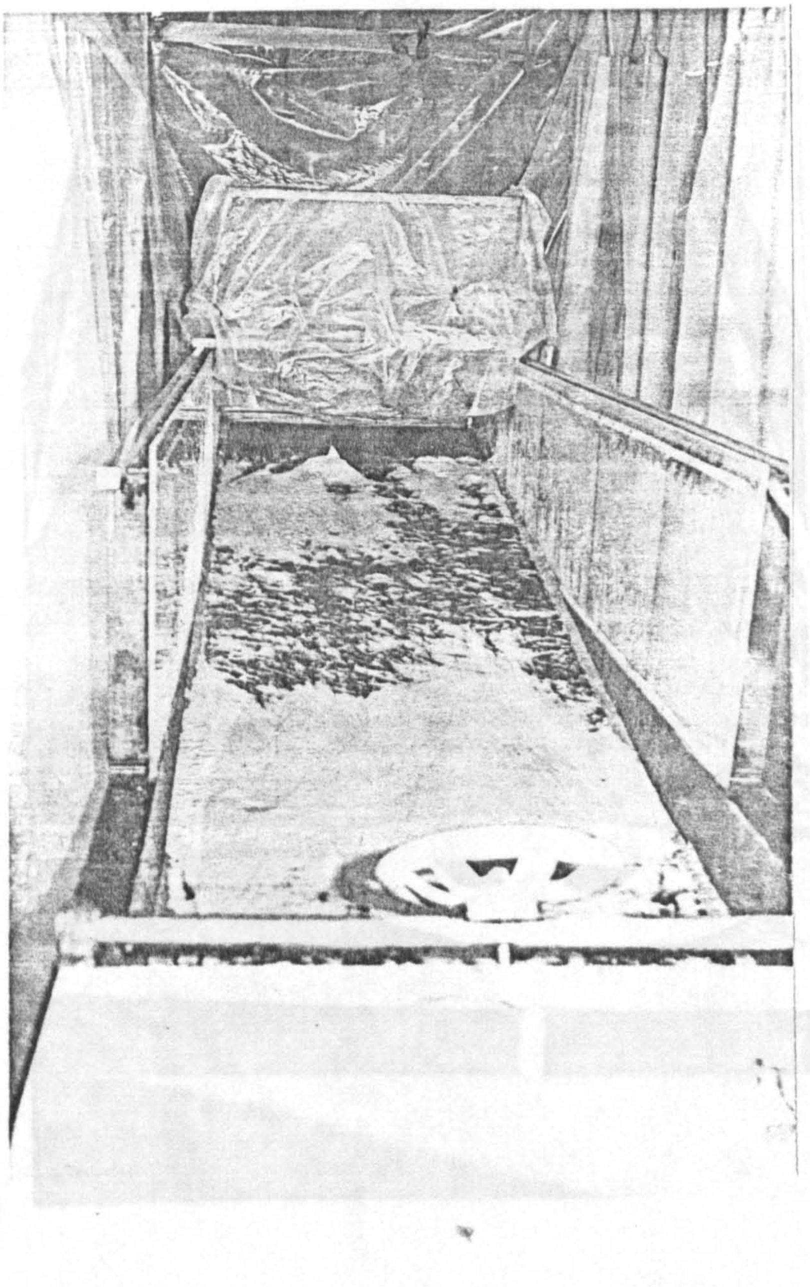

Plate 28 Deposition of standard sand at 14 per cent slope and $50\ mm\ h^{-1}$ showing
upslope advance of deposition
pile of particles under sediment dispenser and
splashed particles on extension frame.

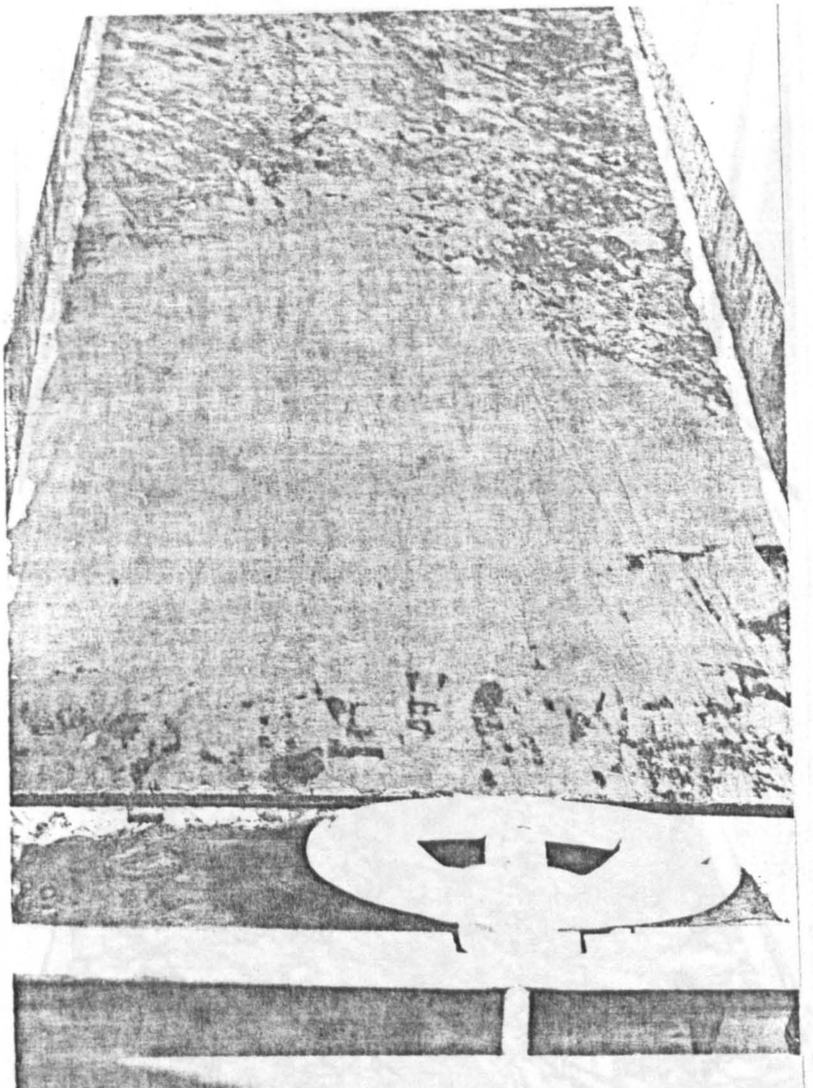

Plate 29 Deposition of sand on 10 per cent slope at 110 mm h^{-1} showing complete cover of exit end of plate with deposited sand, splashed particles on extension frame, flow lines on deposited material and upslope advance of deposition.

Plate 30 Input of Cottenham sand into flow showing dispenser covered with polythene sheet sac, 'mounds' of deposited sand underneath dispenser and deposited sand along soil-plate in microdepressions created by roughness elements.

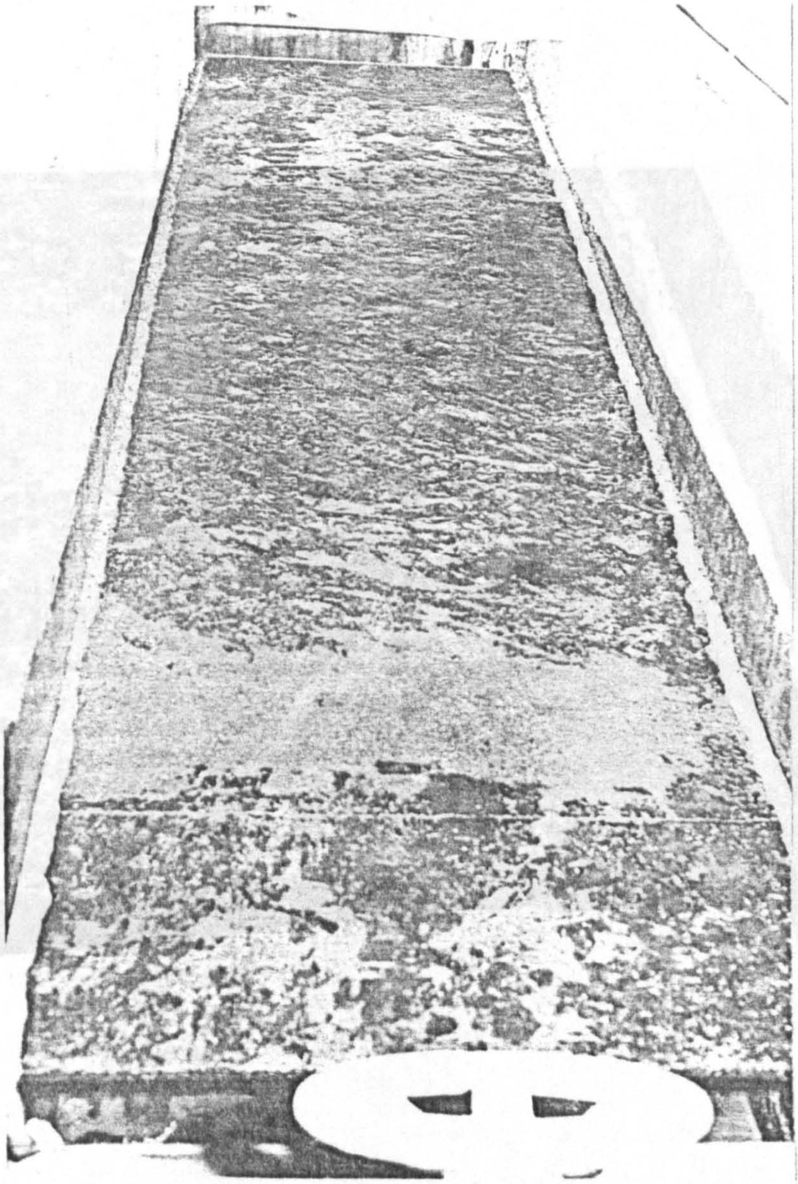

Plate 31 Deposition of clay at 50 mm h^{-1} and 7 per cent slope showing distribution of particles over the soil-plate.

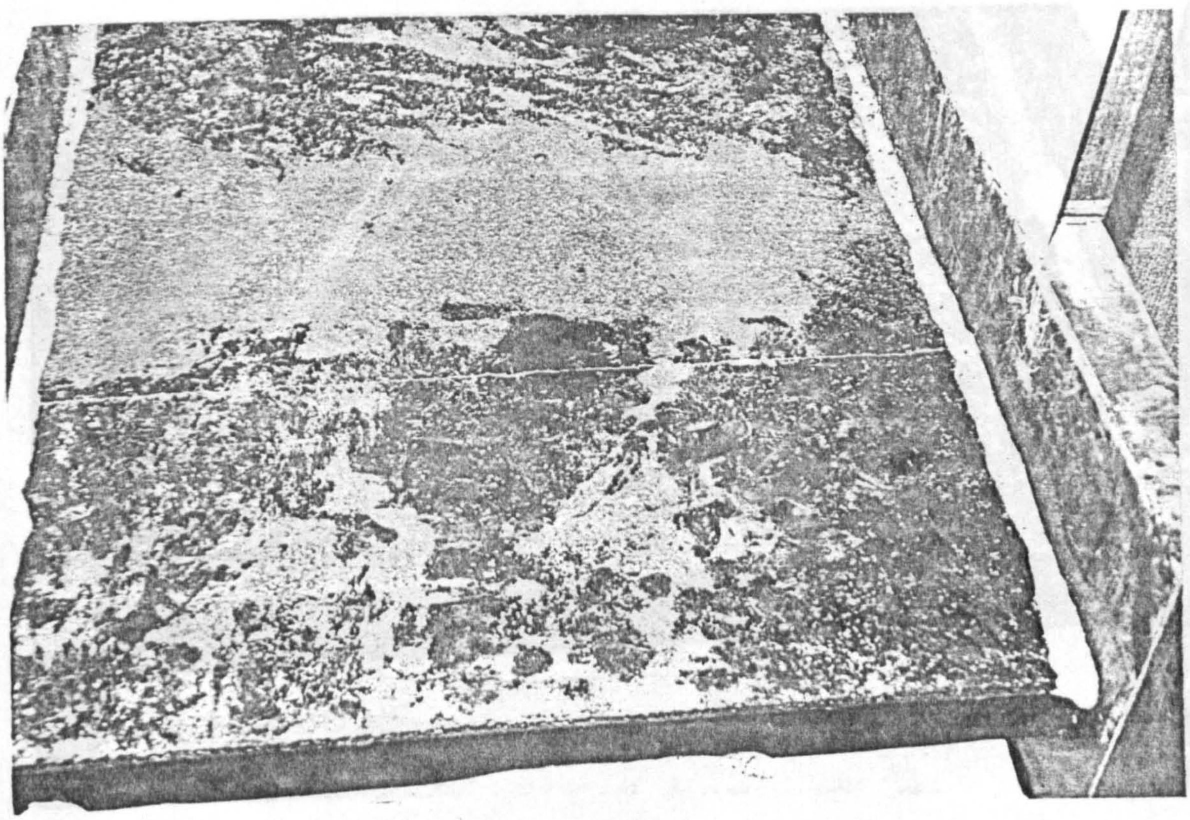

Plate 32 Transport of clay at 50 mm h^{-1} and 7 per cent slope showing significance of splash transport in moving clay aggregates, finer particles protected by coarse aggregates and patches of deposited finer material devoid of coarse aggregates.

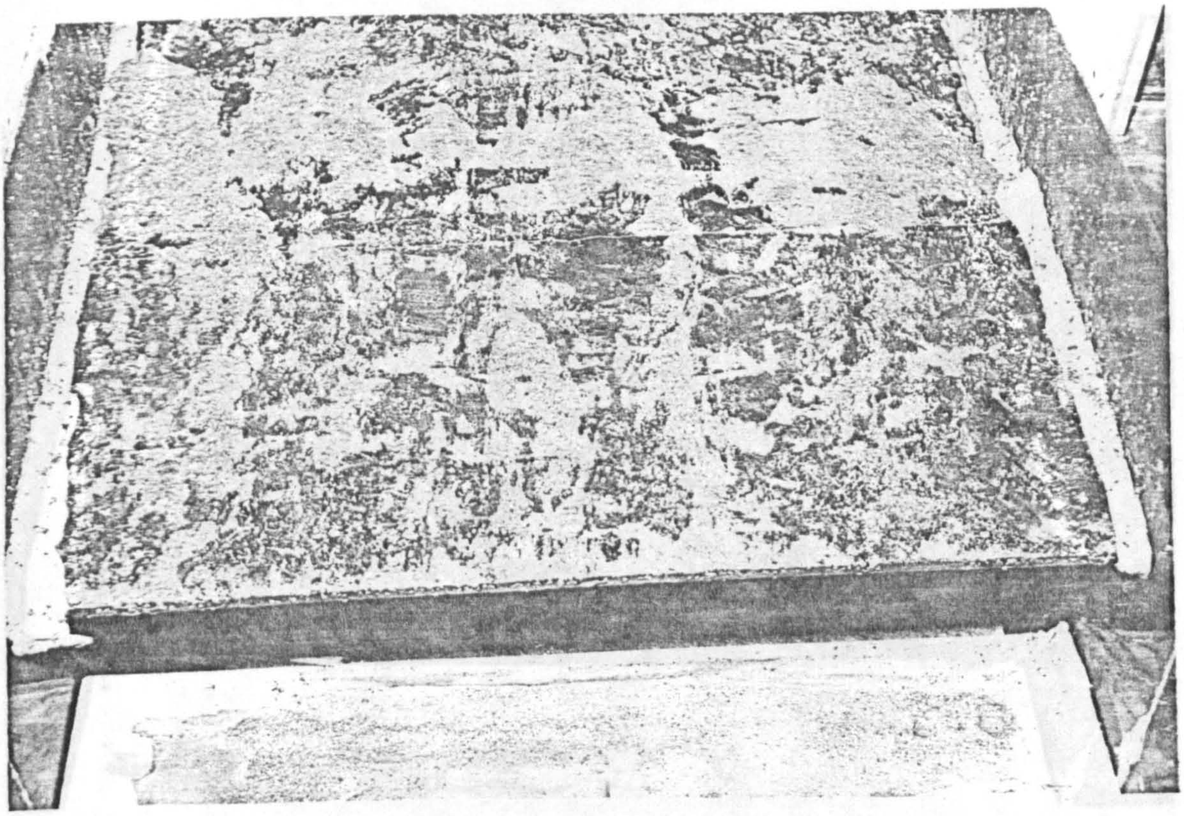

Plate 33 Transport of clay at 50 mm h^{-1} and 14 per cent slope showing sediment yield at end of run, preferential transport of coarse aggregates and evidence of direct splash transport of particles.

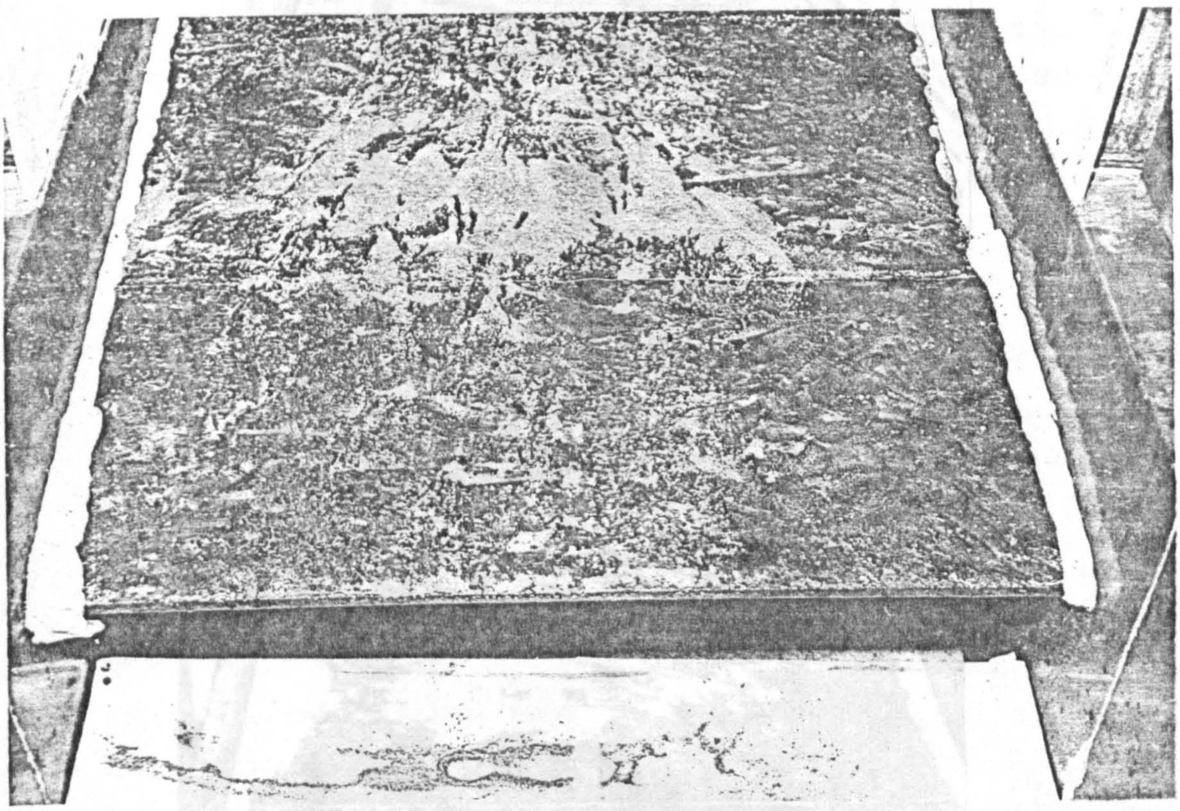

Plate 34 Transport of clay at 50 mm h^{-1} and 14 per cent slope showing sediment collecting tray lined with white cloth, deposition 5 minutes after start of run and sediment yield 5 minutes after start of run.

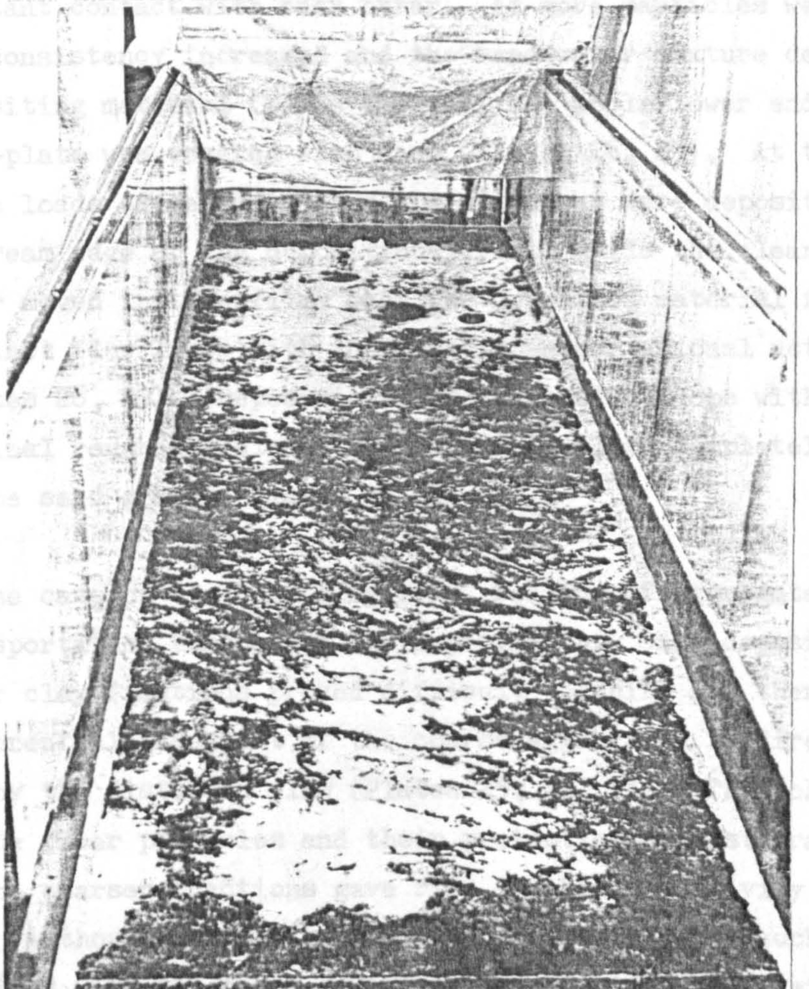

Plate 35 Transport of standard sand at 50 mm h^{-1} and 7 per cent slope showing deposition after 45 minute run.

The intensity of the rolling and saltatory movements increased with increasing discharge and slope steepness. At the higher levels of these factors, particularly in combination, mass movement of particles also occurred. The sand and standard sand moved with porridge-like consistency and particles maintained constant contact with each other. As more particles were added, the consistency increased and the sand-water mixture decelerated depositing material (Plate 34) till the whole lower end of the soil-plate was covered with sand (Plates 26, 29). At this stage, fresh loads of sediment from the dispenser were deposited at the upstream edge of the depositional field while the clear sand-free water moved in thin films over the deposited material forming distinct flow lines with increased transportational activity (Plates 26, 29). Deposition thus advanced upslope with the original roughness elements of the soil-plate completely swamped by the sand grains (Plates 26, 28, 29).

In the case of clay and clay loam, rolling of aggregates dominated transportation throughout the experiments. Once deposited, the finer clay fractions proved difficult to shift and there was a preferential transport of the coarse aggregates by direct splash and by the disturbed flow (Plates 25, 32, 33). The cohesiveness of the finer particles and their protection against transportation by the coarser fractions gave rise to this selectivity (Plates 32, 33). Although deposition occurred, complete cover such as that obtained with the sandy soils was seldom attained (Plates 26, 33).

Early in a run, the rate at which sediment left the soil-plate (sediment yield) (Plate 34) was at a minimum but as deposition progressed sediment yield increased. After a considerable amount of deposition (Plates 26, 33) sediment yield tended to be relatively uniform and was transport capacity limited (Section 2.3.3).

At some factor combinations flow could not entrain and transport enough particles from upslope. Downslope deposition was therefore scanty (Plate 35) and sediment yield erratic. This occurred on the 3.5 and 7.0 per cent slope for sand and standard sand, and the 3.5 per cent slope for the clay and clay loam. For such runs, transport capacity could not be determined. Early in the tests on these slopes, the bulk of sediment load was deposited upslope resulting in no sediment yield. As the 45-minute run progressed, sediment was transported and deposited downslope giving some sediment yield due mainly to direct splash transport (Plates 32, 35).

7.2 FACTORS AFFECTING SEDIMENT TRANSPORT CAPACITY

Altogether the experiment comprised 256 runs but because steady state conditions could not be attained at some factor-combinations as indicated above, one-half of the data was eliminated. The transport capacity (kg m^{-1} min^{-1}) data at the 10.5 and 14.0 per cent slopes for all levels of soil and discharge (128 observations) were used for the analysis (Appendix 32).

The mean transport capacity (Table 67) differed significantly with the various soil types decreasing in the order of sand > standard sand > clay > clay loam. As discharge and slope steepness increased, transport capacity also increased with significant differences ($P = 0.01$) between the levels of the factors. For a discharge range of 1.0 and 2.8 l/min, transport capacity increased about four fold.

The analysis of variance of the data (Table 66) showed that in an order of importance, the factors ranked as discharge, slope steepness, and soil type in their effects on transport capacity. The first and second order interactions of the factors also significantly influenced transport capacity with the slope x soil being the most prominent, followed by discharge x soil and then slope x discharge. Because of these interactions, the magnitude of each factor's effect on transport capacity varies with the level of the other variables. The interactions were examined and deviations from the general trend shown by the main effects are reported. The soil differences at each level of slope indicated that transport capacity was similar for both clay and clay loam at the 10.5 per cent slope but a greater amount of the clay soil was transported at the 14 per cent slope. The soil x discharge interaction revealed that the 1.6 l/min flow has a greater capacity to transport more clay loam than clay.

TABLE 65 Analysis of variance of the effect of slope steepness, discharge and soil type on sediment yield by overland flow with rain.

Source of Variation	Sums of squares	Degrees of freedom	Mean squares	F
Slope	463.6064	3	154.5355	772677.5 ***
Replication	0.0002	3	0.00007	0.35 NS
Discharge	135.1507	3	45.0502	225251.0 ***
Slope x discharge	98.3787	9	10.9310	54655.0 ***
Soil	19.0305	3	6.3435	31717.5 ***
Slope x soil	53.6169	9	5.9574	29787.0 ***
Discharge x soil	15.2260	9	1.6918	8459.0 ***
Slope x discharge x soil	23.8246	27	0.8824	4412.0 ***
Residual	0.0377	189	0.0002	
Total	808.8717	255		

*** significant at 0.1%   NS - not significant at 5%

TABLE 66 Analysis of variance of the effect of slope steepness, discharge and soil type on sediment transport capacity of overland flow with rain.

Source of Variation	Sums of squares	Degrees of freedom	Mean squares	F
Slope	0.0563	1	0.0563	40214.3 ***
Replication	0.0000	3	0.0000	0.0 NS
Discharge	0.2035	3	0.0678	48428.6 ***
Slope x discharge	0.0038	3	0.0013	928.6 ***
Soil	0.0546	3	0.0182	13000.0 ***
Slope x soil	0.0165	3	0.0055	3928.6 ***
Discharge x soil	0.0249	9	0.0028	2000.0 ***
Slope x discharge x soil	0.0042	9	0.0005	357.1 ***
Residual	0.00013	93	0.0000014	
Total	0.36393	127		

*** significant at 0.1% NS not significant at 5%

TABLE 67 Mean sediment transport capacity of overland flow with rain

Factor level	Mean $kg\ m^{-1}\ min^{-1}$	
Soil		
Standard sand	0.0960	b*
Sand	0.1139	a
Clay loam	0.0647	d
Clay	0.0666	c
Discharge (l/min)		
1.0	0.0355	d
1.6	0.0610	c
2.2	0.1062	b
2.8	0.1387	a
Slope (%)		
10.5	0.0643	b
14.0	0.1063	a

* The differences between values followed by dissimilar letters are significant at 1% level.

LSD at 1% = 0.0008 for soil and discharge means
LSD at 5% = 0.0006 for soil and discharge means

LSD at 1% = 0.0005 for slope means
LSD at 5% = 0.0004 for slope means

TABLE 68 Mean weight of sediment yield by overland flow with rain

Factor level	Mean $kg\ m^{-1}$	
Soil		
Standard sand	1.5681	a*
Sand	1.8218	b
Clay loam	1.1660	d
Clay	1.1949	c
Discharge (l/min)		
1.0	0.5061	a
1.6	0.9777	b
2.2	1.9547	c
2.8	2.3123	d
Slope (%)		
3.5	0.0736	a
7.0	0.4092	b
10.5	1.7787	c
14.0	3.4893	d

* The differences between values followed by dissimilar letters are significant at 1% level.

LSD at 1% = 0.0064 for soil, slope and discharge means
LSD at 5% = 0.0049 for soil, slope and discharge means

7.3 FACTORS AFFECTING SEDIMENT YIELD

The sediment yield data obtained from 256 runs are summarized in Appendix 31. As indicated by the analysis of variance Table 65, sediment yield (kg m^{-1}) is significantly ($P = 0.001$) influenced by slope steepness, discharge and their interactions. The four soils differed significantly in the mean weight of sediment yield (Table 72) which ranked as sand > standard sand > clay > clay loam. Increasing discharge and slope steepness also caused significant increases in sediment yield, the latter being the major influencing factor. Discharge was next in importance, followed by soil type.

The significance of factor interactions on sediment yield was in the order of slope x discharge > slope x soil > discharge x soil. The slope x discharge interaction showed that the effect of slope on sediment yield increased with increasing discharge. The effect was however proportionately greater at the lower than at the higher discharges. The effect of discharge also increased as slope steepened, the increase being greater at the lower slopes.

The slope x soil interaction showed that there were no significant differences between sediment yield for sand, clay loam and clay on the 3.5 per cent slope. However, sediment yield for standard sand was significantly lower than the yields for the other three soils. At the 7 per cent slope, significantly more clay and clay loam than sand and standard sand were transported. Sediment yield for each soil type increased as slope steepened.

The soil x discharge interaction showed that sediment yield at 1.0 l/min flow was significantly greater for clay than for the other three soils and that the differences between clay loam and standard sand were not statistically significant. For the 1.6 l/min flow, the yield was greater for clay loam than clay but did not differ significantly from that of standard sand. Sediment yield for each soil type however increased with increasing discharge.

7.4 RELATIONSHIPS FOR TRANSPORT CAPACITY AND SEDIMENT YIELD

The results presented earlier showed that slope steepness, soil type, flow rate and their interactions significantly influence both the transport capacity of flow and sediment yield. Relationships for predictive purposes were therefore established between the factors and transport capacity through multiple regression analysis. Since the determination of transport capacity for some factor combinations (Section 7.1) was not possible, the number of observations used for the analysis was reduced from 64 to 32 for the sandy soils and from 64 to 48 for the clay and clay loam.

The equations obtained are presented in Table 69. There was a highly significant positive correlation between transport capacity and both slope steepness and flow rate. In all cases, discharge accounted for a greater percentage of the variation in transport capacity. The slope exponent ranged from 1.56 for clay loam to 2.70 for standard sand. The corresponding values for discharge, flow power and intensity were 1.98 and 2.78; 1.73 and 2.75; and 1.20 to 1.67 respectively. A combination of the data for all soils showed transport capacity to increase as 2.27, 2.13, 2.22 and 1.28 power of slope steepness, discharge, flow power and rain intensity respectively. The values of the coefficient of determination were very high. This for the individual soils, ranged from 0.95 to 0.98 while a value of 0.88 was obtained for all soils combined.

Similar equations were established for sediment yield. Since a yield measure was obtained for all combinations of factors, 64 and 256 observations were used for the analysis for the individual and all soils respectively.

The power equations (Table 70) showed a very high coefficient of determination for the individual (0.90 - 0.99) as well as all soils (0.90). The respective ranges of values for the exponent of discharge, slope steepness, flow power and intensity of rain were 2.0 - 3.3, 2.50 - 3.0, 2.49 - 3.07 and 1.25 - 1.97. The corresponding values for all soils were 2.37, 2.79, 2.79, 2.71 and 1.46.

TABLE 69 Sediment transport capacity (Tc; kg m^{-1} min^{-1}) related to discharge (q; m^3 s^{-1} m^{-1}), intensity (I; mm h^{-1}), slope (S; sin S), and flow power (qs; l m^{-1} min^{-1})

Soil	Equation	r_1^2	r_2^2	R^2	SEE	Eq. No.
Standard sand (n = 32)						
	$Tc = e^{29.39}\, q^{2.78}\, S^{2.70}$	0.73	0.25	0.98	1.13	388
	$Tc = e^{-4.34}\, I^{1.67}\, S^{2.70}$	0.73	0.25	0.98	1.13	389
	$Tc = e^{-1.02}\, (qs)^{2.75}$	0.98			1.12	390
Sand (n = 32)						
	$Tc = e^{25.43}\, q^{2.40}\, S^{2.45}$	0.71	0.27	0.98	1.13	391
	$Tc = e^{-3.61}\, I^{2.43}\, S^{2.45}$	0.70	0.27	0.97	1.13	392
	$Tc = e^{-1.02}\, (qs)^{2.40}$	0.98			1.13	393
Clay loam (n = 48)						
	$Tc = e^{19.16}\, q^{1.98}\, S^{1.56}$	0.52	0.45	0.97	1.12	394
	$Tc = e^{-4.96}\, I^{1.20}\, S^{1.56}$	0.52	0.45	0.97	1.12	395
	$Tc = e^{-1.84}\, (qs)^{1.73}$	0.96			1.15	396

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TABLE 69 (continued - 2)

Soil	Equation	r_1^2	r_2^2	R^2	SEE	Eq. No
Clay (n = 48)						
	$Tc = e^{21.38}\ q^{2.18}\ S^{1.73}$	0.51	0.45	0.96	1.17	397
	$Tc = e^{-4.99}\ I^{1.30}\ S^{1.73}$	0.50	0.45	0.95	1.19	398
	$Tc = e^{-1.73}\ (qs)^{1.91}$	0.94			1.19	399
All soils (n = 176)						
	$Tc = e^{22.34}\ q^{2.13}\ S^{2.27}$	0.36	0.50	0.88	1.32	400
	$Tc = e^{-3.54}\ I^{1.28}\ S^{2.27}$	0.36	0.50	0.88	1.32	401
	$Tc = e^{-1.43}\ (qs)^{2.22}$	0.88			1.32	402

TABLE 70 Sediment yield by overland flow with rain (Q_y; kg m^{-1}) related to discharge (q; m^3 s^{-1} m^{-1}), slope (S; sin S), rain intensity (I; mm h^{-1}) and flow power (qs; l m^{-1} min^{-1}) n = 64 for each soil.

Soil	Equation	r_1^2	r_2^2	R^2	SEE	Eq. No
Standard sand						
	$Q_y = e^{38.10}\ q^{3.3}\ S^{3.07}$	0.17	0.72	0.90	1.83	403
	$Q_y = e^{-1.88}\ I^{1.97}\ S^{3.07}$	0.17	0.72	0.90	1.84	404
	$Q_y = e^{1.65}\ (qs)^{3.07}$	0.90			1.83	405
Sand						
	$Q_y = e^{35.07}\ q^{3.0}\ S^{2.94}$	0.17	0.77	0.94	1.57	406
	$Q_y = e^{-1.08}\ I^{1.79}\ S^{2.94}$	0.17	0.77	0.94	1.57	407
	$Q_y = e^{2.39}\ (qs)^{2.94}$	0.94			1.56	408
Clay loam						
	$Q_y = e^{26.69}\ q^{2.21}\ S^{2.50}$	0.14	0.84	0.98	1.25	409
	$Q_y = e^{-0.13}\ I^{1.34}\ S^{2.50}$	0.14	0.84	0.98	1.25	410
	$Q_y = e^{2.68}\ (qs)^{2.49}$	0.98			1.23	411

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TABLE 70 (Continued - 2)

Soil	Equation	r_1^2	r_2^2	R^2	SEE	Eq. No
Clay						
	$Q_y = e^{25.85}\, q^{2.01}\, S^{2.63}$	0.12	0.87	0.99	1.23	412
	$Q_y = e^{0.58}\, I^{1.25}\, S^{2.63}$	0.11	0.87	0.98	1.24	413
	$Q_y = e^{3.57}\, (qs)^{2.60}$	0.97			1.23	414
All soils (n = 256)						
	$Q_y = e^{28.85}\, q^{2.63}\, S^{2.79}$	0.12	0.78	0.90	1.70	415
	$Q_y = e^{-0.05}\, I^{1.46}\, S^{2.78}$	0.12	0.78	0.90	1.70	416
	$Q_y = e^{2.13}\, (qs)^{2.71}$	0.89			1.70	417

7.5 DISCUSSION

7.5.1 Factors affecting sediment transport capacity (Tc) and sediment yield (Qy)

Soil type

The transport and subsequent deposition of sediment depends not only on the flow characteristics but also on the properties of the sediment itself (Vanoni, 1975). The most important property of the sediment, as included in several sediment transport capacity equations (Carson and Kirkby, 1972; Komura, 1976; Morgan, 1980) is the particle size which is inversely related to transport capacity. Since the clay and clay loam were transported mostly as aggregates with sizes greater than the individual grains of the sandy soils, it is not surprising that the transport capacity for sand and standard sand was significantly greater.

Where factors interact significantly, interpretation of results based solely on the main effects may result in the loss of vital information. The examination of the interactions indicated that at the lower slopes (3.5 and 7.0 per cent) sediment yield was significantly more for the larger clay and clay loam aggregates than for the sand and standard sand. Similar observations were made by Meyer and Monke (1965) and Bubenzer et al. (1966) and may be explained by the following reasons:

i) Under conditions of small flow velocities, where raindrop size is greater than flow depth and transport capacity is limiting, as those for the 3.5 and 7.0 per cent slopes, direct transport of particles by splash can significantly influence the amount of sediment yield. Since splashed aggregates move greater distances than individual grains (Savat and DePloey, 1968), the probability of the clay and clay loam being carried off the soil-plate will be greater than for the sand grains.

ii) On the other hand, since the particle density of sand is generally greater than that of clay aggregates (Foster et al., 1980), flow had the competence to transport the latter even at small velocities. Evidence is that transport capacity could be determined for clay and clay loam at 7.0 per cent slope but not for sand (Appendix 23).

iii In contrast to the sand grains, the sizes of the clay and clay loam aggregates (Table 2) relative to flow depth, result in the latter aggregates protruding through the flow. Even though the average hydraulic conditions indicate that flow was subcritical - laminar on the 3.5 and 7.0 per cent slopes, in the presence of the protruding roughness elements and raindrop impact with K as in $f = K/Re$ equals to 83, flow was rough (Graf, 1971). Under such conditions flow is characterized by flow separation with its attendant generation of turbulent free shear layers in the main body of flow (Phelps, 1975; Allen, 1970). Particles that penetrate this area of higher stresses are therefore likely to be transported at a faster rate than those in the laminar sublayer. The clay and clay loam aggregates may have belonged to the former condition. However transport of particles in these boundary layers is not well understood and needs further research. This may lead to a better understanding of sediment transport in overland flow.

Discharge and slope steepness.

The average hydraulic conditions of flow were ones of increasing velocity and tractive force with increasing flow rate and slope steepness. Froude number increased linearly from subcritical on the two lower slopes to supercritical on the 10.5 and 14 per cent slopes. These account for the observed increases in transport capacity and sediment yield as discharge and slope steepness increased.

7.5.2 Relationships for sediment transport capacity and for sediment yield.

The incorporation of flow rate, slope steepness, flow power and intensity of rain into predictive equations is preferred on account of the relative ease with which these parameters are measured or evaluated (Kilinc and Richardson, 1973).

Secondly, as indicated in Chapter 5, slope steepness and discharge are significantly correlated with most of the hydraulic parameters of flow such as velocity and tractive force which are very important in sediment transport relationships.

The high coefficient of determination obtained for the equations incorporating discharge and slope, and flow power are therefore very encouraging and welcome. The exponents vary with soil type and are higher for the sandy soils. An increase in any of the above variables therefore results in a greater proportionate increase in the capacity of flow to transport sand and standard sand than clay and clay loam. The intercept values also indicate that initial transportability is greater for the standard sand and sand than for the clay and clay loam.

The discharge and slope exponents are comparable to those presented in Table 71 for other workers. The values are generally higher but are closer to the upper ranges reported by Meyer and Monke (1965); Bubenzer et al. (1966); and Kilinc and Richardson (1973). The exponents for the sediment yield equations are even higher still. Because the flushes that characterized the supply of soil particles into the test area were very sensitive to discharge and slope steepness, sediment yield increased rapidly as these variables increased. This is the trend shown by the higher exponents.

The flow power exponents ranging between 1.56 and 2.75 and 2.49 and 3.07 for transport capacity and sediment yield respectively compare well with the range 1.7 - 3.5 quoted by Kirkby (1980) for rill transporting capacity.

7.5.3 Hydraulics of sediment transport - Results and Discussion

The transport capacity of flow was also characterized by flow variables presented in Table 72. Because the same soil plate was used for all tests (Section 3.6.4), the same values of the variables were used in the transport capacity analysis for each soil.

TABLE 71 Values for m and n in the relationship between transport capacity (Tc), discharge (q) and slope (S) in the form $Tc \propto q^m S^n$

m	n	Sources
1.98 - 2.78 (2.33)	1.56 - 2.70 (2.11)	Present study
1.5	2 - 2.5 (2.2)	Meyer and Monke (1965)
1.666	1.666	Meyer and Wischmeier (1969)
2.03	1.664	Kilinc and Richardson (1973)
1.3 - 2.1 (1.70)	1.5 - 2.0 (1.75)	Bubenzer, Meyer and Monke (1966)
1.80	1.13	Morgan (1980)
1.75	1.625	Carson and Kirkby (1972)
1.875	1.5	Komura (1976)

TABLE 72 Flow characteristics for transport by overland flow with rain: Velocity (V), Depth (D), Reynolds number (Re), Froude number (F), Friction factor (f), Tractive stress (τ_o), Stream Power (P_s), Manning's n, and Total kinetic energy (RE).

Slope %	Discharge l/min	V mm s^{-1}	D mm	Re	F	f	T_o N m^{-2}	P_s J s^{-1} m^{-2}	n	RE J m^{-2}
3.5	1.0	48.00	1.20	46.56	0.44	2.50	0.72	0.03	0.15	81.00
	1.6	59.00	1.25	59.62	0.53	1.72	0.75	0.04	0.13	108.00
	2.2	67.10	1.40	75.94	0.57	1.49	0.84	0.06	0.14	162.00
	2.8	74.40	1.50	90.22	0.61	1.30	0.90	0.07	0.14	189.00
7.0	1.0	61.40	0.95	47.15	0.64	1.43	1.14	0.07	0.15	189.00
	1.6	70.90	1.10	63.05	0.68	2.11	1.33	0.09	0.17	243.00
	2.2	78.00	1.20	75.67	0.72	1.90	1.45	0.11	0.18	297.00
	2.8	86.00	1.35	93.86	0.75	1.76	1.63	0.14	0.19	378.00
10.5	1.0	75.00	0.80	48.50	0.85	2.07	1.45	0.11	0.13	297.00
	1.6	91.80	0.85	63.08	1.01	1.47	1.55	0.14	0.12	378.00
	2.2	105.60	0.90	76.83	1.12	1.17	1.64	0.17	0.12	459.00
	2.8	118.40	0.94	89.97	1.23	0.98	1.71	0.20	0.11	540.00
14.0	1.0	96.00	0.62	48.12	1.23	1.32	1.52	0.15	0.09	405.00
	1.6	115.40	0.68	63.44	1.41	1.00	1.66	0.19	0.09	513.00
	2.2	143.20	0.78	90.30	1.64	0.74	1.91	0.27	0.09	729.00
	2.8	154.40	0.82	102.35	1.72	0.67	2.01	0.31	0.09	837.00

The power equations (Table 73) show that with the exception of flow depth, there was a highly significant correlation between transport capacity and all the other flow parameters. Transport capacity increased as the 3.34, 3.0, 2.29 and 2.54 power of flow velocity for standard sand, sand, clay loam and clay respectively. According to Horton (1970), the transport capacity of overland flow must vary at least as the square or some higher power of flow velocity. Reported values range from 2 to 5.

The exponents of the other parameters vary from 1.90 to 2.51 for Reynolds number, 1.69 to 3.10 for Froude number, - 1.49 to - 2.18 for friction factor and 4.3 to 6.76 for tractive force. Kilinc and Richardson (1973) reported a value of 2.05 for the Re exponent.

Sediment transport capacity is very sensitive to Darcy-Weisbach's friction factor as indicated by the negative exponent. Increasing surface roughness is therefore an effective measure for reducing the transport capacity of flow. The effectiveness of surface roughness in this role depends on whether erosion is detachment or transport capacity limited.

In the latter case, sediment concentration is very high and a considerable area of the eroding surface is covered by deposited material as shown in 7.1. The original surface roughness is thus significantly altered and the deposited material or the sediment carried by flow may constitute effective roughness. Under such conditions values selected for Manning's n based on the original conditions of the eroding surface may be unrepresentative and sediment transport capacity may instead be more sensitive to an appropriate particle size diameter. This is the trend shown by the low and the high exponents of Manning's n and grain size respectively in the transport capacity equation used by Morgan and Morgan (1981)

In a detachment capacity-limited case, the original roughness of the eroding surface remains effective. The importance of determining the erosion limiting process as a guide to the

TABLE 73 Power equations relating transport capacity of overland flow (Tc; kg m^{-1} min^{-1}) to flow parameters

Soil	Equation	r_1^2	r_2^2	R^2	SEE	Eq. No
Standard sand (n = 32)						
	$Tc = e^{4.80} V^{3.34}$	0.95			1.19	418
	$Tc = e^{4.66} D^{1.01}$	0.03			2.16	419
	$Tc = e^{-13.27} Re^{2.51}$	0.73			1.43	420
	$Tc = e^{-3.27} F^{3.10}$	0.83			1.38	421
	$Tc = e^{-2.36} f^{-2.18}$	0.96			1.17	422
	$Tc = e^{-6.05} \tau_o^{6.75}$	0.85			1.31	423
	$Tc = e^{2.15} P_s^{2.75}$	0.98			1.13	424
	$Tc = e^{-19.57} RE^{2.74}$	0.98			1.13	425
	$Tc = e^{-8.0} Re^{2.37} S^{2.63}$	0.73	0.25	0.98	1.13	426
Sand (n = 32)						
	$Tc = e^{4.26} V^{3}$	0.95			1.17	427
	$Tc = e^{3.51} D^{0.82}$	0.03			2.00	428
	$Tc = e^{-11.88} Re^{2.24}$	0.73			1.42	429
	$Tc = e^{-2.99} F^{2.79}$	0.84			1.32	430
	$Tc = e^{-2.18} f^{1.95}$	0.96			1.15	431

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TABLE 73 (Continued - 2)

Soil	Equation	r_1^2	r_2^2	R^2	SEE	Eq. No
Sand (continued)						
	$Tc = e^{-5.51}\ \tau_o^{\ 6.10}$	0.87			1.29	432
	$Tc = e^{1.75}\ P_s^{\ 2.40}$	0.96			1.17	433
	$Tc = e^{-17.21}\ RE^{2.40}$	0.96			1.17	434
	$Tc = e^{-7.23}\ Re^{2.24}\ S^{2.45}$	0.73	0.26	0.99	1.11	435
Clay loam						
	$Tc = e^{2.24}\ V^{2.29}$	0.90			1.24	436
	$Tc = e^{-8.58}\ D^{-0.78}$	0.07			1.91	437
	$Tc = e^{-11.23}\ Re^{1.91}$	0.52			1.54	438
	$Tc = e^{-3.18}\ F^{1.69}$	0.73			1.41	439
	$Tc = e^{-2.68}\ f^{-1.49}$	0.85			1.30	440
	$Tc = e^{-5.09}\ \tau_o^{\ 4.35}$	0.93			1.19	441
	$Tc = e^{0.16}\ P_s^{\ 1.73}$	0.96			1.17	442
	$Tc = e^{-13.54}\ RE^{1.73}$	0.96			1.17	443
	$Tc = e^{-7.40}\ Re^{1.90}\ S^{1.55}$	0.52	0.45	0.97	1.11	444

/...

TABLE 73 (Continued - 3)

Soil	Equation	r_1^2	r_2^2	R^2	SEE	Eq. No
Clay (n = 48)	$Tc = e^{2.78}\ V^{2.54}$	0.89			1.28	445
	$Tc = e^{-9.19}\ D^{-0.86}$	0.06			2.06	446
	$Tc = e^{-12.12}\ Re^{2.11}$	0.52			1.68	447
	$Tc = e^{-3.21}\ F^{1.87}$	0.73			1.48	448
	$Tc = e^{-2.66}\ f^{-1.65}$	0.84			1.35	449
	$Tc = e^{-5.33}\ \tau_o^{4.83}$	0.93			1.22	450
	$Tc = e^{0.48}\ P_s^{1.90}$	0.94			1.20	451
	$Tc = e^{-14.62}\ RE^{1.90}$	0.94			1.20	452
	$Tc = e^{-7.87}\ Re^{2.10}\ S^{1.73}$	0.52	0.45	0.97	1.17	453

selection of appropriate n - values for use in sediment transport capacity equation, which though inadequate in situations where transport capacity is non-limiting, is therefore obvious.

For the same reasons, friction factor values calculated from flow velocity and depth will vary since the latter two variables are very sensitive to effective surface roughness.

The most important flow parameters that singly predicted transport capacity were flow velocity with a coefficient of determination of 0.89 - 0.95, flow power, and total kinetic energy of flow (r^2 = 0.94 - 0.98). Others were friction factor (r^2 = 0.84 - 0.96), tractive force (r^2 = 0.85 - 0.93). In combination with slope steepness the r^2 for Reynolds number (0.52 - 0.73) was significantly improved (R^2 = 0.97 - 0.99).

7.6 SUMMARY

1. Transport of soil particles by flow with rain was influenced by soil type, slope steepness, flow rate and their first and second order interactions. Transport capacity decreased in the order of sand > standard sand > clay > clay loam. Increases in discharge and slope steepness significantly increased transport capacity. For a discharge range of 1.0 - 2.8 l/min, transport capacity increased four fold.

2. The magnitude of the effect of each factor depended on the level of the other variables examined, the most significant interaction being soil x discharge.

3. Where factors interact significantly, interpretation of results based solely on the main effects of the influencing factors may result in loss of vital information. Examination of slope x soil interaction, for example, showed that at the lower slopes (3.5 and 7 per cent) sediment yield was greater for the larger clay and clay loam aggregates than for the fine grains of sand and standard sand. This is obscured when effects are averaged over all slopes as is the case when only main effects are considered.

4. Movement of particles was mainly in rolling and saltatory modes, processes which are associated with bed-load transportation.

5. Whilst clay and clay loam were transported as aggregates those of sand and standard sand proceeded as individual grains with rolling and saltation dominating the movement of clay aggregates and sand grains respectively.

6. The intensity of the rolling and saltatory movements increased with increasing discharge and slope steepness.

7. Movement of particles, particularly sand and standard sand, with porridge-like consistency and maintaining constant contact with each other was also observed.

8. For transport capacity-limited conditions, deposited material or sediment carried by flow may constitute effective surface roughness.

9. Flow was predominantly subcritical laminar on the 3.5 and 7.0 per cent slopes while supercritical laminar flow prevailed on the 10.5 and 14 per cent slopes. Reynolds number ranged from 46.56 to 93.86 and 48.50 to 102.35 respectively. The corresponding ranges for Froude number were 0.44 to 0.75 and 0.85 to 1.72.

10. Important flow parameters that singly predicted transport capacity were flow velocity (r^2 = 0.89 - 0.95) with exponents of 2.54 - 3.34, flow power (r^2 = 0.94 - 0.98), total flow kinetic energy (r^2 = 0.94 - 0.98), friction factor (r^2 = 0.84 - 0.96) and tractive force (r^2 = 0.85 - 0.93). The coefficient of determination of the equation incorporating Reynolds number and slope steepness was also very high (R^2 = 0.97 - 0.99).

11. Predictive equations incorporating slope steepness, discharge, rain intensity and flow power were established for sediment transport capacity. The coefficient of determination of the equations for the individual soils ranged from 0.95 to 0.98. For all soils (178 observations) the following equations were obtained:

	R^2	
$Tc = e^{22.34}\, q^{2.13}\, S^{2.27}$	0.88	Eq. 454
$Tc = e^{-1.43}\, (qs)^{2.22}$	0.88	Eq. 455

12. Similar equations were established for sediment yield. The R^2 for the equations for the individual soils varied from 0.90 for standard sand to 0.98 for clay. The equations for all soils (256) observations were:

	R^2	
$Q_y = e^{28.85}\, q^{2.63}\, S^{2.79}$	0.90	Eq. 456
$Q_y = e^{2.13}\, (qs)^{2.71}$	0.89	Eq. 457

13. i) The use of the transport capacity (kg m^{-1} min^{-1}) and sediment yield equations with discharge and slope components allows for instantaneous modelling of sediment yield using the Meyer-Wischmeier (1969) approach.

ii) The choice of equation will depend on whether the requirement is for transport rates on individual soils or an average for a variety of soils.

iii) Similar applications can be made using the flow power equations where the Kirkby (1980) type modelling is of interest.

iv) For the runoff energy approach, the transport capacity equations incorporating total runoff kinetic energy may be used.

14. Whilst the general applicability awaits validation for field conditions, the equations can be used for preliminary prediction of sediment transport rates.

CHAPTER 8

IMPLICATIONS FOR MODELLING AND EROSION CONTROL

So far in this study the subprocesses of erosion have been treated separately. Whilst this approach allows the individual contributions of the processes to soil loss to be assessed, it also enhances the understanding of the mechanics of erosion, knowledge of which is essential for the design and implementation of soil conservation practices.

In reality, however, soil loss is the product of the interaction between the detachment and transport of soil particles by raindrops and by runoff. For a given set of conditions the severity of erosion depends on the limiting process and the ability to define this is of great importance since it affords a stronger base for selecting and directing conservation measures.

Rather than developing a specific model, an attempt is made in this Chapter to show the potential uses of the material presented in the earlier Chapters for

1) predicting soil detachment and transport rates by adopting several modelling strategies;
2) improving some of the current erosion models by incorporating rainfall-runoff interactions into such models;
3) selecting strategies for erosion control based on the concept of the erosion-limiting process;
4) modelling the effects of plant covers; and
5) erodible channel design.

It must be emphasized that the material presented here is not a study of examples but a general review of strategies used in these research areas pointing out potentially fruitful areas for further research and development and giving guidelines for carrying out some of these studies.

8.1 PREDICTION OF DETACHMENT AND TRANSPORT RATES

A prerequisite for the design and implementation of soil conservation is the prediction of the rate of soil loss under both existing conditions and those expected to prevail with conservation (Morgan et al. 1981). As indicated in Chapter 1, a predictive model that is based on a physical understanding of the subprocesses of erosion is more desirable since this provides a better opportunity for identifying the erosion limiting process and designing appropriate control measures. In this regard, Ellison (1947) identified four important subprocesses of erosion namely, i) soil detachment by rainfall, ii) detachment by runoff, iii) transport by rainfall, and iv) transport by runoff which are used by Meyer and Wischmeier (1969) to develop a basic mathematical model of soil erosion. The model which considers the above subprocesses as separate but interrelated phases of the process of erosion by water is described in Section 8.2.

Whilst the basic structure of the model is maintained throughout this Chapter, several approaches for modelling the detachment and transport phases can be identified when the relevant predictive equations previously cited in Chapter 2 are assembled together. In outlining these approaches, new equations which take account of additional factors are suggested.

Ellison (1947) expressed the susceptibility of soils to detachment as a function of the detaching capacity of the erosive agent and the soil's detachability (k_{det}). Since then, a power function has been widely used to model the rate of rainsplash detachment as a function of some characteristic of rainfall including drop size, velocity, intensity (Ellison, 1944; Bisal, 1960; Meyer and Wischmeier, 1969) and kinetic energy (Mihara, 1950; Free, 1960; Bubenzer and Jones, 1971; and Morgan, 1981). Some of these equations are presented in Table 74.

The total rainfall kinetic energy approach is often used and is expressed in the form shown by Eq. 460. Equations of this type are presented in Chapter 4 for estimating detachment rates on standard sand, sand, clay loam, and clay. The magnitude of the exponents ranging between 0.8 and 1.4 compare very well with those reported

TABLE 74 Predictive equations for splash detachment and transport

Rainsplash detachment	Source	Eq. No.
$Q_{det} = k_{det} V^{4.33} D^{1.07} I^{0.57}$	(1)	1
$Q_{det} = k_{det} V^{1.4} D$	(2)	2
$Q_{det} = k_{det} A \ I^{2}$	(3)	458
$Q_{det} = k_{det} I^{2}/d^{*}$	(4)	459
$Q_{det} = 7.50 \ I^{0.41} KE^{1.14} \% \ Clay^{-0.52}$ ($R^2 = 0.86$)	(5)	3
$Q_{det} = k_{det} KE^{0.8 - 1.4}$	(6)	460
$Q_{det} = 0.00004 \ KE^{1.10} S^{0.20} d_{50}^{-0.43}$ ($R^2 = 0.84$)	(6)	58
Rainsplash transport		
$Q_{trans} = k_{trans} SI$	(3)	8
$Q_{trans} = k_{trans} \sin S^{0.75}$	(7)	461
$Q_{trans} = 0.0003 \ KE^{0.84} + S^{2.29}$	(8)	7
$Q_{trans} = 0.00004 \ KE^{0.81} S^{0.98} d_{50}^{-0.34}$ ($R^2 = 0.73$)	(6)	61

(1) Ellison (1944); (2) Bisal (1960); (3) Meyer and Wischmeier (1969); (4) Kirkby (1980); (5) Bubenzer and Jones (1971); (6) Study; (7) Moeyersons and DePloey (1976); (8) Morgan (1978).

* d = grain size

in the literature and recommended values are suggested in Table 15. To operate the equation for different soil types, appropriate values of k_{det} (Table 75) are required and these are scarce at present. It is also assumed that the total kinetic energy of rain is known. For laboratory conditions this can be determined by either the stain technique (Hall, 1970) or the flour pellet method (Hudson, 1964b). The former technique is illustrated in Chapter 3. In the field, total kinetic energy of rain can be calculated from intensity data obtained from autographic rain gauge charts using either Eq. 41 (Wischmeier and Smith, 1978)

$$KE = 11.87 + 8.7 \log_{10} I \qquad \text{Eq. 41}$$

or Eq. 42 (Hudson, 1965)

$$KE = 29.8 - \frac{127.5}{I} \qquad \text{Eq. 42}$$

also $KE = 9.81 + 11.25 \log_{10} I$ (Zanchi and Torri, 1981) Eq. 462

where KE is in J m^{-2} and I, mm h^{-1}

Although detachment rates on slopes typical of arable lands (0 - 15 per cent) increase with increasing slope steepness, none of the existing detachment equations incorporate these effects. To model these effects, the detachment equations in Chapter 4 incorporating kinetic energy and slope steepness can be used. It must be emphasized however that the linear increase in detachment rates as slope steepens is valid for small slopes (0 - 15 per cent) and cannot be extrapolated to higher slopes (33 per cent) where the relationship may become inverse (Foster and Martin, 1969).

Equations incorporating grain size parameter (d_{50}, d_{84}) are also provided in Chapter 4 for modelling the effects of particle size on detachment rates as proposed by Kirkby (1980). However these grain size terms do not account for the temporal changes that may occur in the effective grain size, and the effects of surface armouring or crusting. Until further work has sorted out these problems, Eq. 58 (Table 74) may be used.

TABLE 75 Values of k

Soil	d_{50}	d_{84}	k_{det}	k_{trans}
Standard sand	0.20	0.28	0.0002	0.00005
Sand	0.30	0.40	0.0003	0.0001
Clay loam	0.61	1.50	0.00003	0.00004
Clay	0.93	1.75	0.00002	0.00001

k_{det} = soil detachability index (splash detachment)

k_{trans} = soil transportability index (splash detachment)

The rainfall kinetic energy and slope steepness approach is also used for estimating splash transport rates. The relevant equations are presented in Chapter 4 and in Table 74. Other workers have expressed splash transport as a function of slope steepness and rainfall intensity (Meyer and Wischmeier, 1969; Moeyersons and DePloey, 1976). Table 74 shows that to operate these equations values for the susceptibility of soils to splash transport (k_{trans}) are required. Some of these are listed in Table 75. In an attempt to provide a general splash transport equation, Eq. 61 (Table 74) was obtained. However with a coefficient of determination of 0.73, it is not so satisfactory for predictive purposes.

Power functions are also widely used to model detachment and transport rates by overland flow as a function of

i) slope steepness and flow rate,

ii) slope steepness, flow rate and a particle size parameter,

iii) slope steepness, flow rate, particle size parameter and Manning's n,

iv) tractive force,

v) flow velocity,

vi) runoff energy.

Examples of equations for these strategies obtained by different workers are presented in Tables 76 and 77 for detachment and transport rates respectively.

The application of these strategies using appropriate equations for flow with and without rain has been shown in Chapter 6 for detachment and Chapter 7 for transport rates. The equations for flow without rain (Tables 76 and 77) are used for estimating the individual contribution of overland flow to the detachment and transport processes. Such equations neglect the important effects of rainfall-runoff interactions which are shown to contribute significantly to soil loss. However, these are intrinsically catered for by the equations produced in this study for flow with rain (Tables 76 and 77). Since the detachment and transport

TABLE 76 Predictive equations for detachment rates by overland flow with and without rain

Without rain	Source	Eq. No
$Q_{odet} = k\ Q^{\frac{2}{3}}\ S^{\frac{2}{3}}$	(1)	
$Q_{odet} = k\ V^2$	(1)	463
$Q_{odet} = k\ \tau^{n*}$	(2)	464
$Q_{odet} = k\ (qs)^{2*}$	(3)	33
$Q_{odet} = e^{16.37}\ q^{1.50}\ S^{1.44}\ d_{50}^{-1.54}\ (R^2 = 0.91)$	(4)	268
$Q_{odet} = e^{0.04}\ (qs)^{1.41}\ d_{50}^{-1.51}\ (R^2 = 0.91)$	(4)	270
With rain		
$Q_{rodet} = e^{13.40}\ q^{1.12}\ S^{0.66}\ d_{50}^{-0.47}\ (R^2 = 0.90)$	(4)	284
$Q_{rodet} = e^{-4.51}\ KE^{1.0}\ S^{0.66}\ d_{50}^{-0.47}\ (R^2 = 0.90)$	(4)	290
$Q_{rodet} = e^{1.80}\ (qs)^{0.82}\ d_{50}^{-0.47}\ (R^2 = 0.85)$	(4)	292

(1) Meyer and Wischmeier (1969); (2) Foster and Meyer, (1975) (n = 1.5), and Meyer and Wischmeier, (1969) (n = 1.0); (3) Kirkby (1980); (4) Study.

* rill-flow.

TABLE 77 Predictive equations for transport rates by overland flow with and without rain

Without rain	Source	Eq. No.
$T_c = k\, Q^{5/3}\, S^{5/3}$	(1)	38
$T_c = k\, Q^{1.5} \sin S^{2.2}\, d_{50}^{-0.5}$	(2)	37
$T_c = 0.0085\, Q^{1.75} \sin S^{1.625}\, d_{84}^{-1.11}$	(3)	35
$T_c = 0.00611\, Q^{1.80} \sin S^{1.13}\, n^{-0.15}\, d_{35}^{-1}$	(4)	34
With rain		
$T_c = e^{22.34}\, q^{2.13}\, S^{2.27}$ ($R^2 = 0.88$)	(5)	400
$T_c = e^{-1.43}\, (qs)^{2.22}$ ($R^2 = 0.88$)	(5)	402
$T_c = 0.59\, KE^{0.49}\, RE^{0.33*}$ ($R^2 = 0.67$)	(4)	465

(1) Meyer and Wischmeier (1969); (2) Meyer and Monke (1965); (3) Carson and Kirkby (1972); (4) Morgan (1980); (5) study.

* RE = runoff energy ($J\ m^{-2}$)

equations given in Tables 76 and 77 respectively were based on studies which did not specifically include the rainfall-runoff interaction, improvements to them await the availability of appropriate data such as those obtained in this study (Chapters 6 and 7).

The use of the equations requires that runoff volume, flow power, runoff kinetic energy, flow velocity and tractive force are known. This is not always the case and often these parameters must be estimated for modelling purposes. The peak rate of runoff can be estimated by using the Rational formula in which runoff is expressed as a function of a dimensionless runoff coefficient (C), rain intensity (I), and catchment area (A). Its use is illustrated by Schwab et al. (1966) and Hudson (1971; 1975). The latter author recognizes the paucity of rainfall and hydrological records in areas where erosion is a problem and gives guidelines for obtaining an estimate of runoff rate under such conditions.

The predicted runoff volume and slope steepness can then be substituted into Eq. 25

$$P_s = \gamma_w \; q \; s \qquad \text{Eq. 25}$$

to give values for flow power from which total runoff kinetic energy is calculated (Section 5.9). Standard equations, Eqs. 23 and 24, may be used to estimate flow velocity and tractive force respectively.

Most of the equations in Tables 76 and 77 require values for the soil constant (k) for which information is scarce. Values for fine sand, sand, clay loam and clay can be obtained from the detachment and transport equations in Chapters 6 and 7 respectively. There is also an urgent need to validate these equations in the field in order to ascertain their applicability.

In order to avoid misuse of the equations obtained in this study, the following points should be borne in mind.

1) The equations were produced under laboratory conditions with simulated rainfall intensities of 50 - 140 mm h^{-1}, 3.5 - 14.0 per cent slope, bare prepared soil samples (fine sand, sand, clay loam and clay) and flow rates ranging from 1.0 - 2.8 l/min.

2) The equations for flow are valid only for overland flow and incipient channel flow. They should not be used for the prediction of gully erosion.

3) Although several aspects of the equations, such as the exponents compare very well with those derived for field conditions, they have not yet been verified in the field. Until validated, their use in predicting detachment and transport rates or soil loss in the field should be considered only as a first approximation.

4) The equations are valid for instantaneous conditions and for detachment and transport capacity limited conditions.

8.2 IMPROVING SOME OF THE CURRENT EROSION MODELS BY INCORPORATING RAINFALL-RUNOFF INTERACTIONS INTO SUCH MODELS

As indicated in Section 8.1 the incorporation of the four sub-processes into erosion models provides a better understanding of the working of the erosion system and the opportunity for defining the erosion-limiting process which, in turn, influences the control measure to adopt. Since the Meyer-Wischmeier model provides the basic structure for accommodating these processes, it will be examined to show what improvements can be made using the material presented in this study.

Before describing the model the following modelling principles taken from the work of Kirkby (1980) and Meyer (1981) are considered important since they form the basis for later modifications.

1) For a model to be efficient those processes which have the greatest influence on the overall behaviour of the model must be simulated in the greatest detail.

2) Quantitatively less important processes can in practice be ignored if never near-dominant or dominant.

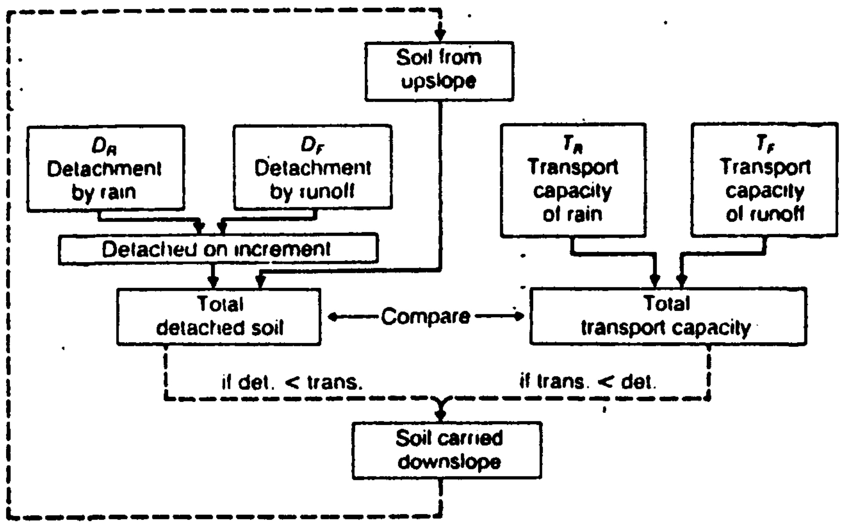
3) If a minor process is locally dominant, it should be modelled with a minimum of parameters and complexity, and with reasonable accuracy necessary only for its zone of dominance.

4) Parameters that can be readily measured or reliably evaluated by users should be used.

5) Models should be designed so that they are useful even for data-deficient conditions because they can accommodate logical quantitative assumptions supplied by the user.

6) Maximise the range of validity for a given number of parameters by using for example functions which take physically reasonable values at zero and infinity, so that responses to extreme conditions remain inherently plausible.

The essential features of the Meyer-Wischmeier model as applied to a small segment of hillslope are shown in Fig. 3c. There is an input of sediment into the segment from the slope above. Rainfall and runoff add to the latter sediment by detaching soil particles within the segment itself ($D_R + D_F$). The sum of the detached particles is compared with the sum of the transport capacities of rainfall and runoff in the segment ($T_R + T_F$). Where the total detached soil is less than the total transport capacity, detachment limits erosion rate in that segment and sediment load is equal to the detachment rate. However, if the total transport capacity is less than the detachment rate, transportation is the limiting factor and the sediment load is equal to the transport capacity. The operation of the model uses four equations each describing a separate process. Soil and water can be routed from the top of the slope through consecutive downslope segments to the base of the slope. This permits the evaluation of the pattern of erosion along a complete slope profile.



$D_R = k_1 A I^2$

$D_F = k_2 A S^{2/3} Q_w^{2/3}$

$T_R = k_3 S I$

$T_F = k_4 S^{5/3} Q_w^{5/3}$

Where A = area, I = rainfall intensity,

S = ground slope ($\sin \theta$),

Q_w = runoff

Fig.3c Flow chart for the model of the processes of soil erosion by water (after Meyer and Wischmeier, 1969).

By computing, for example, the total detachment rate by adding the individual contributions of flow and rainsplash, the model presumes the sum of the latter two to be equal to the total detachment by combined flow and rain. This study however shows that when the amount of soil detached by rainsplash (Appendix 9) is added to that by overland flow (Appendix 20) the sum is always significantly less than the amount detached by combined flow and rain (Appendix 21). The difference is therefore attributed to interaction effects and must be considered if realistic estimates of transport and detachment rates or soil loss are to be obtained. In order to achieve this in the Meyer-Wischmeier model, new equations incorporating the effects of rainfall-runoff interactions must be used. On the other hand, the effects of the interactions may be isolated and modelled separately in which case the original equations used in the model can be retained. This is illustrated later in this section for instantaneous modelling using the equations obtained in this study.

For ease of operation, the model may also be simplified by considering the modelling principles outlined earlier in this section. This requires some reasoned assumptions about the relative importance of the processes. A comparison of the relative contribution to total detachment by rainsplash and overland flow (Section 6.6.3) showed the former to be the principal detaching agent over the range of slopes studied. Also, although impacting raindrops cause significant movement of soil particles within the field and on short steep slopes, its direct contribution to soil loss is often insignificant on longer slopes and in areas where erosion is a severe problem. Based on these observations, a model comprising two major processes, namely, detachment by rainsplash and transport by overland flow can be developed to predict erosion rates.

The feasibility of this procedure is demonstrated by the model developed by Morgan et al. (1981) for predicting mean annual soil loss from hillslopes. Basically the model uses power functions to model splash detachment as a function of rainfall kinetic energy and an index of soil detachability; and transport capacity as a function of discharge and slope steepness. The model consists of two phases. The equations for splash detachment and runoff transport constitute the sediment phase. Respective inputs to these equations of rainfall energy and runoff volume must be determined from the water phase. The details of the structure, operation and application of the model are in the above cited paper. However, the model predicts soil loss in terms of whichever process, splash detachment or runoff transport, limits erosion.

The results from the limited validation under Malaysian conditions have shown the model to be very promising and worthy of further development and study. The model is easy to operate and data inputs are generally obtainable from published sources. More diverse data are however required for validation purposes. Maximization of parameter values is also required to broaden the applicability of the model. Since the effects of rainfall-runoff interactions significantly influence soil loss, their accommodation in the model is expected to improve soil loss estimates. Therefore equations similar to those developed here for instantaneous conditions need to be derived for annual conditions. When fully developed, the model can be of tremendous use in assessing erosion risks particularly in areas where erosion is a major problem and where data are often scarce.

Whilst rainfall-runoff interactions are important, the degree of sophistication in modelling them should be viewed in the light of their practical significance in controlling erosion in the field. Two approaches are suggested and illustrated in Table 78 for the Meyer-Wischmeier (1969) model.

In the first procedure (Table 78) the interaction effect is isolated and modelled separately. When the magnitudes of the processes are compared, it may emerge that soil loss is limited by the rainfall-runoff interaction. In such a situation the erosion-limiting process concept dictates that conservation practices should be directed at the interaction. This is extremely difficult to achieve in the field.

TABLE 78 Modelling rainfall-runoff interactions in the erosion process - complex procedure

First procedure	**Eq. No.**
Detachment by overland flow = Q_{odet}	268
Detachment by rainsplash = Q_{det}	58
Detachment by combined flow and raindrop impact plus interaction = Q_{rodet}	284
Detachment due to rainfall-runoff interaction (Q_{dint}) = $Q_{rodet} - Q_{odet} - Q_{det}$	466
Transport by overland flow = T_{of}^{*}	
Transport by rainsplash = Q_{trans}	61
Transport by combined flow and raindrop impact plus interaction = T_c	467
Transport due to rainfall-runoff interaction (T_{int}) = $T_c - T_{of} - Q_{trans}$	468
Second procedure	
Detachment by overland flow = Q_{odet}	268
Detachment by combined flow and raindrop impact plus interaction = Q_{rodet}	290
Detachment by rainsplash plus interaction (Q_{det}) = $Q_{rodet} - Q_{odet}$	244a
Transport by rainsplash = Q_{trans}	61
Transport by combined flow and raindrop impact plus interaction = T_c	467
Transport by overland flow plus interaction = $T_c - Q_{trans}$	469

* not determined in these experiments

Considering the remoteness of the possibility of isolating these interactions in the field and designing special strategies to control them separately, some amount of lumping the interaction effects with the other processes would appear desirable for practical reasons. In each case it would seem reasonable to lump them with the dominant process. This is demonstrated in the second procedure (Table 78). Predicted in this way the contribution of rainfall-runoff interactions to the detachment and transport processes is lumped with rainsplash detachment and overland flow transport capacity respectively.

In applying this interaction approach to a simple model such as that developed by Morgan et al. (1981), but using equations relating to instantaneous rather than annual conditions, either of two procedures can be used (Table 79). The first option uses two expressions, one for splash detachment plus interaction and the other for overland flow transport capacity plus interaction. The second option combines splash detachment, interaction and overland flow detachment rate in one equation and overland flow transport capacity, interaction and splash transport in another.

An example is given below using the second approach to predict erosion in terms of its limiting process for experimental conditions similar to those used in this study. These comprise 4 bare soils (standard sand, sand, clay loam and clay), 4 slopes (3.5, 7.0, 10.5, and 14.0 per cent), and 4 rain intensities (50, 80, 110, 140 mm h^{-1}) with a test duration of 20 minutes. Equations specific for each soil were used (Table 80).

The results are plotted in Figs. 4 - 7. Examination of the curves reveals the following general features:

1) At lower slopes more soil particles are detached than can be transported.

2) As slope steepens transport capacity increases rapidly in contrast to the gradual increase in detachment rate. A critical slope steepness is eventually reached where neither detachment nor transport capacity is limiting. At this point

TABLE 79 Modelling rainfall-runoff interactions in the erosion process - simple procedure

First option	Eq. No.
Detachment by rainsplash plus interaction (Q_{det})	
$= Q_{rodet} - Q_{odet}$	244a
Transport capacity of overland flow plus interaction	
$= T_c - Q_{trans}$	469
Second option	
Detachment by combined flow, raindrop impact and interaction	
$= Q_{rodet}$	284
Transport by combined flow, raindrop impact and interaction	
$= T_c$	467

where Q_{rodet}, Q_{odet}, T_c, and Q_{trans} are defined as in second procedure Table 86.

TABLE 80 Equations used for modelling rainfall-runoff interactions - simple procedure

Soil	Equation	R^2	Eq. No.
Standard sand	$Q_{rodet} = e^{-3.17}\ KE^{1.03}\ S^{0.93}$	0.94	267
	$T_c = e^{29.39}\ q^{2.78}\ S^{2.70}$	0.98	388
Sand	$Q_{rodet} = e^{-4.14}\ KE^{1.06}\ S^{0.78}$	0.96	272
	$T_c = e^{25.43}\ q^{2.40}\ S^{2.45}$	0.98	391
Clay loam	$Q_{rodet} = e^{-3.86}\ KE^{0.87}\ S^{0.45}$	0.94	277
	$T_c = e^{19.16}\ q^{1.98}\ S^{1.56}$	0.97	394
Clay	$Q_{rodet} = e^{-5.12}\ KE^{1.01}\ S^{0.41}$	0.92	282
	$T_c = e^{21.38}\ q^{2.18}\ S^{1.73}$	0.96	397

equilibrium is established between detachment and transport rates. Beyond the critical slope, both detachment and transport capacities continue to increase but the latter does so more rapidly. Detachment capacity therefore limits the rate of soil loss.

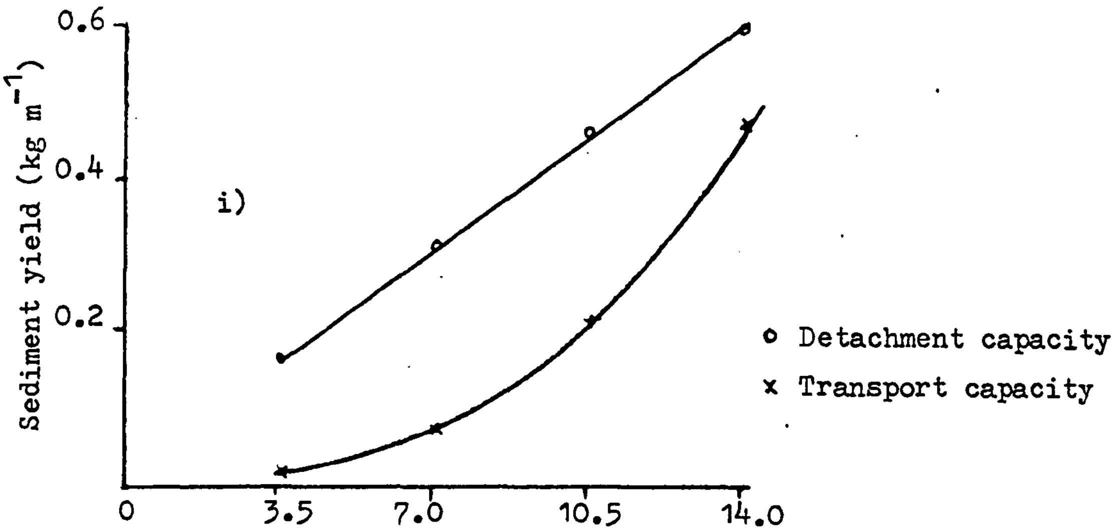
3) The critical slope steepness (Table 81) depends on the type of soil and the intensity of rainfall but decreases generally as the latter increases.

Fig. 4a shows that at 50 and 80 mm h^{-1} the amount of standard sand detached over the range of slopes studied is greater than can be transported. Erosion under these conditions is therefore transport capacity limited. However as rainfall intensity increases (Figs 4b and 4c) critical slopes of 11.9 and 9.8 per cent are reached for the 110 and 140 mm h^{-1} rain respectively beyond which erosion becomes detachment capacity limited.

Fig. 5a indicates that at 50 mm h^{-1} more Cottenham sand is detached than can be transported for all the slopes examined. At the intensity of 80 mm h^{-1} transport capacity limited conditions prevail on slopes up to a critical level of 10.5 per cent after which detachment limits erosion rates. The critical slope is further reduced to 8.57 and 7.0 per cent for the 110 and 140 mm h^{-1} respectively (Figs. 5b and 5c).

Figs. 6a - 6c give critical slopes of 13.30, 8.57, 6.47 and 5.07 per cent for the 50, 80, 110 and 140 mm h^{-1} rain respectively on clay loam. The corresponding slopes for clay (Figs. 7a - 7c) are 14, 10.5, 8.57, 6.93 per cent. At slopes lower than the above critical values, erosion is transport capacity limited.

These curves are similar in every detail to those in Fig. 8 which represents the conceptual model of interrill erosion proposed by Foster and Meyer (1975). The latter curves were produced on the basis of the physical principles of hydraulics, sediment transport and erosion mechanics. Their similarity to those reported here implies that the data produced in this study are appropriate for the development of such models; and that although empirical, the



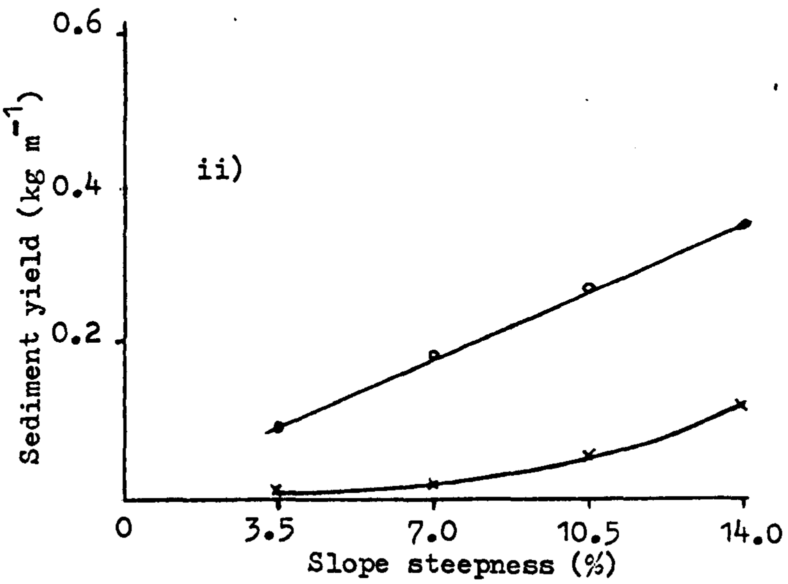


Fig.4a Detachment and transport capacities of overland flow with rain - standard sand

i) 50 mm h^{-1}
ii) 80 mm h^{-1}

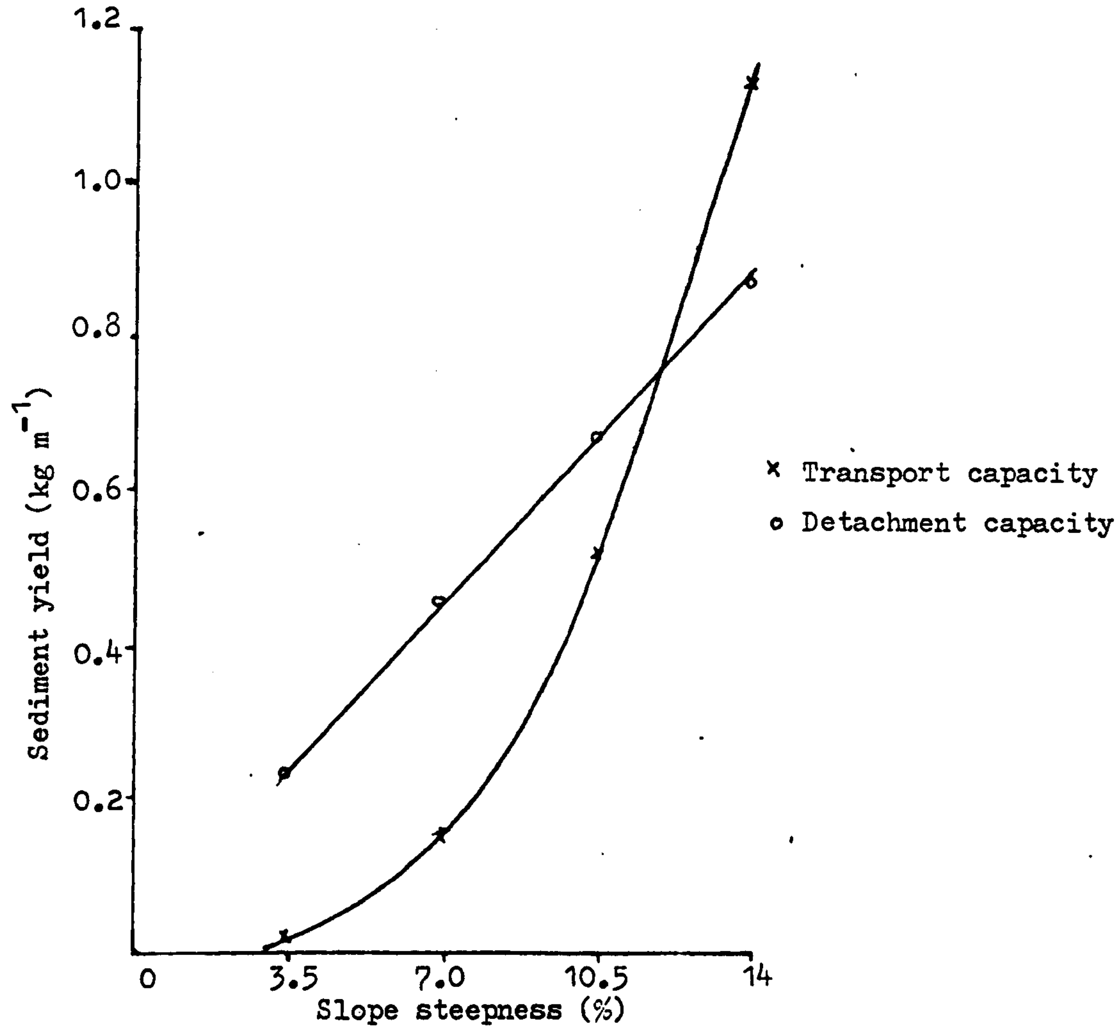


Fig.4b Detachment and transport capacities of overland flow with rain - standard sand, 110 mm h^{-1}

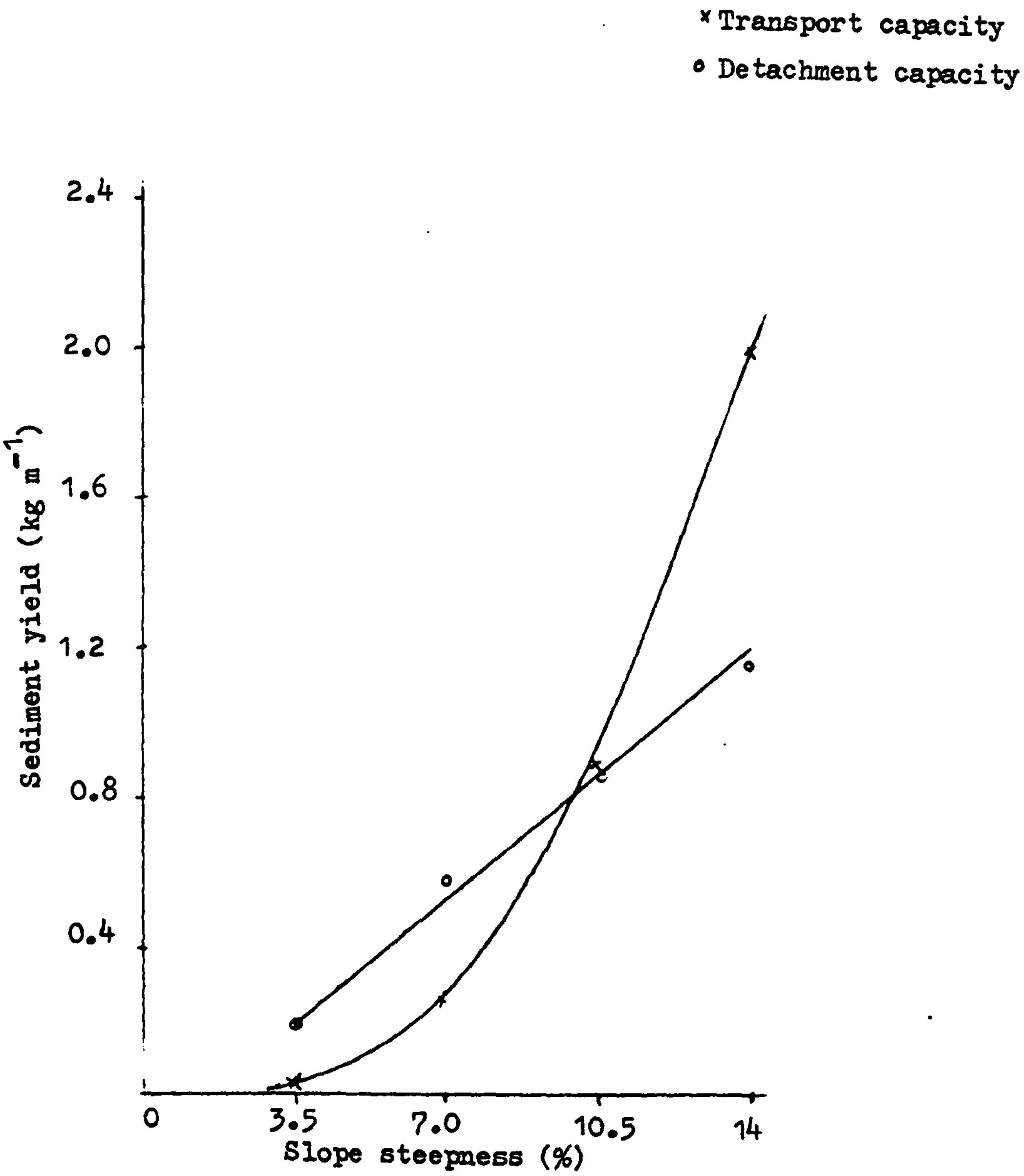


Fig.4c. Detachment and transport capacities of overland flow with rain - standard sand, 140 mm h^{-1}.

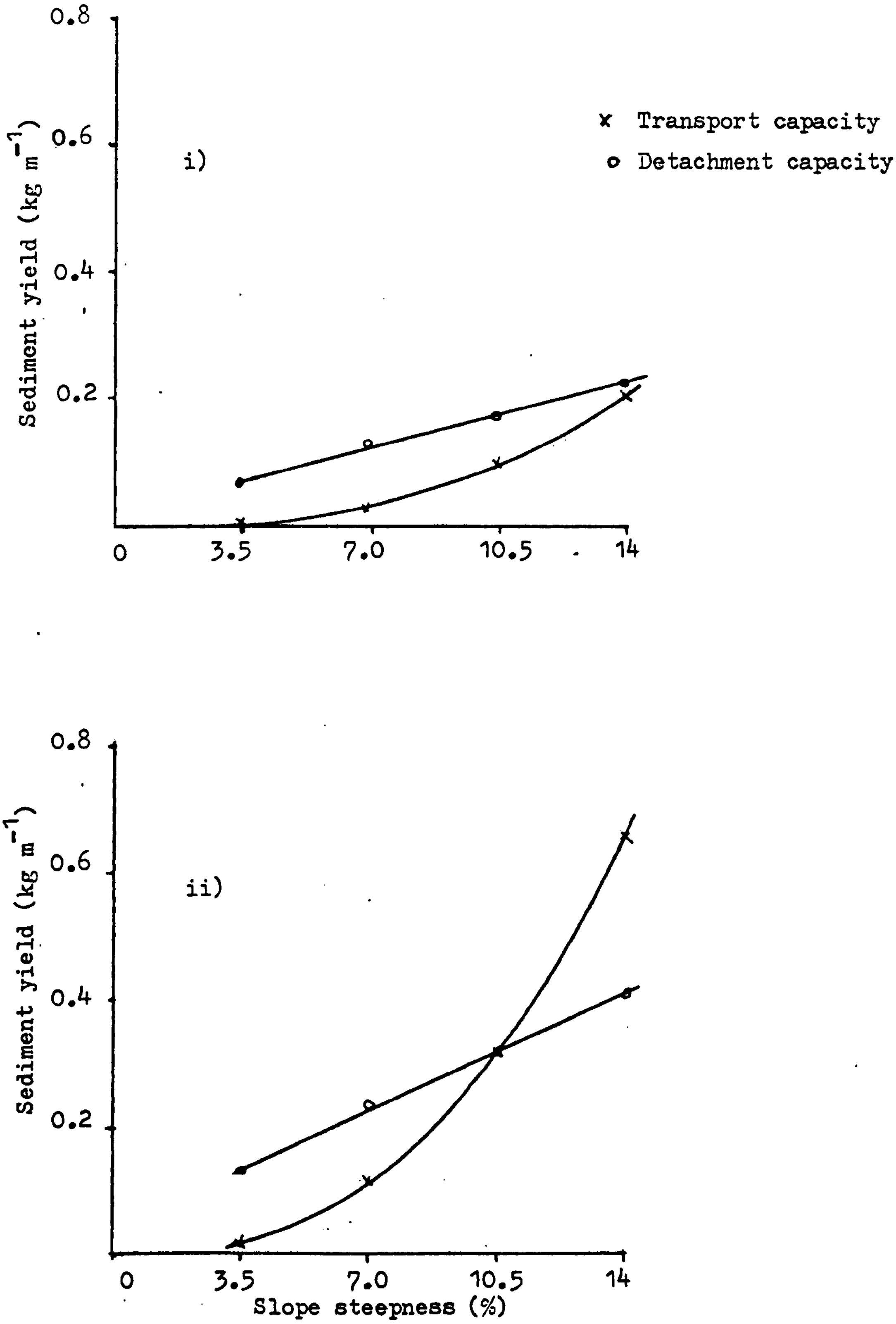


Fig.5a Detachment and transport capacities of overland flow with rain - Cottenham sand

i) 50 mm h^{-1}

ii) 80 mm h^{-1}

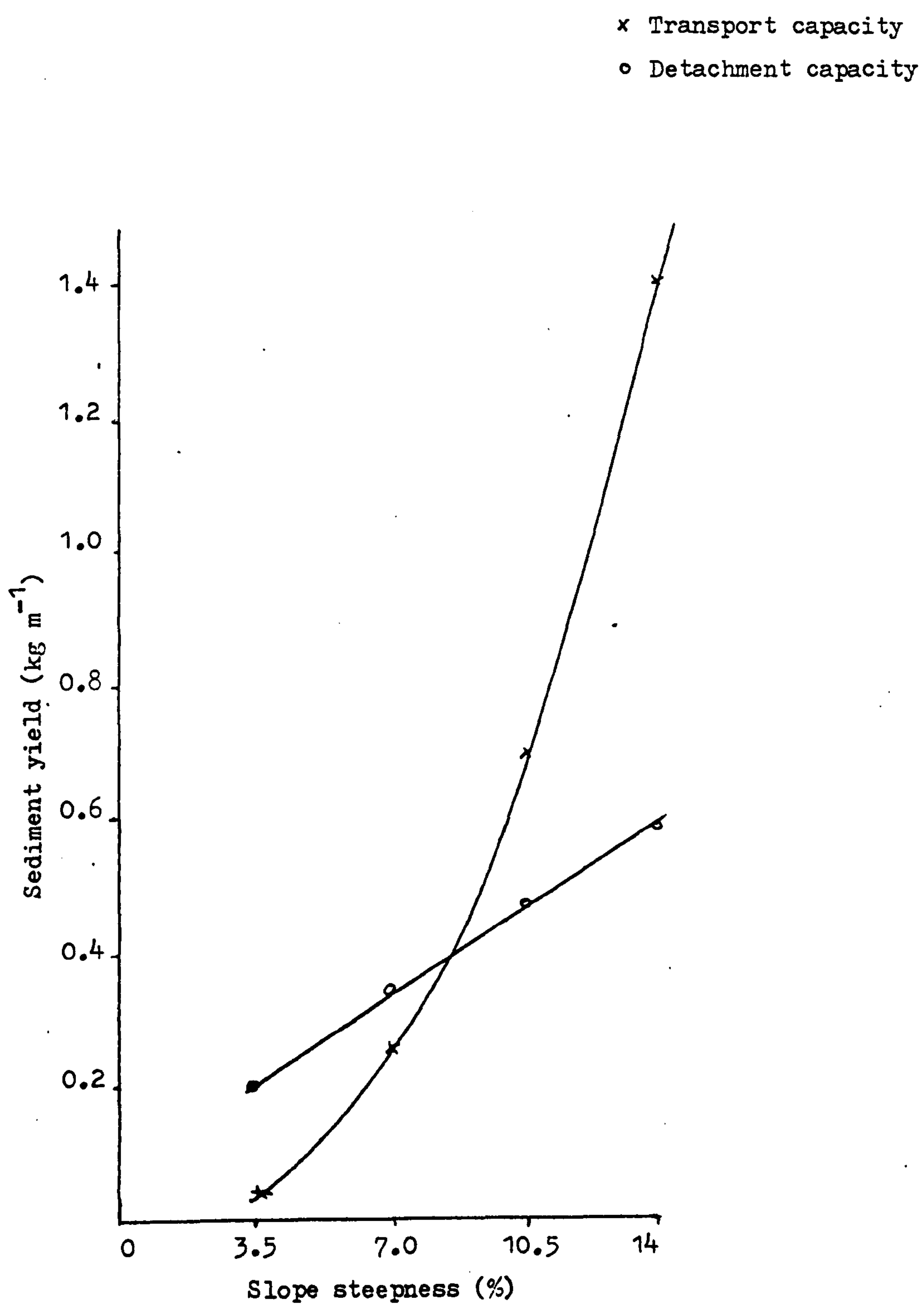


Fig.5b Detachment and transport capacities of overland flow with rain - Cottenham sand, 110 mm h^{-1}

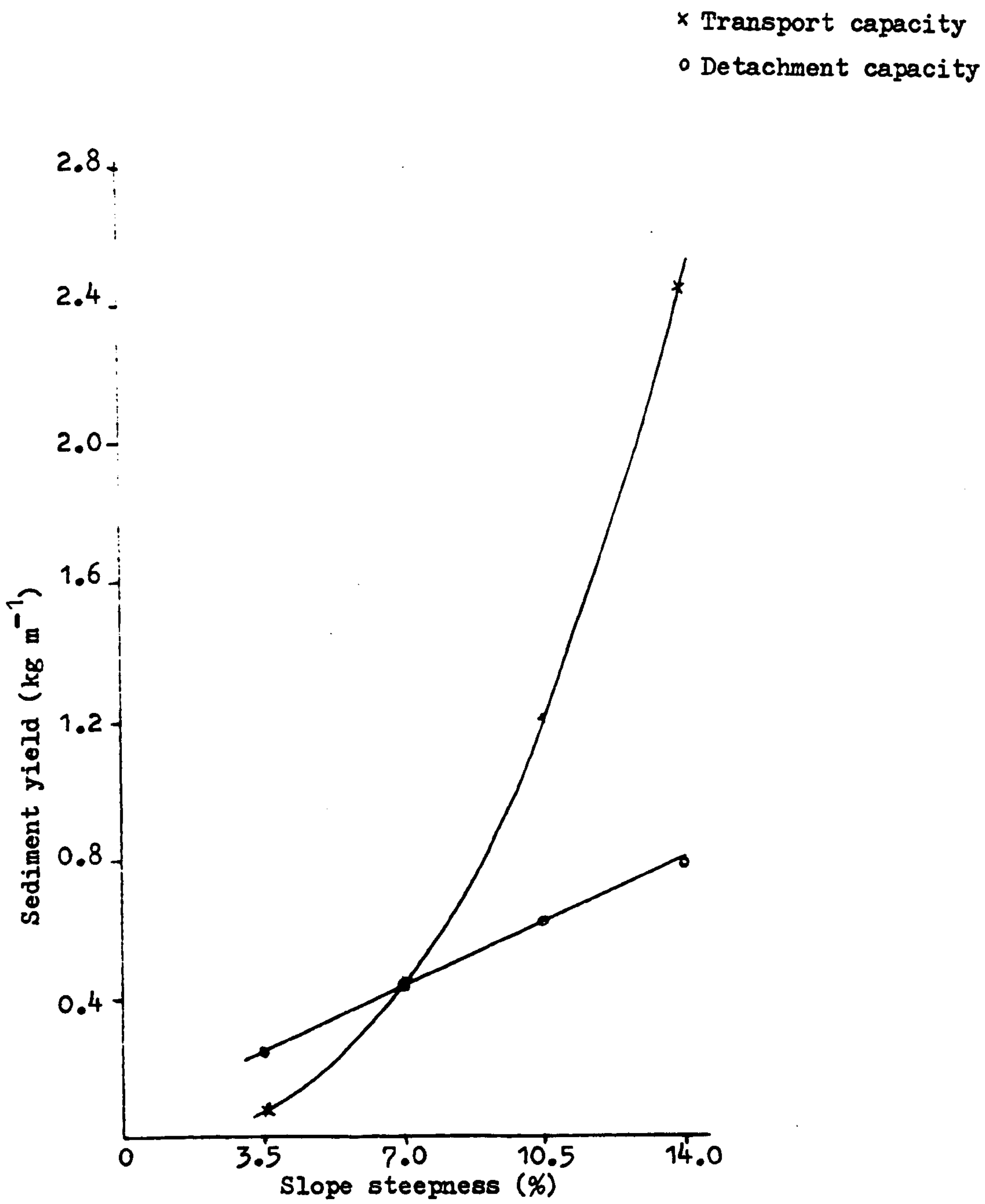


Fig. 5c. Detachment and transport capacities of overland flow with rain - Cottenham sand, 140 mm h^{-1}.

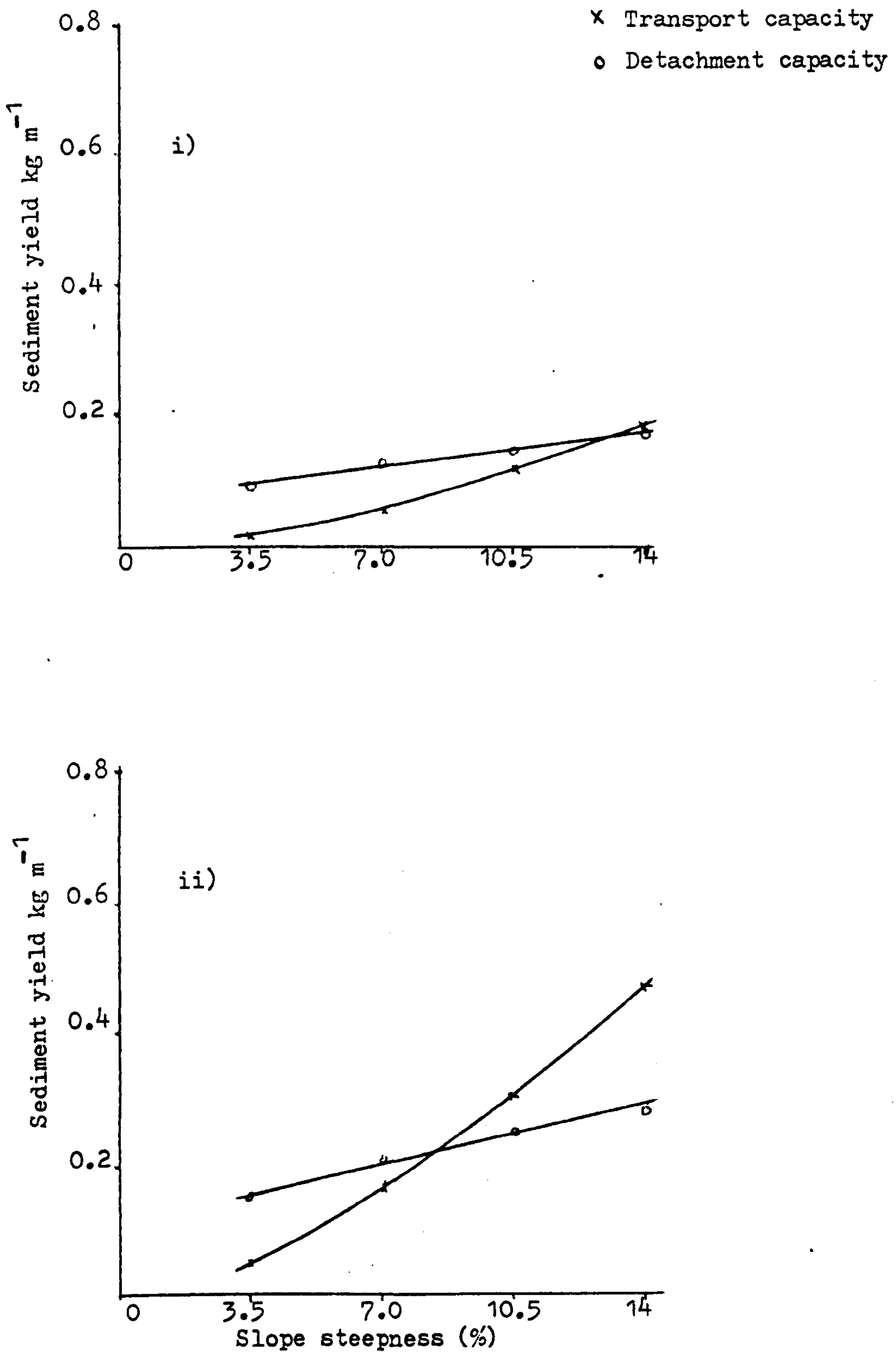


Fig.6a Detachment and transport capacities of overland flow with rain - Clay loam

i) 50 mm h^{-1}

ii) 80 mm h^{-1}

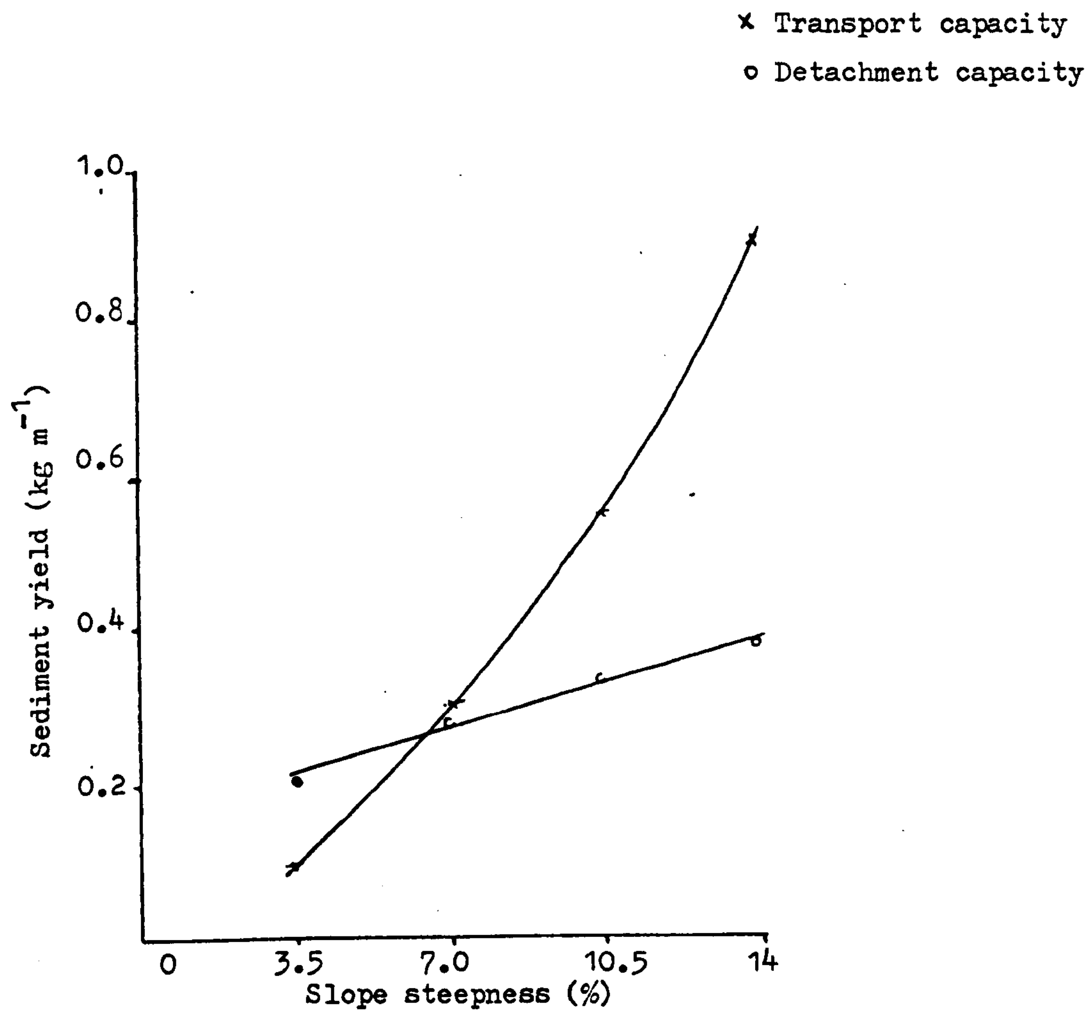


Fig.6b Detachment and transport capacities of overland flow with rain - clay loam, 110 mm h^{-1}

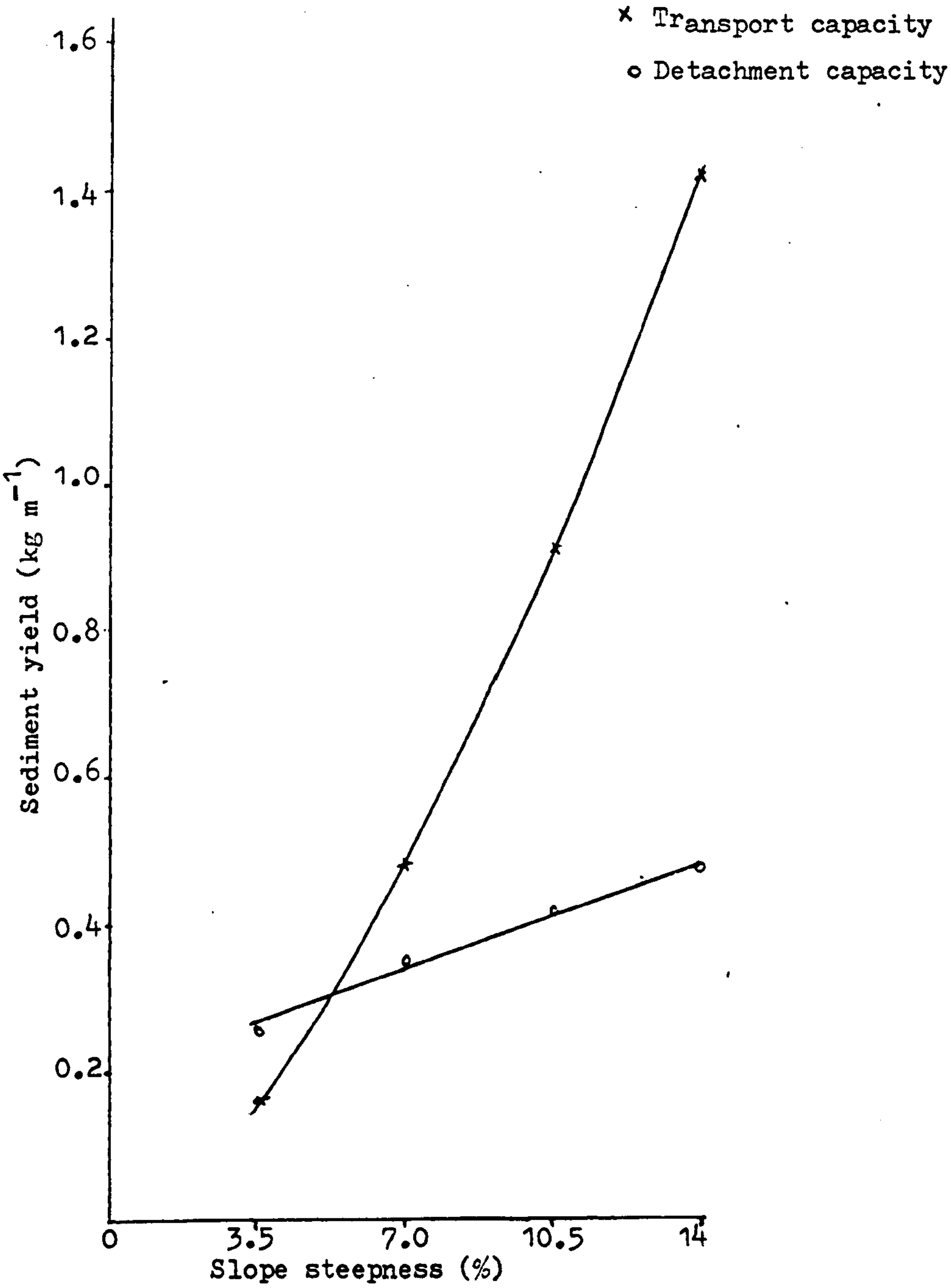
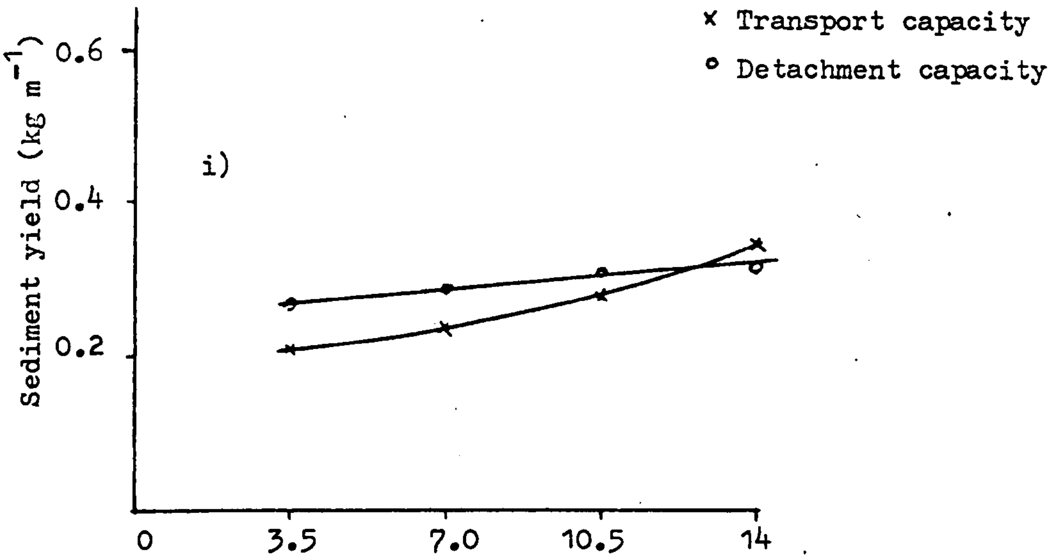


Fig.6c Detachment and transport capacities of overland flow with rain - clay loam, 140 mm h^{-1}



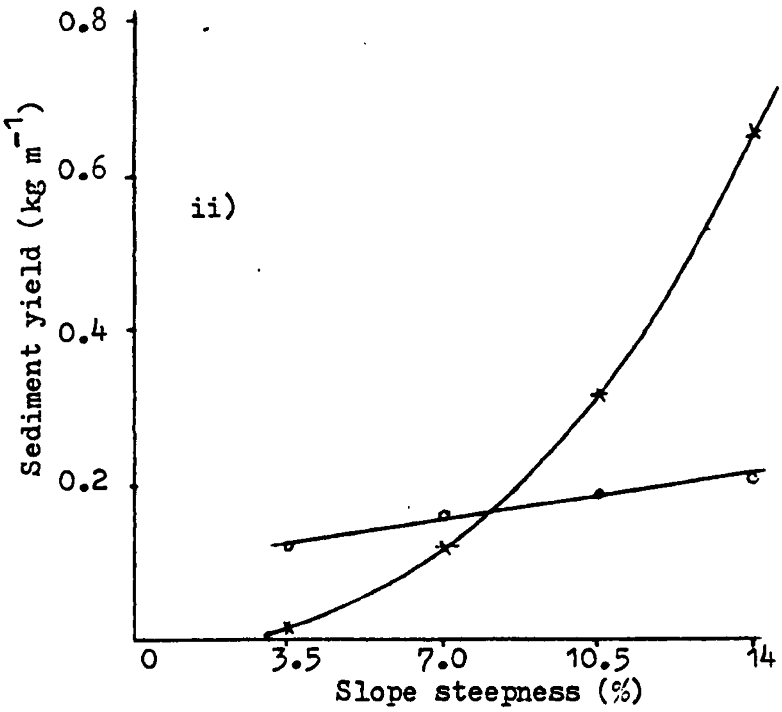


Fig.7a Detachment and transport capacities of overland flow with rain - clay

i) 50 mm h^{-1}

ii) 80 mm h^{-1}

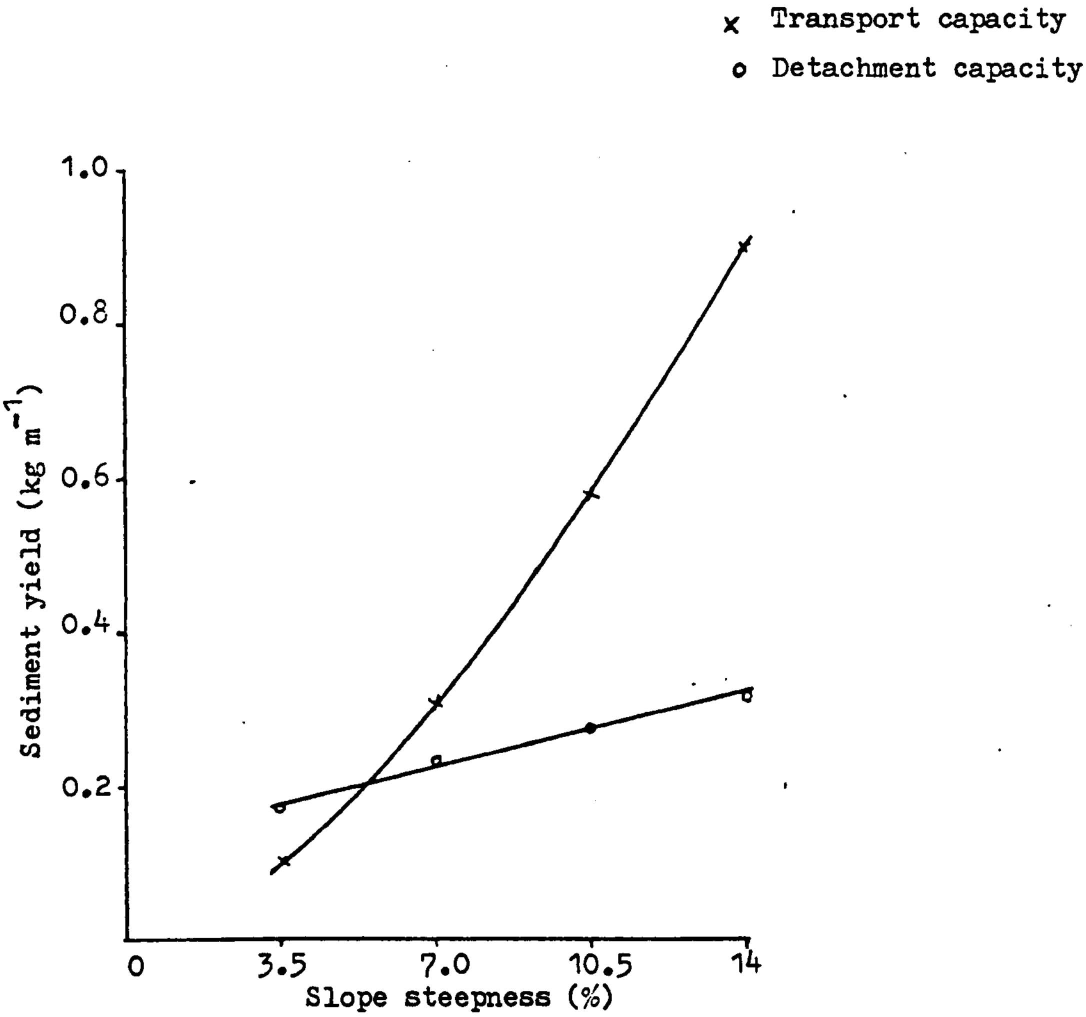


Fig.7b Detachment and transport capacities of overland flow with rain - clay, 110 mm h^{-1}

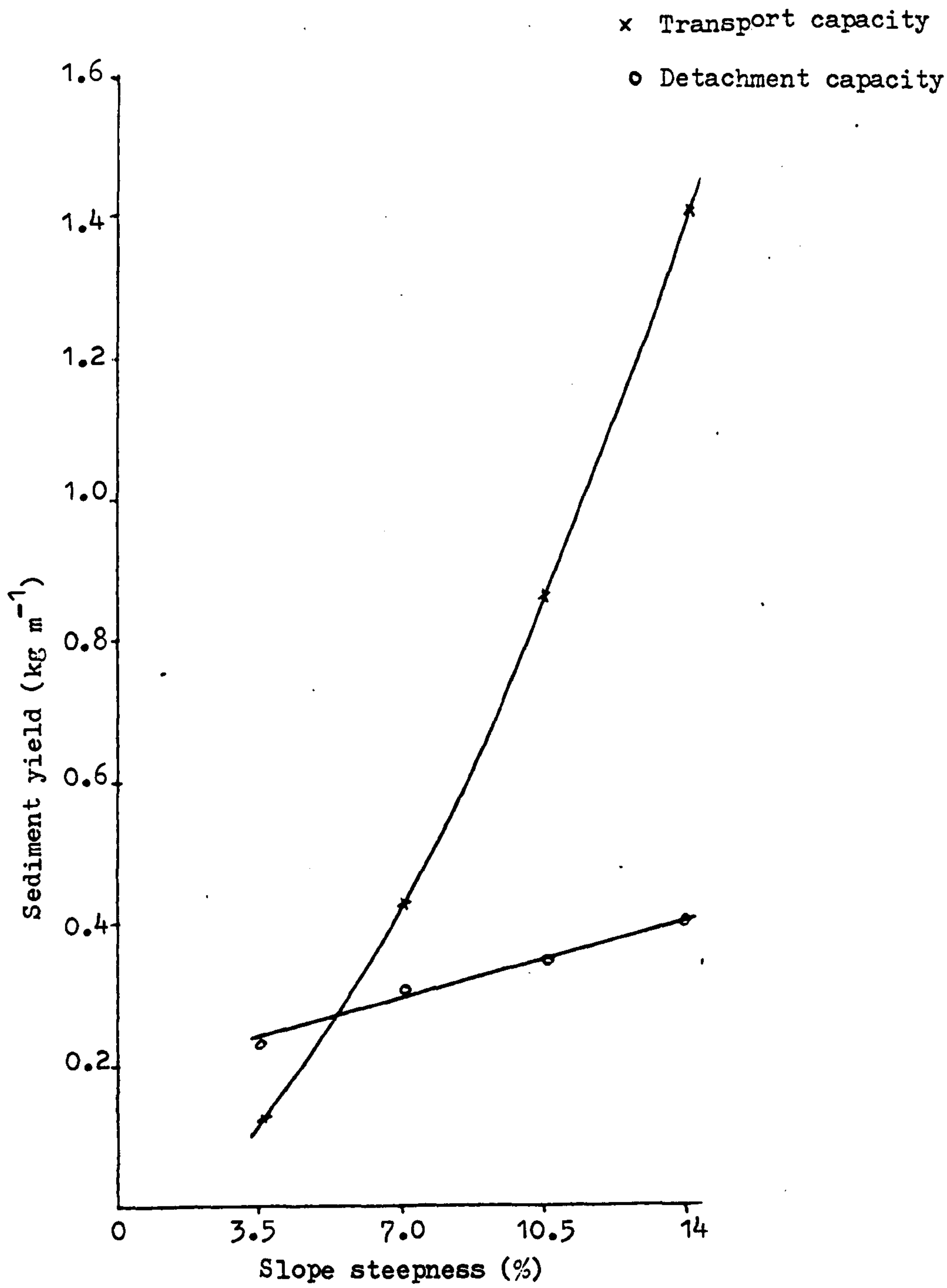


Fig.7c Detachment and transport capacities of overland flow with rain - clay, 140 mm h^{-1}

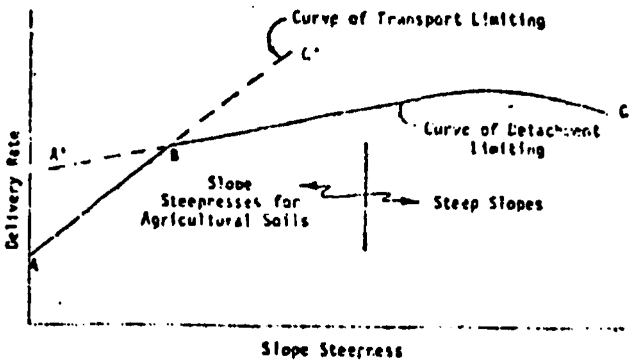


Fig.8-Conceptual model of the delivery rate of detached particles from interrill areas to rill flow.
(After Foster and Meyer, 1975)

equations used in predicting detachment capacity and transport capacity have a strong physical base. This is very welcome and is particularly important considering that because of the scarcity of appropriate data, the development of the above conceptual model of interrill erosion is still in its infancy. Thus apart from lending empirical support for the concept, the curves obtained in this study and the equations that define them provide an essential data base for the further development of the model. However more work is required to define the processes for slopes greater than those used in these studies.

Only a limited number of studies have examined the effect of erosion influencing factors on detachment/transport interactions. Kirkby (1980) shows by analysing the models developed by Meyer and Wischmeier (1969) and Foster and Meyer (1972) that the concept of a critical point at which the detachment/transport changeover occurs applies also to slope length. Meyer et al. (1975) also obtained a similar changeover curve for interrill and rill erosion.

The variations in the changeover point between detachment/transport capacity limiting conditions explain why fields with varying slopes but the same soil and rainfall conditions exhibit different erosion patterns. For the same reason, considerable variations in rainfall intensities in a given area will exercise a significant influence on the success or failure of conservation measures. This questions for what temporal scales models or indeed conservation systems should be designed.

The sensitivity of the erosion-limiting conditions to varying soils, rainfall intensities and slope steepnesses shows that the transfer of soil conservation practices from one area to another with seemingly identical conditions should be done cautiously. This is one principal area where the modelling procedures that predict erosion in terms of the limiting process can play a significant role in the practice of soil conservation.

8.3 STRATEGIES FOR EROSION CONTROL BASED ON EROSION LIMITING PROCESS

In this section an attempt is made to show how the mechanics of detachment and transport of soil particles and the modelling techniques presented in the earlier Chapters can be used as the basis for the design of strategies for erosion control. For erosion by water raindrop impact and runoff are the agents that detach and transport soil particles. Conservation measures must therefore protect the soil from raindrop impact and the hydraulic forces of runoff. These generally involve:

1) dissipating raindrop impact energy on non-erodible surfaces such as vegetation, plant residues, mulches and using conservation tillage practices;
2) absorbing the erosive forces of overland flow by maintaining surface-contact dense vegetation, mulching and conservation tillage practices;
3) reducing the quantity or rate of runoff by increasing the infiltration capacity of the soil by tillage practices that leave the soil surface rough and cloddy and maintaining large amounts of vegetation or mulches on the soil surface;
4) slowing runoff velocities by contour farming with ridged crop rows at small row gradients, graded terraces, contour strip cropping and increasing the roughness of the soil surface; and
5) improving soil characteristics by sound soil management such as minimum tillage, fertilizer use, cover crops and manuring, mulching, subsoiling and drainage.

However, the type of measure required depends on whether detachment or transport is the major problem. For given conditions, this can be determined by using any of the predictive techniques presented in the earlier sections to delineate the erosion-limiting process. When the Meyer-Wischmeier-type model is used, any of the component subprocesses (Table 78) may be limiting. Using the model developed by Morgan et al. (1981) reduces the problem to either rainsplash detachment or overland flow transport capacity limiting conditions. Where detachment is limiting, efforts to reduce the transport of soil particles would be less effective than practices that reduce detachment capacity. However for conditions where transport is limiting, reducing transport capacity would be more effective. Failure in recognizing these differences may account for why some erosion control practices do not bring about the expected reductions. Morgan (1980) has summarized the measures that may be used to control each of the subprocesses (Table 82).

After identifying the limiting process which determines the rate of soil loss, the next step is to reduce the latter loss to a rate that will permit a high level crop productivity to be sustained economically and indefinitely (Mannering, 1981). This is done by selecting a maximum permissible rate of soil loss, referred to as soil loss tolerance, and using the model to determine separately what values of the variables are required to achieve that rate. This is illustrated for the erosion conditions in Figs. 4a - 7.

The erosion limiting processes for the test conditions are summarized in Table 81. For each soil and rainfall intensity, erosion on slopes lower than the critical value is transport capacity limited. Beyond the critical value, erosion is detachment capacity limited. Whilst in the former case conservation must be directed at reducing the transport capacity of overland flow, control must be exercised on splash detachment in the latter situation.

As indicated earlier splash detachment rates can be reduced by dissipating raindrop impact energy on a non-erodible surface. At field scale, maximum detachment rates generally coincide with periods in the cropping cycle when the soil is bare. The basic control measure is therefore to maintain an adequate cover throughout the growing season especially early in the season when the soil is most vulnerable to rainsplash detachment. This involves all the measures required to grow a good crop including sound soil management systems that maintain soil structure, adequate soil moisture storage and a high level of soil fertility. Some of the latter systems are minimum tillage practices, application of fertilizers and manures, mulching and using optimum spacing to achieve adequate plant density.

TABLE 81 Critical slopes at which erosion changes from transport capacity to detachment capacity limited

Soil Type	Intensity of rain (mm h^{-1})			
	50	80	110	140
	% slope			
Standard sand	>14	>14	11.9	9.8
Sand	>14	10.5	8.57	7.0
Clay loam	13.3	8.57	6.47	5.07
Clay	>14	10.5	8.57	6.93

TABLE 82 Soil Conservation practices

Practice	Control over			
	Rainsplash		Runoff	
	D	T	D	T
Agronomic Measures				
Covering soil surface	*	*	*	*
Increasing surface roughness	-	-	*	*
Increasing surface depression storage	+	+	*	*
Increasing infiltration	-	-	+	*
Soil Management				
Fertilizers, manures	+	+	+	*
Subsoiling, drainage	-	-	+	*
Mechanical Measures				
Contouring, ridging	-	+	+	*
Terraces	-	+	+	*
Waterways	-	-	+	*

- no control; + moderate control; * strong control

(adapted from Morgan, 1980)

D = Detachment, T = Transport.

For overland flow transport capacity, reductions in soil transportability, runoff rate and slope steepness are required to give desired rates. The measures (2) - (5) presented earlier in this section and those in Table 82 may be used often in combinations to control transport rates.

Operated in this way the models presented in this Chapter can be used not only to predict soil loss but to separate erosion into its component subprocesses and predict the erosion-limiting process. This allows soil conservation measures to be directed at the limiting process.

Although this procedure serves as a pointer to the several options available for controlling the limiting process, it does not show which particular one should be used. In order to achieve this, the model should incorporate the effects of soil conservation practices within the separate phases. Thus, for example, the influence of agronomic measures can be allowed for by changes in the volume of runoff, rate of splash detachment and the transport capacity of overland flow as illustrated in the simple model developed by Morgan et al. (1981). This permits the feasibility of attaining desired levels of soil loss by different control strategies to be assessed. For example, erosion may be detachment-limited but the initial strategy of reducing detachment rate may not reduce soil loss low enough under the proposed land use. In such a situation the feasibility of changing the erosion condition from detachment-limited to transport-limited must be assessed. Morgan et al. (1981) demonstrate this for erosion under maize alone and maize plus mulch.

However, in most cases the basis for modelling the effects of conservation practices is very weak. Research effort should therefore be directed at establishing a firm base for modelling the effects of soil conservation practices which in turn will facilitate the choice of appropriate measures to control erosion under given circumstances.

8.3.1 Selection of plant cover for erosion control.

In situations where natural factors are conducive to high rates of erosion, management is the key to erosion control (Hudson, 1971; Stocking and Elwell, 1976). Among the most important aspects of good management is the choice of suitable crops and maintenance of optimum growth rate for cover.

Several studies on erosion indicate that crop cover provides potentially the most effective means of conservation (Hudson and Jackson, 1959; Aina et al. 1977; Shaxson, 1981; Meyer, 1981). Erosion control at the field scale based on agronomic techniques therefore depends largely on maintaining the protection afforded to the soil by the plant cover. Although a vast amount of data indicating the effectiveness of a wide range of plant covers and different treatments in reducing soil loss is available from experimental stations, particularly in the United States, it is very difficult to extrapolate the results to new environments. This is because the reasons underlying why particular treatments work are often obscured. The choice of suitable plant covers to control erosion in different areas is therefore still a problem.

To provide a sounder base for this choice, Morgan (1980) suggests the use of the current available information for modelling the effects of plant covers on erosion. He further develops guidelines that may be used in modelling these effects to place design procedures for plant cover on the same level as the critical velocity and tractive force approaches currently adopted in waterway design. Since the research base for the theoretical development of plant cover effects is very weak at present, recourse must be made to empirical models.

In this section an effort is made following the guidelines provided by Morgan (1980) to show how the material presented in this study can be used for the further development of the hydraulic effects of plant cover. Guidelines are also given for adapting the equipment designed in this study for the rapid development of parameter.

In modelling the hydraulic effects of plant covers, the approach used by Foster and Meyer (1975) for modelling the effects of straw mulch in reducing flow velocity may be adopted. These authors established the following relationship between the cube of the velocity ratio and a straw mulch rate.

$$\left(\frac{V_m}{V_o}\right)^3 = \exp\left\{-3.0\ \left[1.0 - \exp\left(-2.15\ M^{0.65}\right)\right]\right\} \qquad \text{Eq. 470}$$

where V is the flow velocity for conditions with mulch (m) and without mulch (o) and M is the mulch rate (t ac^{-1}). From this equation the mulch rate can be predicted which will reduce a given velocity without mulch (V_o) to a maximum permissible velocity (V_m). The mulch rate can be related to the area of bare or exposed ground (E), using the expression

$$E = e^{-1.27\ M} \qquad \text{Eq. 471}$$

Whilst tests of these equations have been encouraging (Foster and Meyer, 1975), they apply only to straw mulches. Similar equations need to be derived for other types of mulch and plant covers (Morgan, 1980). In addition to flow velocity, changes in friction factor, tractive force, and discharge brought about by plant cover may be similarly modelled.

In applying this procedure, the basic requirement is to predict the latter four flow parameters for bare soil and for different plant covers. For bare soil conditions, typical values of these parameters obtained under varying laboratory conditions are given in Table 22 for velocity, 44 for friction factor, and (51b) 51b for tractive force (Chapter 5). Equations relating these variables to discharge and slope steepness are also provided in Chapter 5 for predictive purposes. These are available for flow with and without rain and for different soil surfaces. The equations with coefficient of determination (R^2) ranging from 0.85 - 0.98 are recommended. On this merit, the equations for friction factor are not satisfactory. It can however be calculated from Eqs. 17 and 18 in which flow velocity and depth are estimated from the discharge slope relationships in Chapter 5.

In order to operate these equations for a given situation, discharge and slope steepness should be known. The latter can easily be measured using for example Abney level whilst the former can be estimated from any of the methods mentioned in Section 8.1. It must be pointed out that although most of the exponents in the equations compare well with those derived theoretically for overland flow, they have not been verified for field conditions. They can however be used to give preliminary values.

Presently there is no body of data on typical values of flow velocity, tractive force and friction factor for different plant covers. It is therefore necessary to obtain these values from experiments. Measuring these parameters for overland flow in the field is extremely difficult. Also because of the great variability in field conditions and the interactions between variables, a long period of data collection will be required to draw reliable conclusions.

However, whilst realistic data await measurement of flow characteristics in the field, a start can be made by using rainfall simulation techniques in the laboratory where the individual effect of factors and their interactions can be evaluated separately. For such laboratory studies, the combined rainfall simulator - bed flume facility used in this study can be easily adapted. This will only require

i) wooden soil trays with drainage holes for growing the test crops in a plant house and

ii) a facility for lifting and lowering the trays in (i) into the flume.

The tests basically involve growing different crops at varying densities in a plant house using the trays (i). At different stages of growth the trays bearing the plants are fitted into the flume at varying slope steepnesses using the facility in (ii). By following the test procedures in Chapter 3, apply different intensities of rain or flow rates and measure flow velocity and depth. Substitute these values in Eqs. 17 and 24 (Chapter 2) to give values for friction factor and tractive force respectively.

For a given rain intensity, slope steepness and soil type, variations in discharge will be due to the type of cover. Values obtained by measuring discharge and slope steepness may therefore be used to obtain flow velocity, tractive force and friction factors as shown for bare soil conditions above.

Where a portable rainfall simulator is available, similar experiments can be conducted in the field on small manageable plots especially where farmers are willing to co-operate. This is very important because eventually the validity of the laboratory studies for field conditions will have to be tested.

The above procedures represent the simplest view of a complex problem. For example, they ignore infiltration and evapotranspiration. Experimental details will differ for varying circumstances and will have to be worked out by the user. However, it is believed that the results of such simple experiments together with those on soil loss, runoff and data on rainfall amount and intensity will allow more critical choices between various agronomic practices to conserve the soil for the sustenance of productivity.

8.3.2 Erodible channel design.

In soil conservation work, the removal of excess runoff from farm lands often involves constructing a network of waterways comprising diversion ditches and grass waterways. The aim is to design channels with sufficient capacity to transmit the runoff supplied to it without scour or fill. Two approaches based on critical flow velocity and tractive force are used. These procedures involve keeping the design velocity or tractive force below a critical value at which scour is initiated. Whilst no definite optimum values can be prescribed, maximum permissible velocities and tractive force based on many years of engineering experience (Schwab et al. 1966; Hudson, 1971) and laboratory experiments (Withers and Vipond, 1974) respectively are available.

Whilst channel design is beyond the scope of this study, certain inconsistencies have been found in that the values of permissible velocities and tractive force used in channel design are higher than those suggested for entrainment. For flow velocity an average of 600 - 900 mm s^{-1} is often considered sufficient to prevent sedimentation in shallow channels (Schwab et al. 1966). As indicated in Chapter 5, the lower value of this range is 3 times greater than the value (200 mm s^{-1}) which according to the graphs of Hjulstrom (1935) is required to entrain the particles of the sizes found in the soils used in this study. The occurrence of erosion in situations where flow velocity is lower than that suggested for entrainment is also not uncommon (Morgan, 1978). Maximum permissible tractive force values used in channel design are also greater than those obtained in this study and the critical values for most agricultural soils (Smerdon, 1964). All these, together with the fact that even at lower flow velocities and tractive force rilling occurred in these tests (Chapter 6), suggest the need for better guidelines for the selection of design velocities and tractive force.

8.4 CONCLUSION

This Chapter describes an attempt to bring together the material presented in the earlier Chapters for improving soil loss prediction and the selection and design of erosion control measures. Through studies of the mechanics of the subprocesses of erosion, predictive equations satisfying several modelling strategies have been developed. Apart from giving estimates of soil loss these models are capable of separating the detachment and transport processes and can predict the erosion-limiting process. This allows conservation measures to be directed at the latter process.

These studies have indicated the need for incorporating

i) rainfall-runoff interactions into erosion models to improve soil loss estimates; and

ii) the effects of soil conservation practices into erosion models.

Since the control of erosion at the field scale depends mainly on agronomic measures, more attention should be directed particularly to modelling the effects of plant covers. In this exercise effort should be made to use critical velocity, tractive force, and friction factor as the basis for modelling. This is required to place design procedures for plant cover on the same level as those currently adopted in waterway design.

Better guidelines are also needed for the selection of appropriate design parameters (velocity, tractive force) to reduce scour in erodible channels.

CHAPTER 9

CONCLUSIONS

This project was initiated as a part of the National College of Agricultural Engineering's soil erosion and conservation research programme to study the effects of individual factors on the erosion process and to take advantage of the hitherto neglected role of the laboratory as a place for studying interactions by controlling factors.

The study was specifically aimed at establishing a sounder research base for modelling the subprocesses of erosion and for soil conservation design. Laboratory experiments were therefore designed to study the individual effects of a graded sand (standard sand) and three soils (sand, clay loam, clay), four rainfall intensities (50, 80, 110 and 140 mm h^{-1}) and four slope steepnesses (3.5, 7.0, 10.5 and 14 per cent) and their interactions on each of the following four subprocesses of erosion:

i) detachment of soil particles by rainfall;
ii) detachment by overland flow;
iii) transport of the detached particles by rainfall; and
iv) transport by overland flow.

For each of the subprocesses, the above variables were replicated four times and studied as a factorial set of treatments. Additionally the effects of four flow rates on the hydraulic characteristics of flow such as velocity, depth, Reynolds number, Froude number and friction factor were studied. These parameters were then used to characterize the detachment and transport of soil particles in these flows. The achievements of the study are summarized in the following sections.

9.1 ACHIEVEMENTS OF THE STUDY

9.1.1 New Equipment

An existing rainsplash tray and a nozzle rainfall simulator with a rotating disc were used for the splash detachment and transport tests. It was however necessary to develop equipment and techniques for measuring detachment of soil particles by overland flow because there is no explicit study on the process. In order to make a more efficient use of existing equipment, an Armfield mobile-bed flume was modified without altering its original use to make possible separate evaluations of soil detachment and transport by overland flow. The main features of the new equipment are:

i) an extension frame and slope formers which allow slopes of 0 - 20 per cent to be obtained within the flume;
ii) special interchangeable soil-plates for evaluating separately the detachment and transport capacities of overland flow;
iii) runoff input and measuring devices which permit small flow rates typical of overland flow to be simulated;
iv) depth gauge;
v) sediment dispenser for transport studies;
vi) a nozzle simulator mounted on the flume permits the assessment of the effects of rainfall-runoff interactions on the subprocesses of erosion to be made; and
vii) by being able to vary and control rainfall intensities, flow rates, soil types and slope steepness, the rainfall simulator - bed flume facility makes it possible to study and analyse not only the individual effects of these factors but also their interaction on the erosion process and on flow characteristics.

9.1.2 Interaction of factors influencing erosion.

The study confirms the results of earlier workers on the individual effects of soil type, slope steepness and rainfall intensities on erosion rates. Whilst the rate of soil detachment by rainfall and by runoff is greater on sand than on clay, the transport of the detached particles does not follow any consistent trend. This is because of the greater dependence of transport on variations in particle size. However for both rainfall and runoff, detachment and transport rates significantly increase with increasing rainfall intensity or flow rate and slope steepness.

The values of the exponent relating splash detachment to total kinetic energy of rain (0.8 - 1.4) and splash transport to slope steepness (0.75 - 1.37) are comparable to the respective values of 0.8 - 1.46 and 0.75 - 2.0 obtained by other investigators of splash erosion. However, the magnitude of the exponent values is soil specific. Whilst the values of the discharge and slope exponents (1.50 and 1.44) in the overland flow detachment equation are about twice greater than the value (0.67) suggested for overland flow detachment, they are similar to those used for rill flow.

Because most previous and present research on erosion tend to treat the influencing factors as independent and evaluate them in isolation, the effects of the interaction of factors such as soil type, slope steepness, rainfall intensities and flow rates have not been explicitly studied.

However, this study shows that each of the subprocesses identified earlier is significantly influenced by the first and second order interaction of the above factors. On a relative basis, the second order interaction is small in all cases. Significant interactions show that the factors are not independent of each other; the simple effects of a factor differ, and the magnitude of any simple effect varies according to the level of the other factors of the interaction term.

The most important interactions that influence splash detachment and transport are soil x rainfall intensity and slope x rainfall intensity respectively.

For detachment by overland flow, the major interaction is slope x soil. As slope steepens, the influence of soil type on detachment rate increases and the proportionate increase is greater for sand and standard sand than for clay and clay loam. The influence of slope steepness also varies significantly among the soil types. Other important interactions are slope x discharge and soil x discharge. For a given soil, detachment rate on all slopes increases as discharge increases and the magnitude of the response is greater at lower than higher slopes. As slope steepness increases, the detachment capacity of flow both with and without rain is also enhanced with the increase being proportionately more for the 1.0 and 1.6 l/min than the 2.2 and 2.8 l/min flows. The soil x discharge interaction shows that, for flow without rain, detachability increases more for clay and clay loam than for sand and standard sand as discharge increases. In the presence of rain however, the response of the soils does not differ much.

The most prominent interaction affecting the transport capacity of flow is soil x slope, followed by discharge x soil and then slope x discharge. Where factors interact significantly, interpretation of results based solely on the main effects of the influencing factors may result in loss of vital information. For example, examination of the slope x soil interaction showed that at lower slopes (3.5 and 7.0 per cent) combined flow and rain has a greater transport capacity for the larger clay and clay loam aggregates than for the fine grains of sand and standard sand. This is obscured when effects are averaged over all the slopes as is the case when only main effects are considered.

9.1.3 Development of predictive equations

For each subprocess, new predictive equations are established accommodating the effects of factors which are important but are not accounted for in existing equations. These include slope steepness for splash detachment, and a grain size term for splash detachment, splash transport and overland flow detachment.

The rainfall-runoff interaction contributes significantly to soil loss and therefore predictive equations which do not account for this interaction underestimate soil loss. The use of such equations for design work in soil conservation may lead to under design and therefore must be replaced by new equations that cater for rainfall-runoff interactions. This study has provided predictive equations which intrinsically incorporate rainfall-runoff interactions for each of the subprocesses of erosion.

The equations can also be used in the Meyer-Wischmeier type models to help determine which process limits erosion rates. Knowledge of this allows conservation measures to be directed at the limiting process.

Given values of acceptable levels of soil loss, the overland flow detachment and transport equations can provide permissible values of slope steepness, flow velocity and tractive force for use in soil conservation design work.

9.1.4 Qualitative observations

Whilst some of these observations are new, others confirm previous studies. The confirmatory evidence shows that

1) velocities and depths of overland flow are generally small and Reynolds numbers are within the laminar range of values. However in the presence of raindrop impact, flow is better described as disturbed flow.
2) The values of Froude number show that whilst flow can be either supercritical or subcritical, overland flow is predominantly subcritical laminar.
3) Friction factors are generally high and for rough surfaces, the magnitude of k in the relationship, $f = k/Re$, always exceeds the theoretical value for laminar flow over smooth surfaces.
4) For a given flow, raindrop impact decreases flow velocity and increases flow depth, friction factor and tractive force.

The new observations indicate slope x soil surface to be the most significant interaction influencing flow characteristics.

2) There is a significant correlation between detachment by overland flow and flow parameters, the most important being velocity, flow power, total runoff kinetic energy and Reynolds number. Detachment is negatively correlated with flow depth and friction factor.
3) Detachment by combined flow and rain is less sensitive to particle size than is detachment by flow without rain.
4) Detachment by flow without rain is mainly by rilling. However in the presence of rain, detachment by flow consists of a relatively even removal of soil particles from the eroding bed and the impacting raindrops appear to inhibit rill formation.
5) There is a critical slope steepness at which both raindrop impact and overland flow contribute equally to total

detachment. At slopes lower than the critical value, raindrop impact is the main detaching agent whilst flow predominates the detachment process at steeper slopes. The critical slope steepness is soil specific and decreases in the order of clay > clay loam > sand > standard sand.

6) Rolling and saltation dominate the movement of soil particles by combined flow and rain. Whilst clay and clay loam are transported as aggregates those of sand and standard sand proceed as individual grains with rolling and saltation dominating the movement of the clay aggregates and sand grains respectively. Movement of particles particularly sand and standard sand with porridge-like consistency and maintaining constant contact with each other was also observed.

7) The effectiveness of surface roughness in reducing the transport capacity of flow depends on whether erosion is detachment or transport capacity limited. In the latter case because a considerable area of the eroding surface is covered by deposited material, values selected for Manning's n based on the original conditions of the eroding surface may be unrepresentative and sediment transport capacity may instead be more sensitive to an appropriate particle size parameter. However with detachment capacity-limited conditions the original roughness of the eroding surface remains effective.

8) Important flow parameters that singly predicted transport capacity were velocity, flow power, total kinetic energy of flow, friction factor and tractive force.

9) There is a critical slope steepness at which erosion is neither detachment nor transport capacity limited. At this point equilibrium is established between detachment and transport rates. Whilst erosion is transport capacity limited at slopes lower than the critical value, it is detachment capacity limited at higher slopes. Failure in recognizing these differences may account for why some erosion control practices do not bring about the expected reductions.

10) The maximum permissible velocities and tractive force used in design work for erodible channels are several orders of magnitude greater than those suggested for entrainment. Better guidelines are therefore needed for the selection of design velocities and tractive force.

9.2 LIMITATIONS OF THE STUDY

The limitations of the study are associated mainly with the use of the equations and the equipment.

1) Since the predictive equations were derived through regression analysis they are strictly valid for the conditions under which they were produced namely, simulated rainfall intensities of 50 - 140 mm h^{-1}, 3.5 - 14.0 per cent slope and bare disturbed soil samples (standard sand, sand, clay loam and clay).
2) The equations for flow are for overland flow and incipient rill flow. They should not be used for the prediction of gully erosion.
3) Validation of the equations in the field has not yet been carried out therefore their use in predicting detachment and transport rates or soil loss should be considered only as a first approximation.
4) The equations are valid for detachment and transport capacity limited conditions.
5) The equations are for instantaneous conditions.
6) Detachment from rills and interrill areas are lumped.
7) The grain size parameters incorporated into the equations do not account for
   i) the temporal changes in particle size;
   ii) the influence of particle cohesiveness which increases as particle size decreases with resulting decline in detachment rates;
   iii) surface armouring; and
   iv) competency of flow.

   All these factors should be considered when interpreting results.
8) The soil-plates used for the detachment and transport tests are made of plywood. These tend to warp in water with constant use. Future use of the equipment should consider using galvanized iron sheets or marine plywood.
9) Sealing the edges of the soil-plate in the flume with mastik is very time consuming. Some kind of a reusable sticky waterproof tape will be more desirable.
10) Control of sediment feed rate from the sediment dispenser was very poor. A new dispenser which will permit better control of sediment input should be designed. Such a design must consider the use of both moist sediment (sand and clay) and 'dry' feed in future experiments. In both cases, a vibrator attached to the dispenser should be provided.

9.3 RECOMMENDATIONS FOR FURTHER WORK

From the results of this study and the review of the literature on the erosion process it is possible to list certain priorities for research.

1) Whilst there is a host of erosion influencing factors, only a limited number could be examined in this study. The results have shown factor interactions to be significant in soil loss estimates and in the understanding of the erosion process. More research therefore needs to be directed at the interaction of erosion influencing factors. This is necessary to bring more realism into soil loss estimates and may point the way to better control measures because after all the soil and water losses which conservation practices aim to control are the product of the interaction of these factors.

2) The study further shows rill formation to be associated mainly with the detachment of soil particles by overland flow. With the formation of flow lines on the eroding bed, particularly sandy soils, seemingly random nicks appear and these form the focal points for rill development. However the details of rill formation and development were beyond the scope of this work. Considering that the presence of rills on hillslopes increases the detachment and transport processes, more attention should be focussed on rills particularly their initiation, development and the processes that occur within them. These aspects should be studied in relation to the spatial and temporal variations in flow characteristics, the effects of rainfall-runoff interactions and soil characteristics. It should be possible to establish thresholds of relevant flow parameters such as velocity, tractive force and friction factor at which rills begin to form. This will provide a firm research base for designing measures to control rilling. A definition of the lower and upper limits of rill flow and overland flow respectively is also necessary for distinguishing processes due to the former from those of the latter.

3) For a better understanding of particle movement in shallow flows, some attention should be given to the mechanics of sediment transport in the laminar boundary layer of overland flow over

rough surfaces. The relationship between sediment movement in shallow flows and the hydraulic parameters of flow has not been explicitly studied in previous research. The direct effects of raindrop impact on sediment transport in shallow flows and on the hydraulic characteristics of flow are also not well understood. All these require research attention if sediment transport equations specific for overland flow are to be established.

4) Variations in soil erodibility within rainstorms, with seasons and tillage practices need to be investigated for better planning of agronomic measures to control erosion on problem soils. Studies on the effects of the chemical properties of the soil on erodibility should also be encouraged to define the role of organic matter in controlling erosion. A consideration should also be given to the effects of surface armouring and the temporal variations in grain size as the detachment and transport of soil particles by flow with and without rain progress. This is necessary for finding a more suitable parameter of effective grain size for use in erosion models.

Other research needs in soil conservation design and soil erosion modelling are presented in Chapter 8. With a few modifications to the equipment and experimental techniques developed in this study most of the investigations can be carried out in the laboratory under controlled conditions. However, in the long term these studies should be extended to the field to ascertain the applicability of the results obtained in the laboratory.

Appendix 1a

RAINFALL INTENSITY AND ITS UNIFORMITY (48.30 mm h^{-1})

Nozzle	:	1.5 H 30 Fulljet
Disc sector angle	:	1 x 10^{o}
Angular velocity	:	44 rpm
Intensity	:	50 mm h^{-1}
Pressure	:	7.5 psi

RUN

1	2	3	4
	mm h^{-1}		
38.50	38.50	39.50	38.50
55.80	59.70	61.60	55.80
44.30	42.30	44.30	44.30
53.90	50.00	53.90	50.00
47.20	44.30	50.00	47.20
38.50	38.50	42.30	38.50
44.30	44.30	44.30	43.30
46.20	43.30	48.10	44.30
40.40	40.40	41.40	41.40

$\bar{x}$ = 48.30 mm h^{-1}

Cu = 87.81%

Appendix 1b

DROP SIZE DISTRIBUTION (48.30 mm h^{-1})

Number of drops in each size group

DROP DIAMETER	RUN 1	2	3	4	Average
0 - 0.50	5	5	11	14	8.75
0.51 - 1.00	310	310	302	248	292.50
1.01 - 1.50	139	168	154	111	143.00
1.51 - 2.00	81	91	86	99	89.25
2.01 - 2.50	24	18	20	22	21.00
2.51 - 3.00	22	23	17	16	19.50
3.01 - 3.50	9	5	7	8	7.25
3.51 - 4.00	8	9	5	10	8.00
4.01 - 4.50	4	2	5	1	3.00
4.51 - 5.00	0	3	1	1	1.25
5.01 - 5.50	1	1	2	0	1.00

Appendix 1c

CUMULATIVE DISTRIBUTION OF DROP SIZE : % BY VOLUME (48.30 mm h^{-1})

DROP DIAMETER mm	AV. NO. OF DROPS	DROP VOL.* ml	VOL OF WATER IN EACH CLASS ml	% TOTAL VOLUME %	CUMULATIVE % %
0 - 0.50	8.75	0.025	.22	.015	.015
0.51 - 1.00	292.50	0.220	64.35	4.40	4.415
1.01 - 1.50	143.00	1.20	171.60	11.73	16.145
1.51 - 2.00	89.25	3.00	267.75	18.30	34.445
2.01 - 2.50	21.00	6.00	126.00	8.61	43.055
2.51 - 3.00	19.50	11.00	214.50	14.66	57.715
3.01 - 3.50	7.25	18.00	130.50	8.92	66.635
3.51 - 4.00	8.00	28.00	224.00	15.31	81.945
4.01 - 4.50	3.00	40.00	120.00	8.20	90.145
4.51 - 5.00	1.25	55.50	69.38	4.74	94.885
5.01 - 5.50	1.00	75.00	75.00	5.13	100.015
			1463.30		

MEDIAN DROP DIAMETER = 2.50 mm

* Data obtained from Gunn and Kinzer (1949) (Appendices 6 and 7)

Appendix 2a

RAINFALL INTENSITY AND UNIFORMITY (79.90 mm h^{-1})

Nozzle : $1\frac{1}{2}$ H 30
Disc slot angle : 1 x 20^{o}
Angular velocity : 44 rpm
Pressure : 7 psi
Intensity : 79.90 mm/hr

RUN			
1	2	3	4
73.10	74.10	73.10	74.10
90.50	82.80	83.70	91.80
80.80	84.70	78.90	79.90
73.10	72.20	75.10	74.10
81.20	84.10	81.20	83.10
88.50	80.80	77.00	78.90

$\bar{x}$ = 79.90 mm/hr

Cu = 94.48%

Appendix 2b

DROP SIZE DISTRIBUTION (79.90 mm/hr)

Number of drops in each size group

DROP DIAMETER mm	RUN 1	2	3	4	Average
0 - 0.50	0	0	0	0	0
0.51 - 1.00	262	236	236	233	241.75
1.01 - 1.50	169	189	204	154	179.00
1.51 - 2.00	104	96	95	90	96.25
2.01 - 2.50	62	55	52	51	55.00
2.51 - 3.00	25	27	25	17	23.50
3.01 - 3.50	16	7	14	11	12.00
3.51 - 4.00	7	8	9	6	7.50
4.01 - 4.50	2	4	3	4	3.25
4.51 - 5.00	3	0	7	4	3.50
5.01 - 5.50	3	2	1	4	2.50

Appendix 2c

CUMULATIVE DISTRIBUTION OF DROP SIZE : % BY VOLUME (79.90 mm h^{-1})

DROP DIAMETER mm	AV. NO. OF DROPS	DROP VOLUME ml	VOLUME OF WATER IN EACH CLASS ml	% TOTAL VOLUME	CUMULATIVE %
0 - 0.50	0.000	.025	0.000	0.000	0.000
0.51 - 1.00	241.750	.220	53.185	2.554	2.554
1.01 - 1.50	179.00	1.200	214.800	10.316	12.870
1.51 - 2.00	96.250	3.000	288.750	13.867	26.737
2.01 - 2.50	55.000	6.000	330.000	15.848	42.585
2.51 - 3.00	23.500	11.000	258.500	12.415	55.00
3.01 - 3.50	12.000	18.000	216.000	10.373	65.373
3.51 - 4.00	7.500	28.000	210.000	10.085	75.458
4.01 - 4.50	3.250	40.000	130.000	6.243	81.701
4.51 - 5.00	3.500	55.500	194.250	9.329	91.030
5.01 - 5.5	2.500	75.000	187.500	9.005	100.035
			2082.235		

MEDIAN DROP DIAMETER = 2.55 mm

Appendix 2d

KINETIC ENERGY PER UNIT OF RAIN (79.90 mm/hr)

DROP DIAMETER mm	AV. NO OF DROPS	DROP MASS gm	MASS OF WATER IN EACH CLASS (M) kg	VELOCITY V $m\ s^{-1}$	V^2 $m^2\ s^{-2}$	MV^2 $kg\ m^2\ s^{-2}$	$\frac{1}{2}MV^2$ J
0 - 0.50	.000	.025	0.000	1.480	2.190	0.000	.000
0.51 - 1.00	241.750	.220	0.053	3.000	9.000	0.477	.239
1.01 - 1.50	179.000	1.200	0.215	4.750	22.563	4.851	2.426
1.51 - 2.00	96.250	3.000	0.289	5.950	35.403	10.231	5.116
2.01 - 2.50	55.000	6.000	0.330	7.000	49.000	16.170	8.085
2.51 - 3.00	23.500	11.000	0.259	7.800	60.840	15.758	7.879
3.01 - 3.50	12.000	18.000	0.216	8.300	68.890	14.880	7.440
3.51 - 4.00	7.500	28.000	0.210	8.700	75.690	15.895	7.948
4.01 - 4.50	3.250	40.000	0.130	8.950	80.103	10.413	5.207
4.51 - 5.00	3.500	55.500	0.194	9.050	81.903	15.889	7.945
5.01 - 5.50	2.500	75.000	0.188	9.130	83.357	15.671	7.836
			2.084				60.121

KE/Unit mass of rain $= \frac{1}{2} MV^2/M$

$= 60.121/2.084$

$= 28.849$ J/kg

$= 28.849$ J/m^2/mm*

* 1 kg of H_2O = 1 litre = $\frac{1m^3}{1000} = \frac{1}{1000} \times m^2 \times m = \frac{1}{\cancel{1000}} \times m^2 \times \cancel{1000}\ mm = m^2\ mm$

Appendix 3a

RAINFALL INTENSITY AND UNIFORMITY (109.60 mm h^{-1})

Nozzle : $1\frac{1}{2}$ H 30
Disc slot angle : 3 x $(^{20}/_{3})^{o}$
Angular velocity : 44 rpm
Intensity : 109.60 mm/hr
Pressure : 7.5 psi

RUN

1	2	3	4
	mm h^{-1}		
111.60	111.60	111.60	111.60
119.30	119.30	119.30	115.50
109.70	111.60	115.50	109.70
102.00	103.90	103.90	103.90
100.10	100.10	100.10	100.10
100.10	96.20	100.10	100.10
130.90	130.90	132.80	130.90
111.60	107.80	107.80	107.80
107.80	107.80	96.20	96.20

$\bar{x}$ = 109.60 mm h^{-1}

Cu = 93.51%

Appendix 3b

DROP SIZE DISTRIBUTION (109.60 mm h^{-1})

Number of drops in each size group.

DROP DIAMETER	RUN				
mm	1	2	3	4	Average
0 - 0.50	0	0	0	0	0
0.51 - 1.00	247	239	237	242	241.25
1.01 - 1.50	187	192	204	195	194.50
1.51 - 2.00	95	80	69	92	84.00
2.01 - 2.50	40	39	46	25	37.50
2.51 - 3.00	10	21	28	16	18.75
3.01 - 3.50	11	11	14	6	10.50
3.51 - 4.00	6	9	15	4	8.75
4.01 - 4.50	2	5	7	3	4.25
4.51 - 5.00	4	6	4	1	3.75
5.01 - 5.50	4	2	1	6	3.25

Appendix 3c

CUMULATIVE DISTRIBUTION OF DROP SIZE : % BY VOLUME (109.60 mm h^{-1})

DROP DIAMETER mm	AV. NO OF DROPS	DROP VOLUME ml	VOLUME OF WATER IN EACH CLASS ml	% TOTAL VOLUME %	CUMULATIVE % %
0 - 0.50	0	.025	0	0	0
0.51 - 1.00	241.25	.220	53.08	2.62	2.62
1.01 - 1.50	194.50	1.20	233.40	11.52	14.14
1.51 - 2.00	84.00	3.00	252.00	12.44	26.58
2.01 - 2.50	37.50	6.00	225.00	11.11	37.69
2.51 - 3.00	18.75	11.00	206.25	10.18	47.87
3.01 - 3.50	10.50	18.00	189.00	9.33	57.20
3.51 - 4.00	8.75	28.00	245.00	12.10	69.30
4.01 - 4.50	4.25	40.00	170.00	8.39	77.69
4.51 - 5.00	3.75	55.50	208.13	10.28	87.97
5.01 - 5.50	3.25	75.00	243.75	12.03	100.00
			2025.61		

MEDIAN DROP DIAMETER = 2.90 mm

Appendix 3d

KINETIC ENERGY PER UNIT OF RAIN (109.60 mm h^{-1})

DROP DIAMETER mm	AV. NO OF DROPS	DROP MASS gm	MASS OF WATER IN EACH CLASS (M) kg	VELOCITY V $m\ s^{-1}$	V^2 $m^2\ s^{-2}$	MV^2 $kg\ m^2\ s^{-2}$	$\frac{1}{2}MV^2$ J
1	2	3	4	5	6	7	8
0 - 0.50	0.000	0.025	0.000	1.480	2.190	.000	.000
0.51 - 1.00	241.250	0.222	0.053	3.000	9.000	.477	.239
1.01 - 1.50	194.500	1.200	0.233	4.750	22.563	5.257	2.629
1.51 - 2.00	84.000	3.000	0.252	5.950	35.403	8.922	4.461
2.01 - 2.50	37.500	6.000	0.225	7.000	49.000	11.025	5.513
2.51 - 3.00	18.750	11.000	0.206	7.800	60.840	12.533	6.267
3.01 - 3.50	10.500	18.000	0.189	8.300	68.890	13.020	6.510
3.51 - 4.00	8.750	28.000	0.245	8.700	75.690	18.544	9.272
4.01 - 4.50	4.250	40.000	0.170	8.950	80.103	13.618	6.809
4.51 - 5.00	3.750	55.500	0.208	9.050	81.903	17.036	8.518
5.01 - 5.50	3.250	75.000	0.244	9.130	83.357	20.389	10.170
			2.025				60.388

K.E. / unit mass of rain $= \frac{1}{2} MV^2/M$

$= 60.388/2.025$

$= 29.821$ J/kg

$= 29.821$ J/m^2/mm

Appendix 4a

RAINFALL INTENSITY AND UNIFORMITY (139.50 mm h^{-1})

Nozzle : $1\frac{1}{2}$ H 30
Disc slot angle : 3 x 10°
Angular velocity : 44 rpm
Pressure : 7 psi
Intensity : 139.50 mm h^{-1}

RUN		
1	2	3
134.70	150.10	150.10
177.10	159.80	158.80
154.00	154.00	155.00
121.30	125.10	125.10
139.60	139.60	137.60
142.40	142.40	144.40
132.80	130.90	131.90
131.90	132.80	132.80
136.70	134.70	133.80
123.20	125.10	126.10

$\bar{x}$ = 139.50 mm h^{-1}

Cu = 92.99%

Appendix 4b

DROP SIZE DISTRIBUTION (139.50 mm h^{-1})

Number of drops in each size group.

DROP DIAMETER mm	RUN 1	2	3	4	Average
0 - 0.50	0	0	0	0	0
0.51 - 1.00	268	225	157	224	218.50
1.01 - 1.50	227	188	174	205	198.50
1.51 - 2.00	97	95	90	94	94.00
2.01 - 2.50	54	46	38	33	42.75
2.51 - 3.00	38	15	18	30	22.75
3.01 - 3.50	19	9	9	14	12.75
3.51 - 4.00	8	8	5	12	8.25
4.01 - 4.50	7	3	3	5	4.50
4.51 - 5.00	2	7	6	1	4.00
5.01 - 5.5	6	1	5	4	4.00

Appendix 4c

CUMULATIVE DISTRIBUTION OF DROP SIZE : % BY VOLUME (139.50 mm h^{-1})

DROP DIAMETER mm	AV. NO OF DROPS	DROP VOLUME ml	VOLUME OF WATER IN EACH CLASS ml	% TOTAL VOLUME %	CUMULATIVE % %
0 - 0.50	0.00	.025	0	0	0
0.51 - 1.00	218.50	.220	48.07	2.15	2.15
1.01 - 1.50	198.50	1.20	238.20	10.65	12.80
1.51 - 2.00	94.00	3.00	282.00	12.60	25.40
2.01 - 2.50	42.75	6.00	256.50	11.46	36.86
2.51 - 3.00	22.75	11.00	250.25	11.18	48.04
3.01 - 3.50	12.75	18.00	229.50	10.26	58.30
3.51 - 4.00	8.25	28.00	231.00	10.32	68.62
4.01 - 4.50	4.50	40.00	180.00	8.04	76.66
4.51 - 5.00	4.00	55.50	222.00	9.92	86.58
5.01 - 5.50	4.00	75.00	300.00	13.41	99.99
			2237.52		

MEDIAN DROP DIAMETER = 2.85 mm.

Appendix 4d

KINETIC ENERGY PER UNIT OF RAIN : (139.50 mm h^{-1})

DROP DIAMETER mm	AV. NO OF DROPS	DROP MASS gm	MASS OF WATER IN EACH CLASS (M) kg	VELOCITY V $m\ s^{-1}$	V^2 $m^2\ s^{-2}$	MV^2 $kg\ m^2\ s^{-2}$	$\frac{1}{2}MV^2$ J
1	2	3	4	5	6	7	8
0 - 0.50	.000	0.025	0.000	1.480	2.190	.000	.000
0.51 - 1.00	218.500	0.220	0.048	3.000	9.000	.432	.216
1.01 - 1.50	198.500	1.200	0.238	4.750	22.563	5.370	2.685
1.51 - 2.00	94.000	3.000	0.282	5.950	35.403	9.984	4.992
2.01 - 2.50	42.750	6.000	0.257	7.000	49.000	12.593	6.297
2.51 - 3.00	22.750	11.000	0.250	7.800	60.840	15.210	7.605
3.01 - 3.50	12.750	18.000	0.230	8.300	68.890	15.845	7.923
3.51 - 4.00	8.250	28.000	0.231	8.700	75.690	17.484	8.742
4.01 - 4.50	4.500	40.000	0.180	8.950	80.103	14.419	7.210
4.51 - 5.00	4.000	55.500	0.222	9.050	81.903	18.182	9.091
5.01 - 5.50	4.00	75.000	0.300	9.130	83.357	25.007	12.504
			2.238				67.265

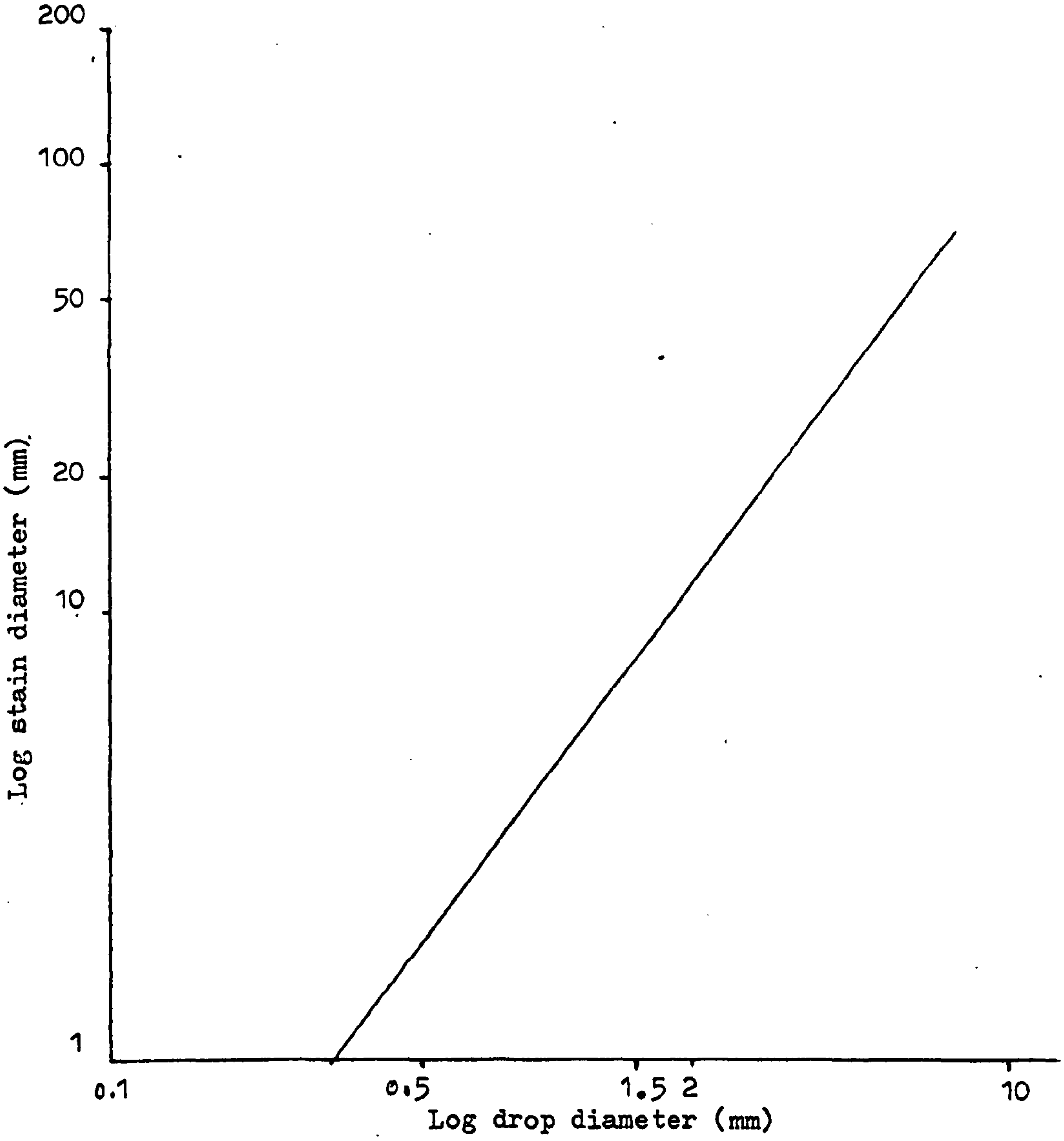
K.E / Unit mass of rain = $\frac{1}{2}$ MV^2/M

= 67.265/2.238

= 30.056 J/kg

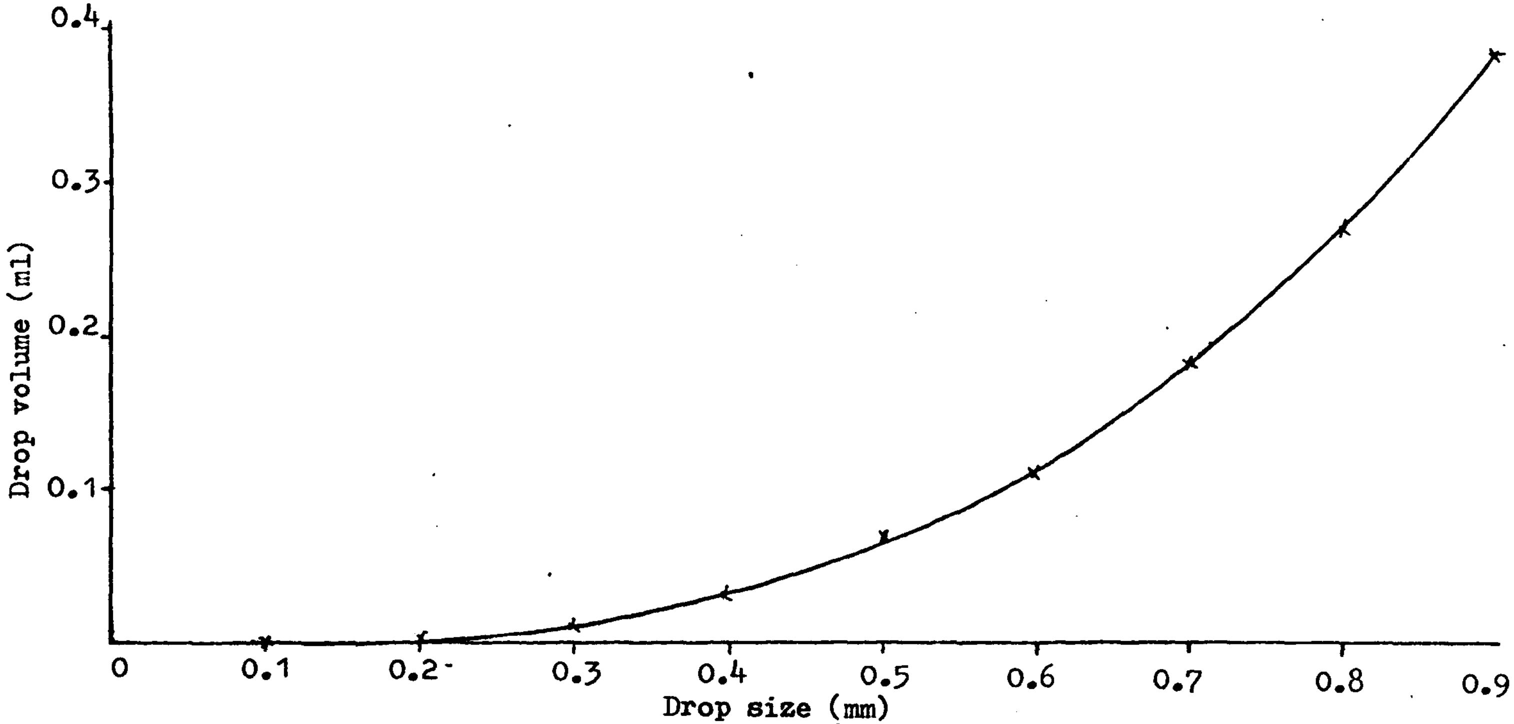
= 30.056 J/m^2/mm.

APPENDIX 5



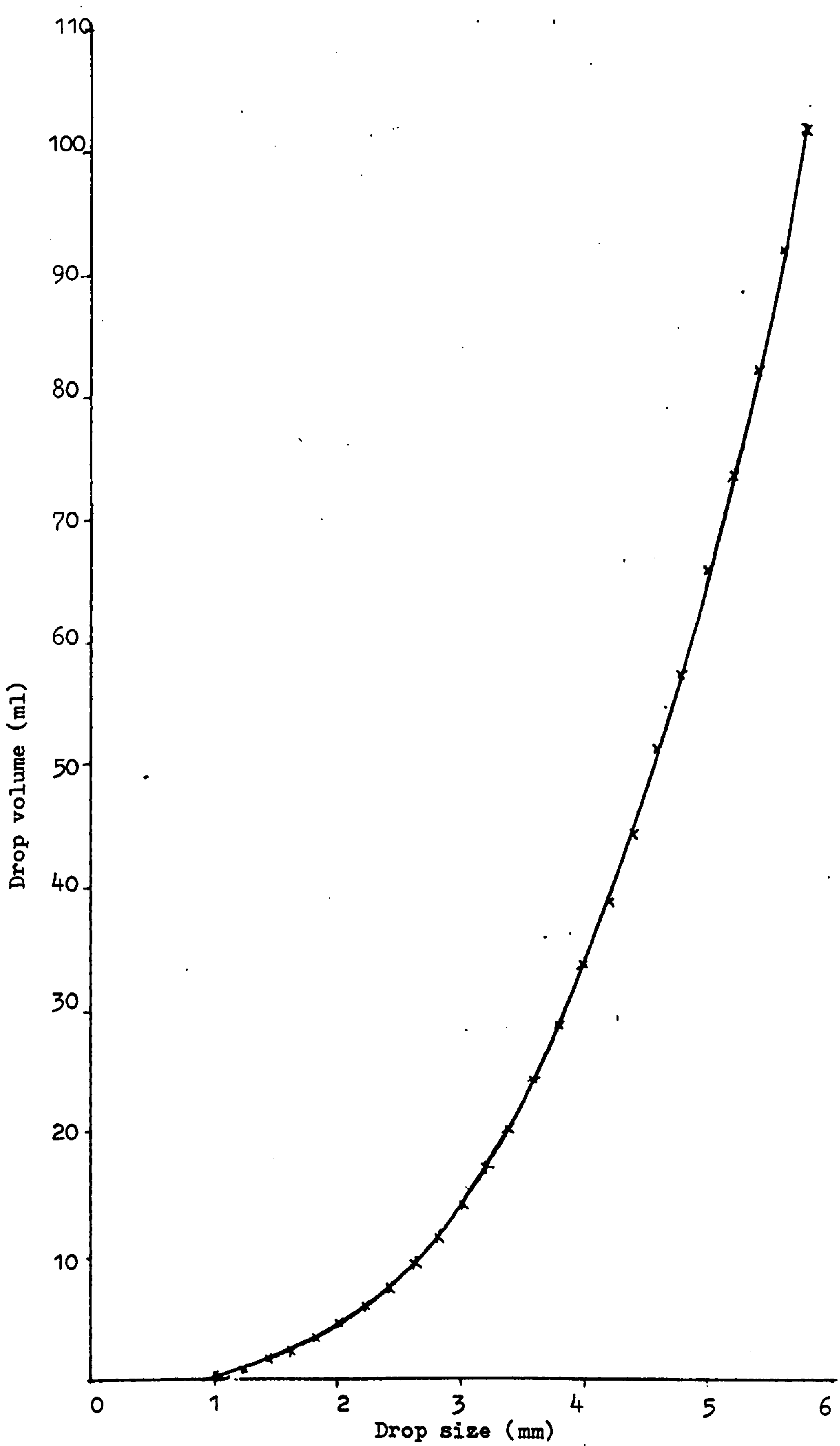
Calibration plot of stain diameter against drop size diameter (After D'Souza, 1973)

APPENDIX 6



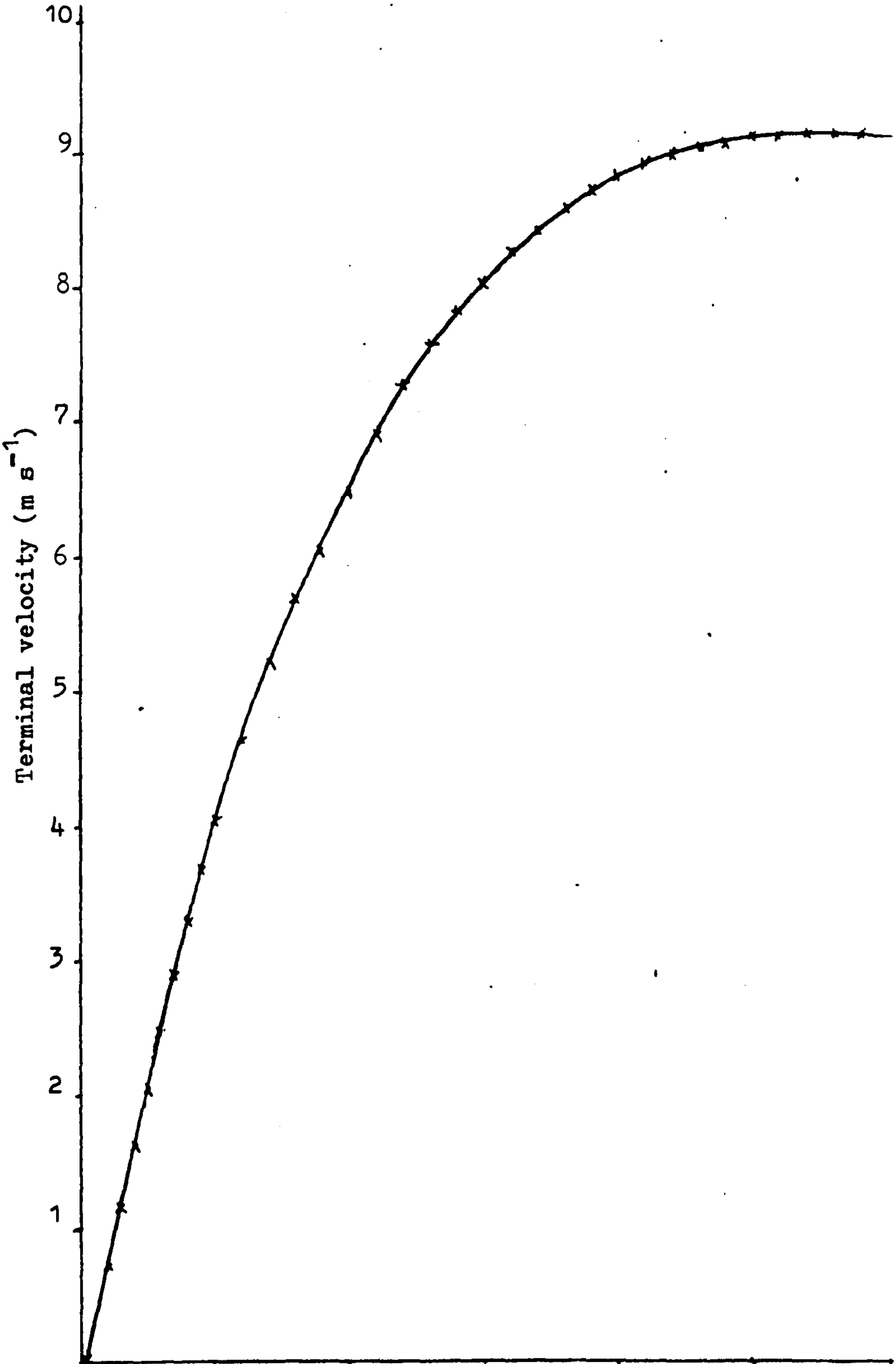
Volume of raindrops (After Gunn and Kinzer, 1949)

APPENDIX 7



Volume of raindrops (After Gunn and Kinzer, 1949)

APPENDIX 8



Terminal velocity of raindrops (After Gunn and Kinzer, 1949)

Appendix 9

MEAN SPLASH DETACHMENT kg m^{-2}

SOIL	INTENSITY	SLOPE (%)				
		0.0	3.5	7.0	10.5	14.0
	mm h^{-1}			kg m^{-2}		
Standard sand	48.30	0.166	0.170	0.178	0.183	0.203
	79.90	0.219	0.233	0.229	0.262	0.333
	109.60	0.330	0.370	0.381	0.428	0.492
	139.50	0.440	0.570	0.680	0.740	0.690
Sand	48.30	0.156	0.080	0.134	0.135	0.169
	79.90	0.166	0.184	0.180	0.205	0.243
	109.60	0.238	0.245	0.260	0.268	0.342
	139.50	0.286	0.270	0.330	0.420	0.490
Clay loam	48.30	0.064	0.042	0.050	0.080	0.102
	79.90	0.095	0.084	0.098	0.147	0.202
	109.60	0.139	0.147	0.149	0.245	0.298
	139.50	0.201	0.209	0.229	0.290	0.377
Clay	48.30	0.061	0.037	0.093	0.092	0.124
	79.90	0.066	0.136	0.181	0.184	0.194
	109.60	0.178	0.171	0.204	0.290	0.322
	139.50	0.280	0.280	0.378	0.432	0.522

Appendix 10

MEAN SPLASH TRANSPORT kg m^{-2}

SOIL	INTENSITY $mm\ h^{-1}$	SLOPE (%) 3.5	7.0	10.5	14.0
		kg m^{-2}			
Standard sand	48.30	0.049	0.071	0.092	0.137
	79.90	0.080	0.108	0.129	0.222
	109.60	0.102	0.112	0.168	0.318
	139.50	0.139	0.212	0.393	0.430
Sand	48.30	0.023	0.051	0.064	0.108
	79.90	0.065	0.087	0.112	0.158
	109.60	0.069	0.092	0.128	0.182
	139.50	0.043	0.095	0.177	0.218
Clay loam	48.30	0.018	0.029	0.053	0.080
	79.90	0.039	0.079	0.128	0.163
	109.60	0.031	0.045	0.128	0.182
	139.50	0.045	0.073	0.121	0.208
Clay	48.30	0.014	0.043	0.051	0.099
	109.60	0.024	0.087	0.172	0.210
	139.50	0.050	0.178	0.265	0.348

Appendix 11

DETACHMENT BY OVERLAND FLOW WITH AND WITHOUT RAIN : FLOW VELOCITY (V : mm s^{-1})

Soil plate (roughened)	Discharge l/min	Velocity (with rain) % Slope 3.5	7.0	10.5	14.0	Velocity (no rain) % Slope 3.5	7.0	10.5	14.0
Standard sand	1.0	37.40	41.10	48.00	62.00	39.20	43.00	49.00	65.40
	1.6	55.00	64.00	72.00	87.00	57.00	64.00	70.60	92.10
	2.2	66.00	73.40	84.00	113.00	74.30	80.20	85.00	127.00
	2.8	70.00	81.10	92.00	143.00	81.00	88.00	93.50	135.40
Sand	1.0	33.50	39.00	47.00	56.30	34.30	38.50	43.00	62.40
	1.6	49.50	54.30	63.00	75.00	51.60	58.20	64.70	81.50
	2.2	55.70	68.00	78.00	88.00	66.30	72.00	79.60	107.20
	2.8	62.50	72.00	85.00	105.30	70.30	78.10	92.50	107.20
Clay loam	1.0	24.00	38.70	45.00	76.30	34.00	40.00	46.80	73.00
	1.6	38.40	53.30	61.80	96.00	48.60	55.10	69.00	100.00
	2.2	52.30	65.00	80.00	114.20	64.00	76.10	85.30	127.00
	2.8	57.10	69.00	89.10	133.90	69.00	81.60	96.00	137.40
Clay	1.0	21.10	34.00	42.70	60.00	30.00	37.00	42.90	65.00
	1.6	34.30	49.00	58.70	94.20	44.50	55.80	65.00	96.00
	2.2	45.00	56.70	76.70	109.70	54.00	70.50	82.00	125.00
	2.8	51.60	64.00	85.40	126.20	62.30	81.30	94.00	138.40

Appendix 12

DETACHMENT BY OVERLAND FLOW WITH AND WITHOUT RAIN : FLOW DEPTH (D : mm)

Soil plate (roughened)	Discharge l/min	Depth (with rain) % slope				Depth (no rain) % slope			
		3.5	7.0	10.5	14.0	3.5	7.0	10.5	14.0
Standard sand	1.0	0.80	0.73	0.65	0.50	0.78	0.70	0.63	0.45
	1.6	0.85	0.75	0.75	0.54	0.84	0.77	0.70	0.50
	2.2	1.10	0.94	0.81	0.60	0.91	0.82	0.80	0.53
	2.8	1.20	1.10	0.90	0.63	1.00	0.94	0.86	0.60
Sand	1.0	0.90	0.85	0.72	0.55	0.87	0.80	0.70	0.50
	1.6	0.95	0.85	0.80	0.62	0.93	0.84	0.73	0.55
	2.2	1.20	1.00	0.90	0.75	1.04	0.95	0.86	0.64
	2.8	1.30	1.15	0.98	0.80	1.14	1.02	0.96	0.68
Clay loam	1.0	1.20	0.80	0.70	0.40	0.92	0.80	0.63	0.40
	1.6	1.25	0.92	0.80	0.50	0.98	0.86	0.70	0.48
	2.2	1.30	1.00	0.85	0.60	1.07	0.90	0.80	0.53
	2.8	1.40	1.20	0.90	0.62	1.20	1.00	0.84	0.60
Clay	1.0	1.30	0.90	0.72	0.50	1.00	0.85	0.75	0.47
	1.6	1.40	1.00	0.80	0.52	1.10	0.88	0.76	0.50
	2.2	1.50	1.20	0.90	0.62	1.24	0.95	0.83	0.60
	2.8	1.55	1.25	0.96	0.65	1.30	1.00	0.90	0.64

Appendix 13a

DETACHMENT BY OVERLAND FLOW WITH AND WITHOUT RAIN : Reynolds number (Re)

Soil plate (roughened)	Discharge l/min	Re (with rain) % Slope 3.5	7.0	10.5	14.0	Re (no rain) % Slope 3.5	7.0	10.5	14.0
Standard sand	1.0	23.52	23.59	23.85	25.06	24.04	23.66	23.60	23.79
	1.6	36.75	37.74	41.28	37.98	37.64	38.74	37.78	37.23
	2.2	57.08	54.24	52.02	54.81	53.15	51.70	51.99	55.44
	2.8	66.04	70.13	63.30	72.83	63.68	65.03	61.48	65.68
Sand	1.0	23.70	26.80	26.60	24.34	23.46	24.90	23.66	24.53
	1.6	36.97	37.31	39.62	36.56	37.73	39.52	37.13	35.24
	2.2	52.55	54.97	55.19	51.89	54.21	55.30	53.82	53.94
	2.8	63.88	66.94	65.49	66.23	63.56	64.40	66.92	57.31
Clay loam	1.0	22.64	25.03	24.76	23.99	24.59	25.87	23.18	22.96
	1.6	37.74	39.64	38.87	37.74	37.44	38.31	37.97	37.74
	2.2	53.45	52.55	53.46	53.87	53.84	55.37	53.65	52.92
	2.8	62.85	66.94	63.04	65.27	65.09	65.97	63.40	64.81
Clay	1.0	24.18	24.74	23.50	24.92	24.92	25.42	22.96	25.37
	1.6	39.88	39.61	35.90	40.68	40.66	39.70	37.77	39.87
	2.2	56.06	55.00	52.78	56.49	55.61	54.14	52.03	62.29
	2.8	66.43	64.67	62.68	68.13	67.27	65.72	64.68	73.57

Appendix 13b

TEMPERATURE AND KINEMATIC VISCOSITIES USED IN THE EXPERIMENT

Temperature ^{o}C	Kinematic viscosity $\times 10^{-5}\ m^2\ s^{-1}$
10	0.1308
11	0.1272
12	0.1237
13	0.1204

Appendix 14

DETACHMENT BY OVERLAND FLOW WITH AND WITHOUT RAIN : FROUDE NUMBER (F)

Soil plate (roughened)	Discharge l/min	F (with rain) % Slope 3.5	7.0	10.5	14.0	F (no rain) % Slope 3.5	7.0	10.5	14.0
Standard sand	1.0	0.42	0.49	0.60	0.89	0.45	0.52	0.62	0.98
	1.6	0.60	0.75	0.84	1.20	0.63	0.74	0.85	1.32
	2.2	0.64	0.76	0.94	1.47	0.79	0.89	0.96	1.74
	2.8	0.65	0.78	0.98	1.82	0.82	0.92	1.02	1.76
Sand	1.0	0.36	0.43	0.56	0.77	0.37	0.43	0.52	0.89
	1.6	0.51	0.59	0.71	0.96	0.54	0.64	0.76	1.11
	2.2	0.51	0.69	0.83	1.03	0.66	0.75	0.87	1.35
	2.8	0.55	0.68	0.87	1.19	0.66	0.78	0.97	1.31
Clay loam	1.0	0.22	0.44	0.54	1.22	0.36	0.45	0.60	1.17
	1.6	0.35	0.56	0.70	1.37	0.50	0.60	0.83	1.46
	2.2	0.46	0.66	0.88	1.49	0.62	0.81	0.96	1.76
	2.8	0.49	0.64	0.95	1.72	0.64	0.82	1.06	1.79
Clay	1.0	0.18	0.36	0.51	0.86	0.30	0.40	0.52	0.96
	1.6	0.29	0.49	0.66	1.32	0.40	0.60	0.75	1.37
	2.2	0.37	0.52	0.82	1.41	0.49	0.73	0.91	1.63
	2.8	0.42	0.58	0.88	1.58	0.55	0.82	1.00	1.75

Appendix 15

DETACHMENT BY OVERLAND FLOW WITH AND WITHOUT RAIN : FRICTION FACTOR (f)

Soil plate (roughened)	Discharge l/min	f (with rain) % slope 3.5	7.0	10.5	14.0	f (no rain) % slope 3.5	7.0	10.5	14.0
Standard sand	1.0	2.75	4.16	4.10	2.55	2.44	3.65	3.82	2.05
	1.6	1.35	1.76	2.10	1.40	1.24	1.81	2.04	1.15
	2.2	1.21	1.68	1.67	0.92	0.79	1.23	1.61	0.66
	2.8	1.18	1.61	1.55	0.60	0.73	1.17	1.43	0.64
Sand	1.0	3.85	5.39	4.74	3.40	3.55	5.20	5.51	2.51
	1.6	1.86	2.78	2.93	2.16	1.68	2.39	2.54	1.62
	2.2	1.86	2.08	2.15	1.90	1.14	1.77	1.97	1.09
	2.8	1.60	2.14	1.97	1.41	1.12	1.61	1.56	1.16
Clay loam	1.0	10.00	5.15	5.03	1.34	3.82	4.82	4.18	1.47
	1.6	4.07	3.12	3.05	1.06	1.99	2.73	2.13	0.94
	2.2	2.28	2.28	1.93	0.90	1.25	1.50	1.60	0.64
	2.8	2.06	2.43	1.65	0.68	1.21	1.45	1.33	0.62
Clay	1.0	14.88	7.50	5.74	2.72	5.33	5.98	5.53	2.18
	1.6	5.71	4.01	3.38	1.15	2.67	2.72	2.62	1.06
	2.2	3.56	3.60	2.23	1.01	2.04	1.84	1.80	0.75
	2.8	2.79	2.94	1.91	0.80	1.61	1.46	1.48	0.65

Appendix 16

DETACHMENT BY OVERLAND FLOW WITH AND WITHOUT RAIN : MANNINGS n

Soil plate (roughened)	Discharge l/min	n (with rain) % slope 3.5	7.0	10.5	14.0	n (no rain) % slope 3.5	7.0	10.5	14.0
Standard sand	1.0	0.10	0.14	0.15	0.10	0.09	0.13	0.14	0.08
	1.6	0.07	0.10	0.13	0.08	0.07	0.10	0.11	0.06
	2.2	0.09	0.12	0.12	0.07	0.06	0.09	0.12	0.05
	2.8	0.10	0.15	0.13	0.06	0.06	0.10	0.12	0.06
Sand	1.0	0.13	0.20	0.18	0.12	0.12	0.18	0.19	0.10
	1.6	0.10	0.14	0.16	0.11	0.09	0.13	0.13	0.09
	2.2	0.13	0.15	0.16	0.14	0.08	0.13	0.14	0.08
	2.8	0.13	0.18	0.17	0.13	0.09	0.13	0.14	0.09
Clay loam	1.0	0.30	0.18	0.18	0.05	0.13	0.17	0.14	0.06
	1.6	0.20	0.16	0.16	0.06	0.10	0.14	0.12	0.06
	2.2	0.16	0.15	0.14	0.07	0.09	0.11	0.12	0.05
	2.8	0.16	0.20	0.14	0.06	0.10	0.12	0.11	0.06
Clay	1.0	0.43	0.25	0.20	0.10	0.17	0.21	0.19	0.08
	1.6	0.27	0.21	0.17	0.07	0.14	0.15	0.14	0.06
	2.2	0.23	0.24	0.16	0.08	0.14	0.13	0.13	0.07
	2.8	0.21	0.23	0.16	0.07	0.13	0.12	0.13	0.07

Appendix 17

DETACHMENT BY OVERLAND FLOW WITH AND WITHOUT RAIN : Tractive Stress (τ_o : N m^{-2})

Soil plate (roughened)	Discharge	τ_o (with rain) % Slope 3.5	7.0	10.5	14.0	τ_o (no rain) % Slope 3.5	7.0	10.5	14.0
Standard sand	1.0	0.48	0.88	1.18	1.22	0.47	0.84	1.15	1.10
	1.6	0.51	0.90	1.36	1.32	0.50	0.93	1.27	1.22
	2.2	0.66	1.13	1.47	1.47	0.55	0.99	1.45	1.32
	2.8	0.72	1.33	1.64	1.54	0.60	1.13	1.56	1.47
Sand	1.0	0.54	1.02	1.31	1.35	0.52	0.96	1.27	1.22
	1.6	0.57	1.02	1.45	1.52	0.56	1.01	1.33	1.35
	2.2	0.72	1.20	1.64	1.83	0.62	1.14	1.56	1.57
	2.8	0.78	1.39	1.78	1.96	0.69	1.23	1.67	1.66
Clay loam	1.0	0.72	0.96	1.27	0.98	0.55	0.96	1.15	0.98
	1.6	0.75	1.11	1.45	1.22	0.59	1.04	1.27	1.17
	2.2	0.78	1.20	1.55	1.47	0.64	1.08	1.45	1.30
	2.8	0.84	1.45	1.64	1.52	0.72	1.20	1.53	1.47
Clay	1.0	0.82	1.08	1.31	1.22	0.60	1.02	1.27	1.15
	1.6	0.84	1.20	1.45	1.27	0.66	1.06	1.38	1.22
	2.2	0.90	1.45	1.64	1.52	0.74	1.14	1.51	1.47
	2.8	0.93	1.51	1.75	1.59	0.78	1.20	1.64	1.57

Appendix 18

DETACHMENT BY OVERLAND FLOW WITH AND WITHOUT RAIN : STREAM POWER PER UNIT BOUNDARY AREA (P_s : J m^{-2} s^{-1})

Soil Plate (roughened)	Discharge l/min	P_s (with rain) % Slope				P_s (no rain) % Slope			
		3.5	7.0	10.5	14.0	3.5	7.0	10.5	14.0
Standard sand	1.0	0.018	0.036	0.057	0.076	0.018	0.036	0.056	0.072
	1.6	0.028	0.058	0.098	0.115	0.029	0.059	0.090	0.113
	2.2	0.044	0.083	0.124	0.166	0.041	0.079	0.124	0.168
	2.8	0.050	0.107	0.151	0.220	0.049	0.100	0.146	0.199
Sand	1.0	0.018	0.040	0.062	0.076	0.018	0.037	0.055	0.076
	1.6	0.028	0.056	0.092	0.114	0.029	0.059	0.086	0.110
	2.2	0.040	0.082	0.128	0.161	0.041	0.082	0.124	0.168
	2.8	0.049	0.100	0.151	0.206	0.049	0.096	0.155	0.178
Clay loam	1.0	0.017	0.037	0.057	0.075	0.019	0.039	0.054	0.071
	1.6	0.029	0.059	0.090	0.117	0.029	0.057	0.088	0.117
	2.2	0.041	0.078	0.124	0.168	0.041	0.083	0.124	0.165
	2.8	0.048	0.100	0.146	0.203	0.040	0.098	0.147	0.202
Clay	1.0	0.017	0.037	0.056	0.073	0.018	0.038	0.055	0.075
	1.6	0.029	0.059	0.085	0.120	0.029	0.059	0.090	0.117
	2.2	0.041	0.082	0.126	0.166	0.040	0.081	0.124	0.183
	2.8	0.048	0.096	0.149	0.201	0.049	0.098	0.154	0.217

Appendix 19

DETACHMENT BY OVERLAND FLOW WITH AND WITHOUT RAIN : TOTAL KINETIC ENERGY OF FLOW (RE. J m^{-2})

Soil Plate (roughened)	Discharge l/min	RE (with rain) % slope				RE (no rain) % slope			
		3.5	7.0	10.5	14.0	3.5	7.0	10.5	14.0
Standard sand	1.0	21.60	43.20	68.40	91.20	21.60	43.20	67.20	86.40
	1.6	33.60	69.60	117.60	138.00	34.80	70.80	108.00	135.60
	2.2	52.80	99.60	148.80	199.20	49.20	94.80	148.80	201.60
	2.8	60.00	128.40	181.20	264.00	58.80	120.00	175.20	238.80
Sand	1.0	21.60	48.00	74.40	91.20	21.60	44.40	66.00	91.20
	1.6	33.60	67.20	110.40	136.80	34.80	70.80	103.20	132.00
	2.2	48.00	98.40	153.60	193.20	49.20	98.40	148.80	201.60
	2.8	58.80	120.00	181.20	247.20	58.80	115.20	186.00	213.60
Clay loam	1.0	20.40	44.40	68.40	90.00	22.80	46.80	64.80	85.20
	1.6	34.80	70.80	108.00	140.40	34.80	67.20	105.60	140.40
	2.2	49.20	93.60	148.80	201.60	49.20	99.60	148.80	198.00
	2.8	57.60	120.00	175.20	243.60	60.00	117.60	176.40	242.40
Clay	1.0	20.40	44.40	67.20	87.60	21.60	45.60	66.00	90.00
	1.6	34.80	70.80	102.00	144.00	34.80	70.80	108.00	140.40
	2.2	49.20	98.40	151.20	199.20	48.00	97.20	148.80	219.60
	2.8	57.60	115.20	178.80	241.20	58.80	117.60	184.80	260.40

Appendix 20

MEAN DETACHMENT BY OVERLAND FLOW WITHOUT RAINDROP IMPACT (Q_{rodet})

SOIL	DISCHARGE	PER CENT SLOPE			
		3.5	7.0	10.5	14.0
	l/min	kg m^{-2}			
	1.0	0.170	0.580	1.877	3.961
	1.6	0.233	0.894	2.535	4.548
Standard sand	2.2	0.610	1.363	4.078	5.731
	2.8	0.666	1.917	4.374	6.861
	1.0	0.178	0.254	0.722	1.298
	1.6	0.218	0.346	0.722	2.314
Sand	2.2	0.349	0.604	2.148	2.821
	2.8	0.543	0.905	2.480	3.763
	1.0	0.058	0.069	0.099	0.153
	1.6	0.089	0.130	0.188	0.241
Clay loam	2.2	0.108	0.385	0.641	1.083
	2.8	0.288	0.678	0.913	1.496
	1.0	0.022	0.052	0.070	0.115
	1.6	0.080	0.097	0.163	0.325
Clay	2.2	0.095	0.132	0.183	0.633
	2.8	0.246	0.380	0.449	0.848

Appendix 21

MEAN DETACHMENT BY OVERLAND FLOW PRODUCED BY RAINFALL (^{Q}rodet)

SOIL	DISCHARGE	PER CENT SLOPE			
		3.5	7.0	10.5	14.0
	l/min	kg m^{-2}			
	1.0	0.731	1.743	2.966	4.745
	1.6	1.738	3.446	4.353	7.075
Standard sand	2.2	2.677	4.381	6.904	8.787
	2.8	4.519	5.987	7.540	10.212
	1.0	0.762	1.112	1.688	2.480
	1.6	1.869	2.406	3.580	5.075
Sand	2.2	2.024	3.195	5.332	6.173
	2.8	2.750	3.987	5.771	7.585
	1.0	0.954	1.254	1.312	1.784
	1.6	1.737	2.057	2.462	3.386
Clay loam	2.2	2.231	2.537	2.980	3.764
	2.8	2.431	2.885	4.247	5.453
	1.0	0.657	0.853	0.996	1.160
	1.6	1.681	1.869	1.938	2.210
Clay	2.2	1.737	2.057	2.448	3.386
	2.8	1.941	2.362	3.201	4.836

Appendix 22

MEAN SEDIMENT YIELD BY OVERLAND FLOW WITH RAIN

SOIL	DISCHARGE	PER CENT SLOPE			
		3.5	7.0	10.5	14.0
	1/min*	kg m^{-1}			
Standard sand	1.0	0.0195	0.0397	0.2507	1.5098
	1.6	0.0501	0.0923	0.4177	3.1814
	2.2	0.0734	0.1471	2.7889	5.8792
	2.8	0.0920	0.6021	3.5505	6.3940
Sand	1.0	0.0372	0.0684	0.3828	1.5497
	1.6	0.0648	0.1527	0.9875	3.4742
	2.2	0.0947	0.3174	3.2872	6.4930
	2.8	0.1258	0.6808	3.8782	7.5317
Clay loam	1.0	0.0393	0.2354	0.3172	1.2518
	1.6	0.0599	0.3967	1.4050	1.8942
	2.2	0.0948	0.6484	2.1499	3.3326
	2.8	0.1272	0.8694	2.3639	3.4673
Clay	1.0	0.0380	0.1632	0.6935	1.4969
	1.6	0.0509	0.4208	1.3345	1.7214
	2.2	0.0906	0.5220	2.2001	3.1619
	2.8	0.1201	1.1921	2.5301	3.4651

* a base flow of 1.0 1/m was provided in all tests.

Appendix 23

MEAN SEDIMENT TRANSPORT CAPACITY (Tc ; kg m^{-1} min^{-1})

SOIL	DISCHARGE	PER CENT SLOPE			
		3.5	7.0	10.5	14.0
	l/min*	kg m^{-1} min^{-1}			
Standard sand	1.0		-	0.0180	0.0450
	1.6		-	0.0381	0.1026
	2.2		-	0.0858	0.1479
	2.8		-	0.1201	0.2095
Sand	1.0		-	0.0280	0.0643
	1.6		-	0.0434	0.1090
	2.2		-	0.1046	0.1804
	2.8		-	0.1431	0.2385
Clay loam	1.0		0.0109	0.0235	0.0365
	1.6		0.0211	0.0450	0.0632
	2.2		0.0281	0.0692	0.0877
	2.8		0.0485	0.0873	0.1055
Clay	1.0		0.0095	0.0223	0.0459
	1.6		0.0168	0.0355	0.0514
	2.2		0.0279	0.0699	0.1025
	2.8		0.0526	0.0946	0.1107

* a base flow of 1.0 l/min was provided in all tests

APPENDIX 24 - in folder

Extension frame

APPENDIX 25 - in folder

Slope formers

APPENDIX 26 - in folder

Soil plate for detachment tests

APPENDIX 27 - in folder

Soil plate for transport tests

APPENDIX 28 - in folder

Sedimert dispenser

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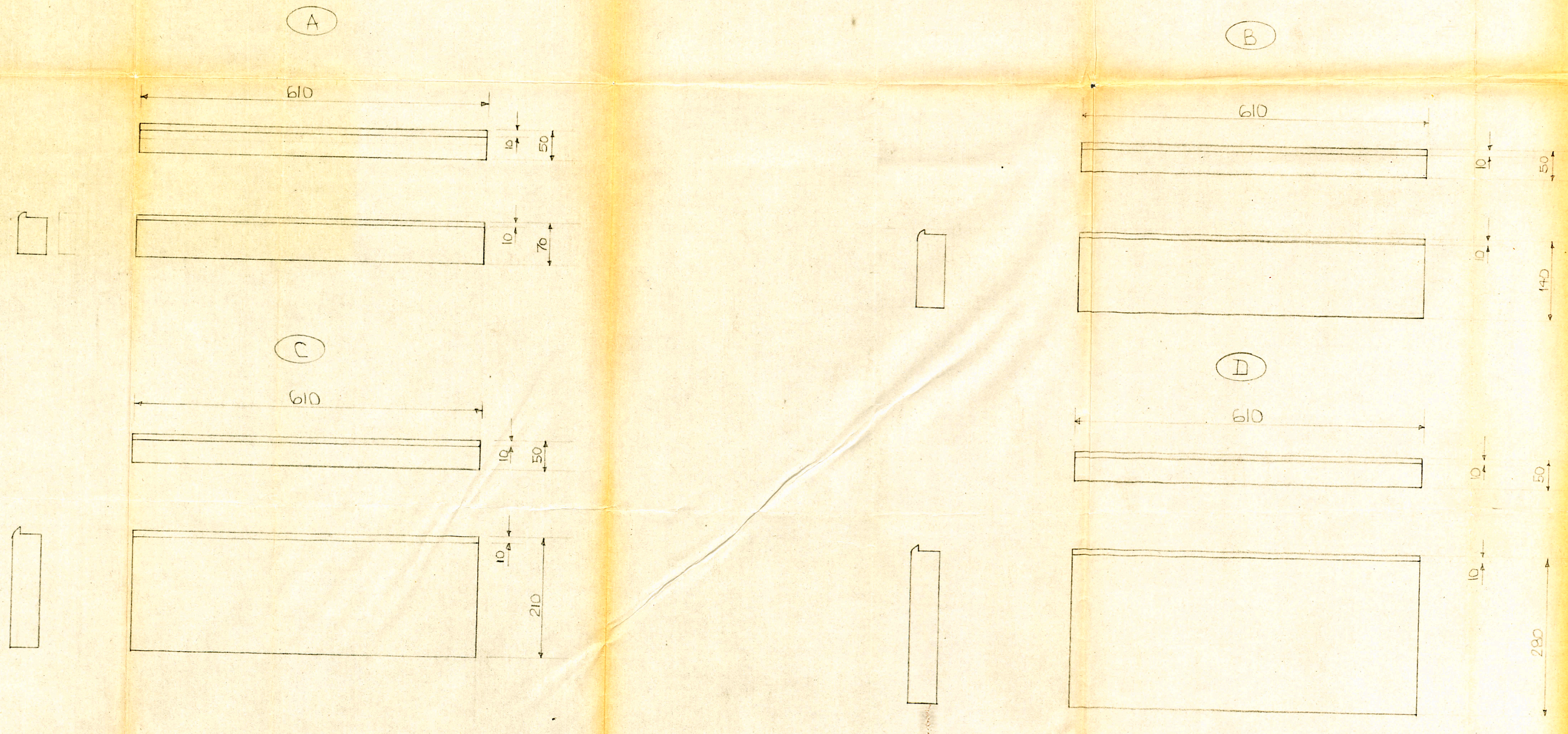


SPECIFICATIONS AND NOTES

PART	SIZE	QUANTITY
A	SEE ABOVE	1
B		1
C		1
D		1

NATIONAL COLLEGE OF AGRICULTURAL ENGINEERING
SILSOE BEDFORD

MATERIAL WATERPROOF PLYWOOD

TOLERANCE

~~FIRST~~ THIRD ANGLE PROJECTION

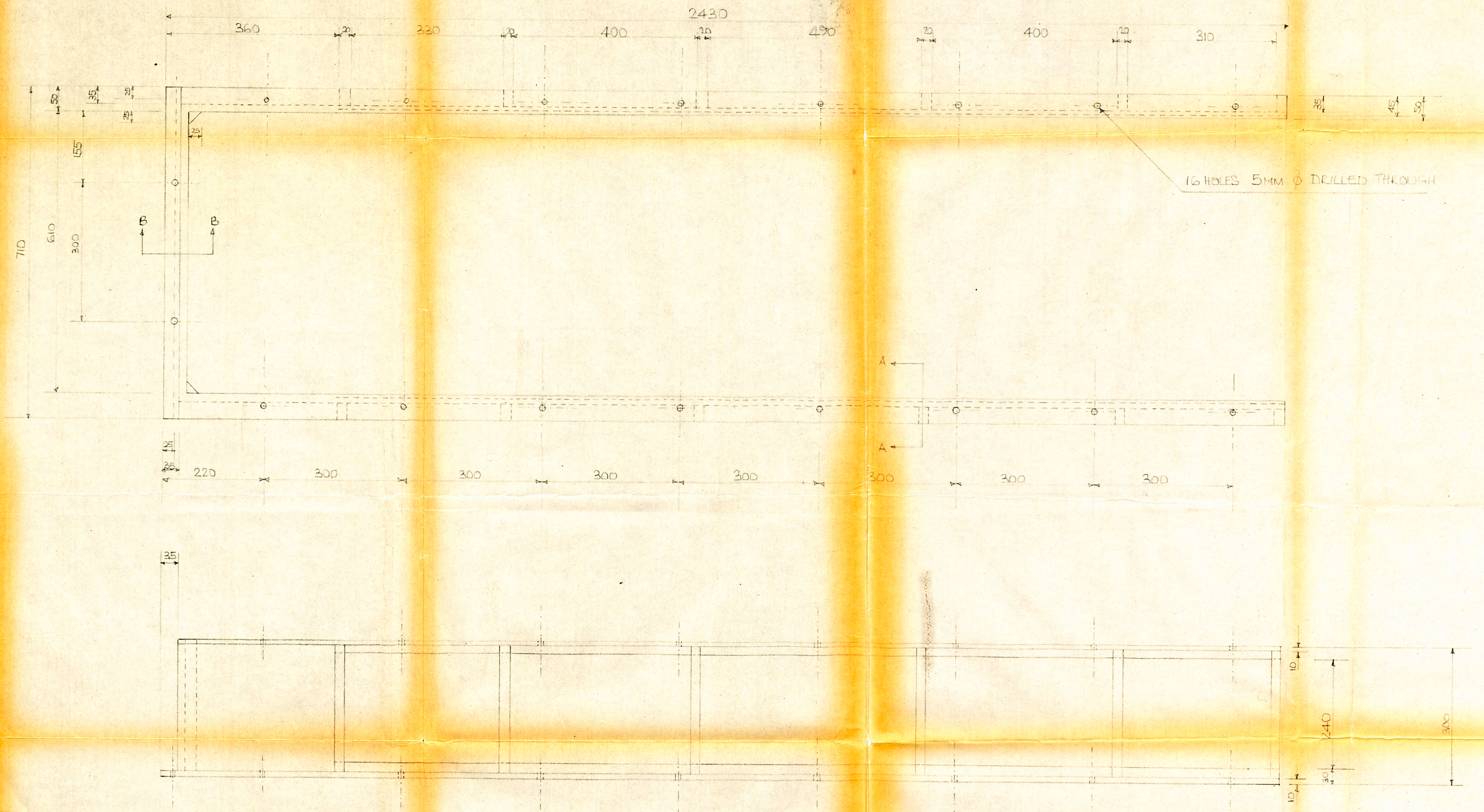
SCALE	DRAWN BY	CHECKED BY	APPROVED BY
1:5	C. QUANSAH	[signature]	[signature]

PROJECT NAME SEDIMENT TRANSPORT IN FLUMES

PART NAME FLUME HEIGHT EXTENSION

PART NUMBER C SHEET 1 OF 1

Appendix 25



NATIONAL COLLEGE OF AGRICULTURAL ENGINEERING

MATERIAL	PLYWOOD AND PERSPEX (5MM)
TOLERANCE	

~~FIRST~~ THIRD ANGLE PROJECTION

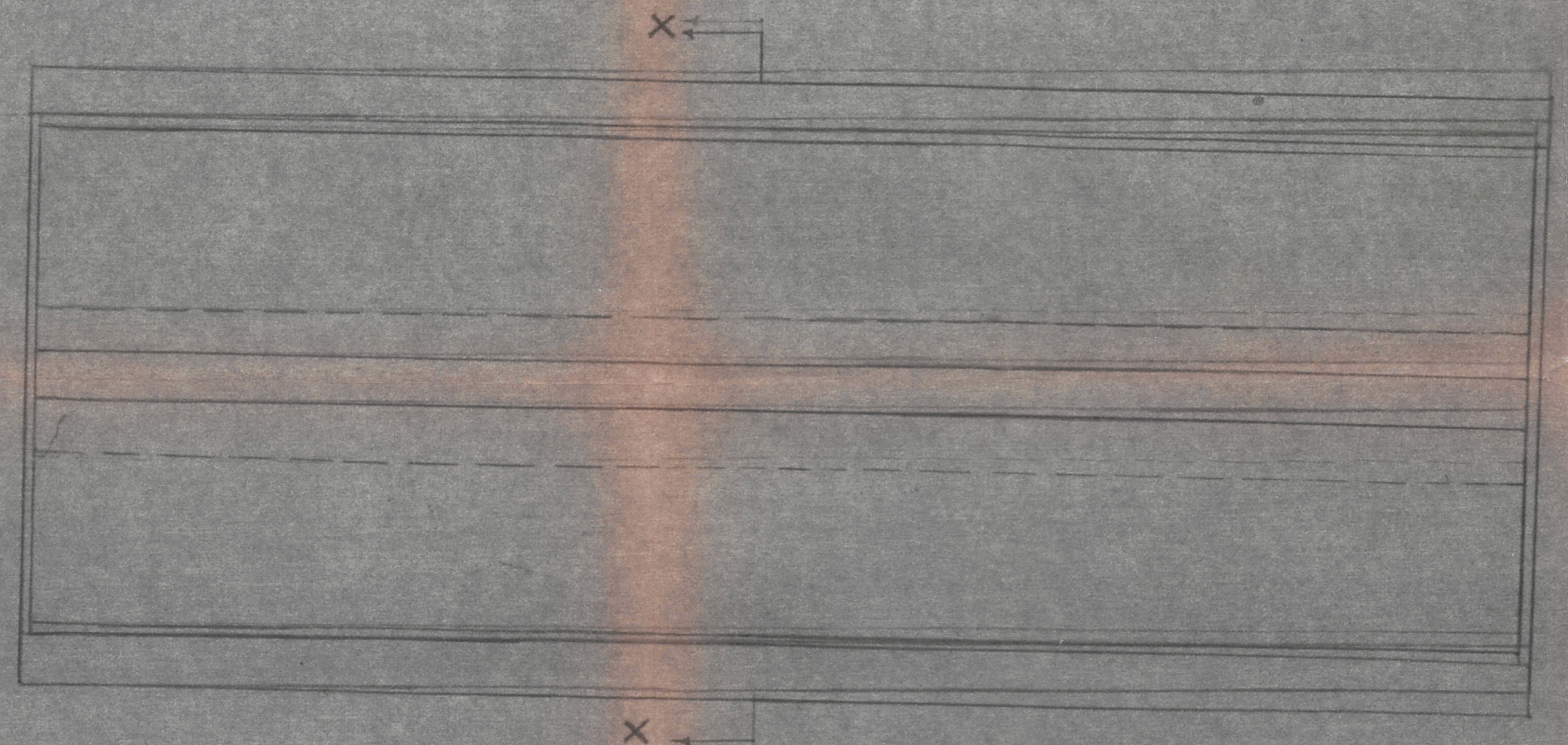
SCALE	DRAWN BY	CHECKED BY	APPROVED BY
1:5	C. QUANSAH	[signature]	[signature]

PROJECT NAME SEDIMENT TRANSPORT IN FLUMES

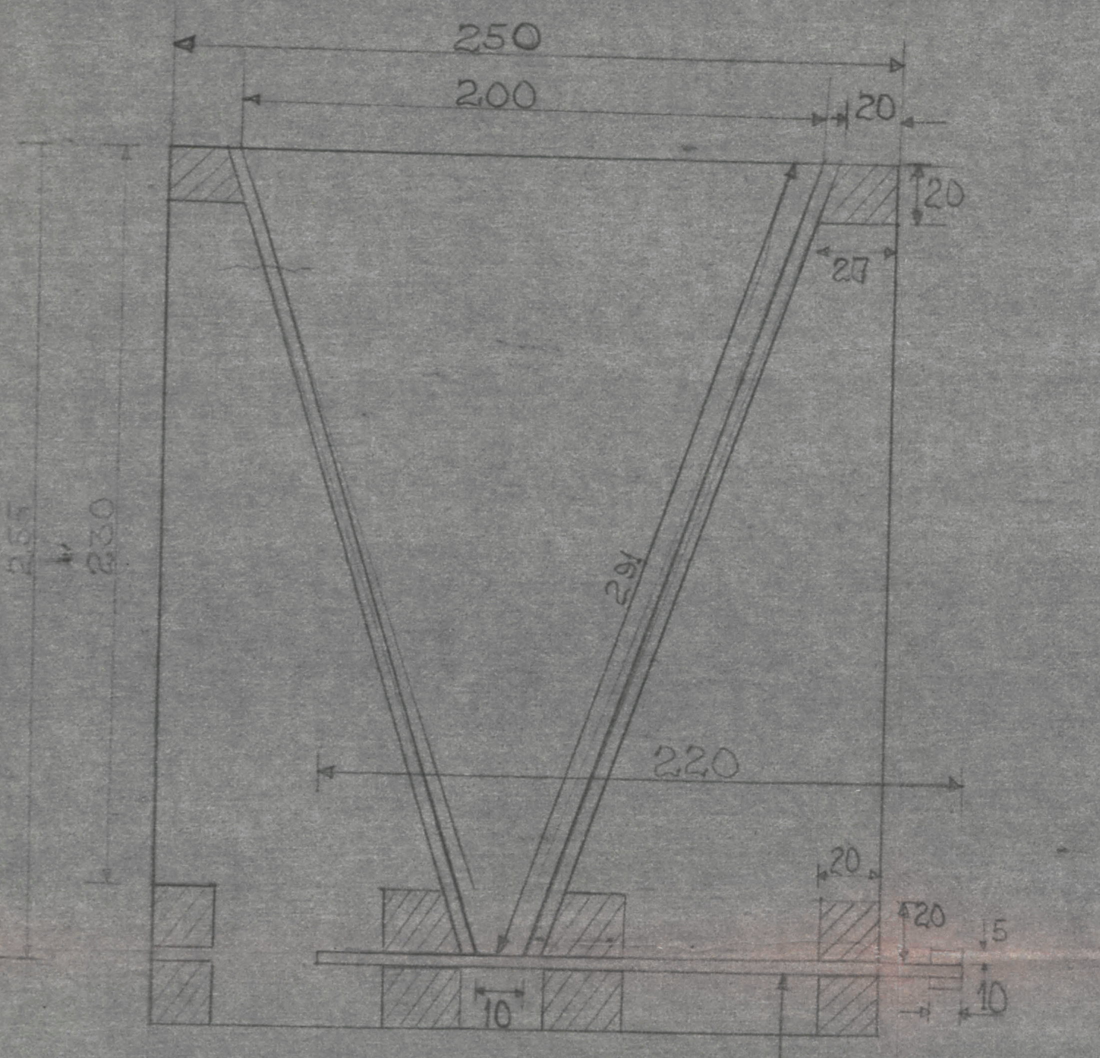
PART NAME FLUME HEIGHT EXTENSION

PART NUMBER SHEET 1 OF 2

Appendix 24a



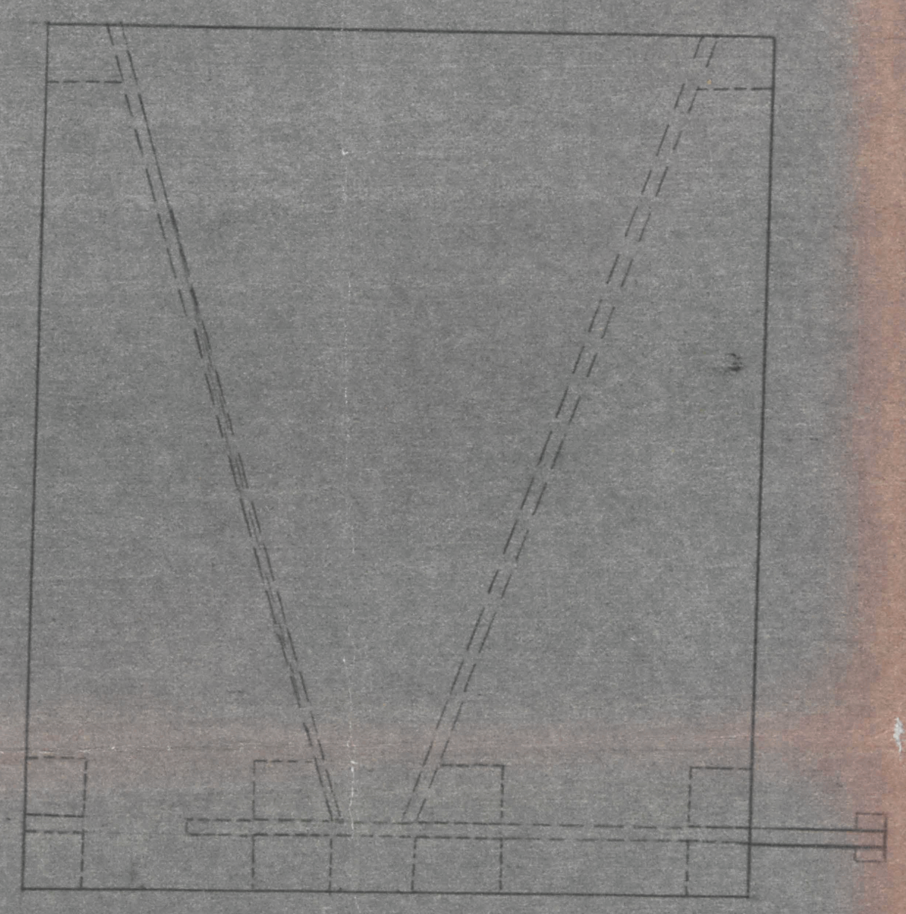
PLAN (GATE OUT OF POSITION)



SECTION X-X

FRONT ELEVATION

(GATE OUT OF POSITION)



END ELEVATION

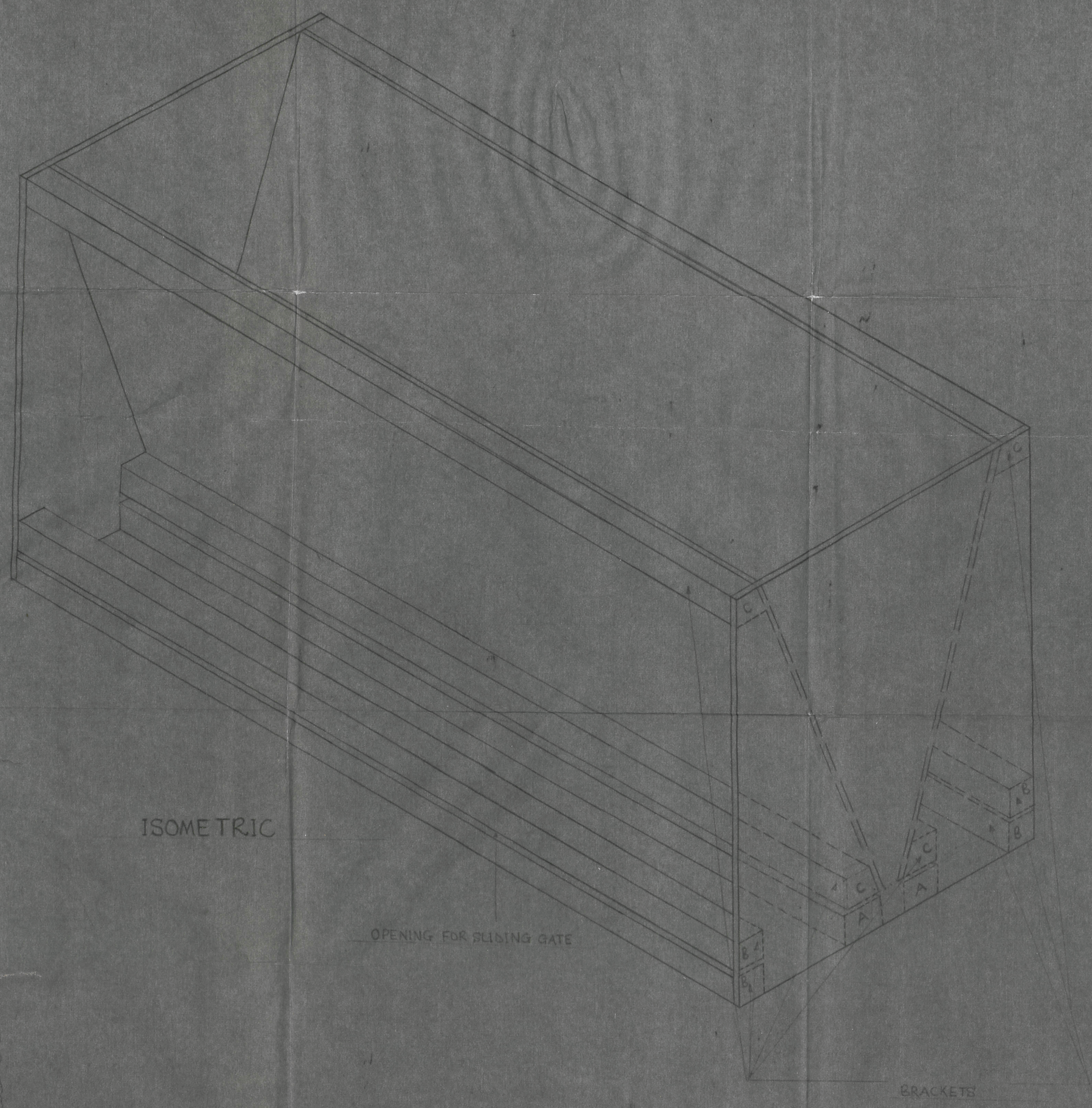
SPECIFICATIONS & NOTES

PART NO	SIZE	NO REQUIRED
1. FRONT & BACK	603×275×5	2
2. ENDS	250×300×5	2
3. SLIDING GATE	603×220×5	1
4 HANDLES (GATE)	603×10×5	2
5. BRACKETS (A)	603×27×20	2
6. BRACKETS (B)	603×20×20	4
7. BRACKETS (C)	603×27/20/20/21	4

8. SLIDING GATE TO JUST FIT OPENING
9. JOINTS TO BE NAILED TOGETHER

NATIONAL COLLEGE OF AGRICULTURAL ENGINEERING SILSOE BEDFORD			
MATERIAL	5MM WATERPROOF PLYWOOD		
TOLERANCE			
THIRD ANGLE PROJECTION			
SCALE	DRAWN BY	CHECKED BY	APPROVED BY
1:2	C. QUANSAH	[signature]	[signature] 25/4/79
PROJECT NAME	SEDIMENT FLOW IN FLUMES		
PART NAME	SEDIMENT HOPPER		
PART NUMBER		SHEET 1 OF 1	

APPENDIX 28b

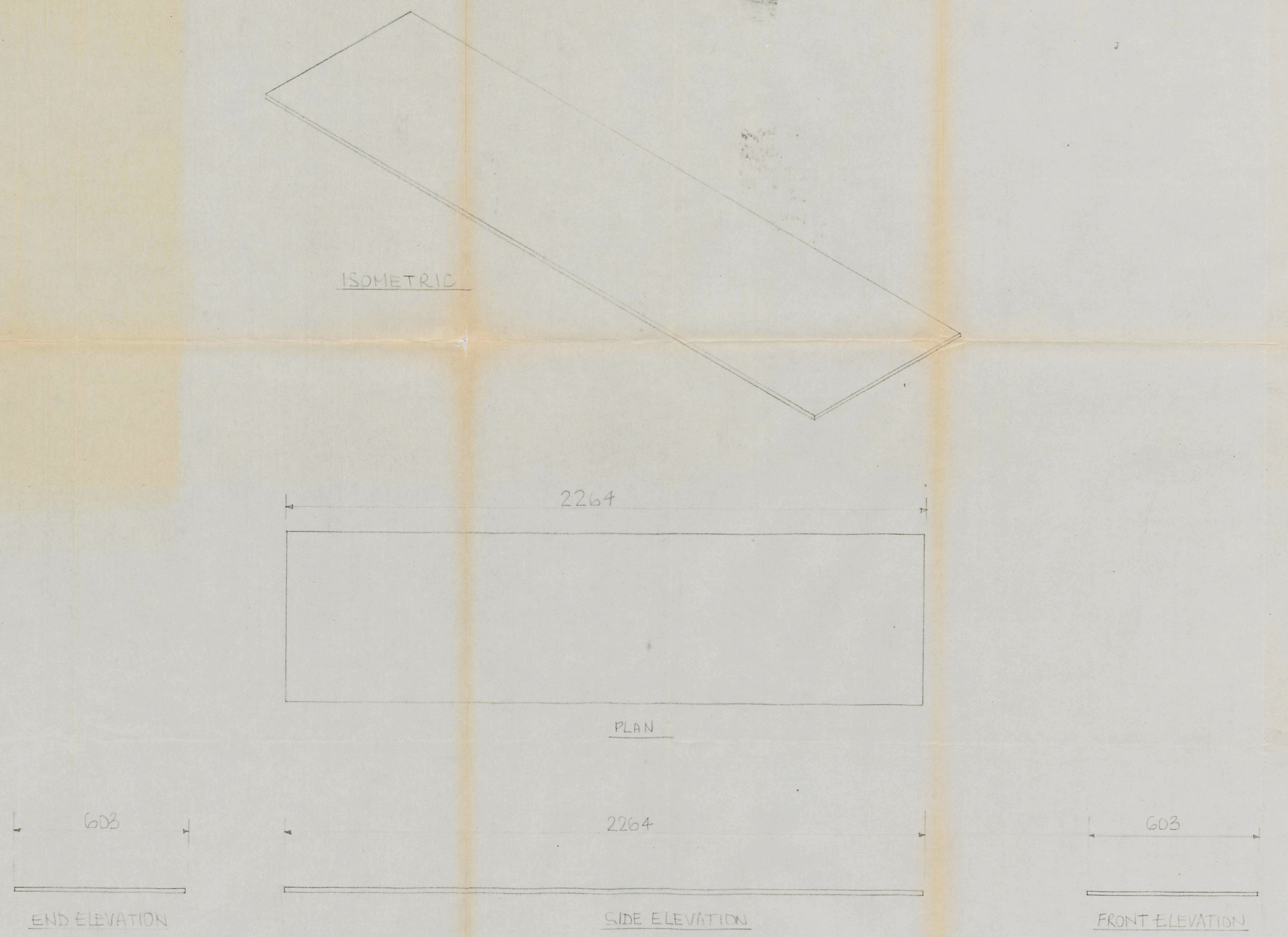


ISOMETRIC

NATIONAL COLLEGE OF AGRICULTURAL ENGINEERING
SILSOE BEDFORD

MATERIAL	5MM WATERPROOF PLYWOOD		
TOLERANCE			
~~FIRST~~ THIRD ANGLE PROJECTION			
SCALE	DRAWN BY	CHECKED BY	APPROVED BY
1:2	C. QUANSAH		25/4/79
PROJECT NAME	SEDIMENT FLOW IN FLUMES		
PART NAME	SEDIMENT HOPPER		
PART NUMBER		SHEET 1 OF 2	

APPENDIX 2.28a

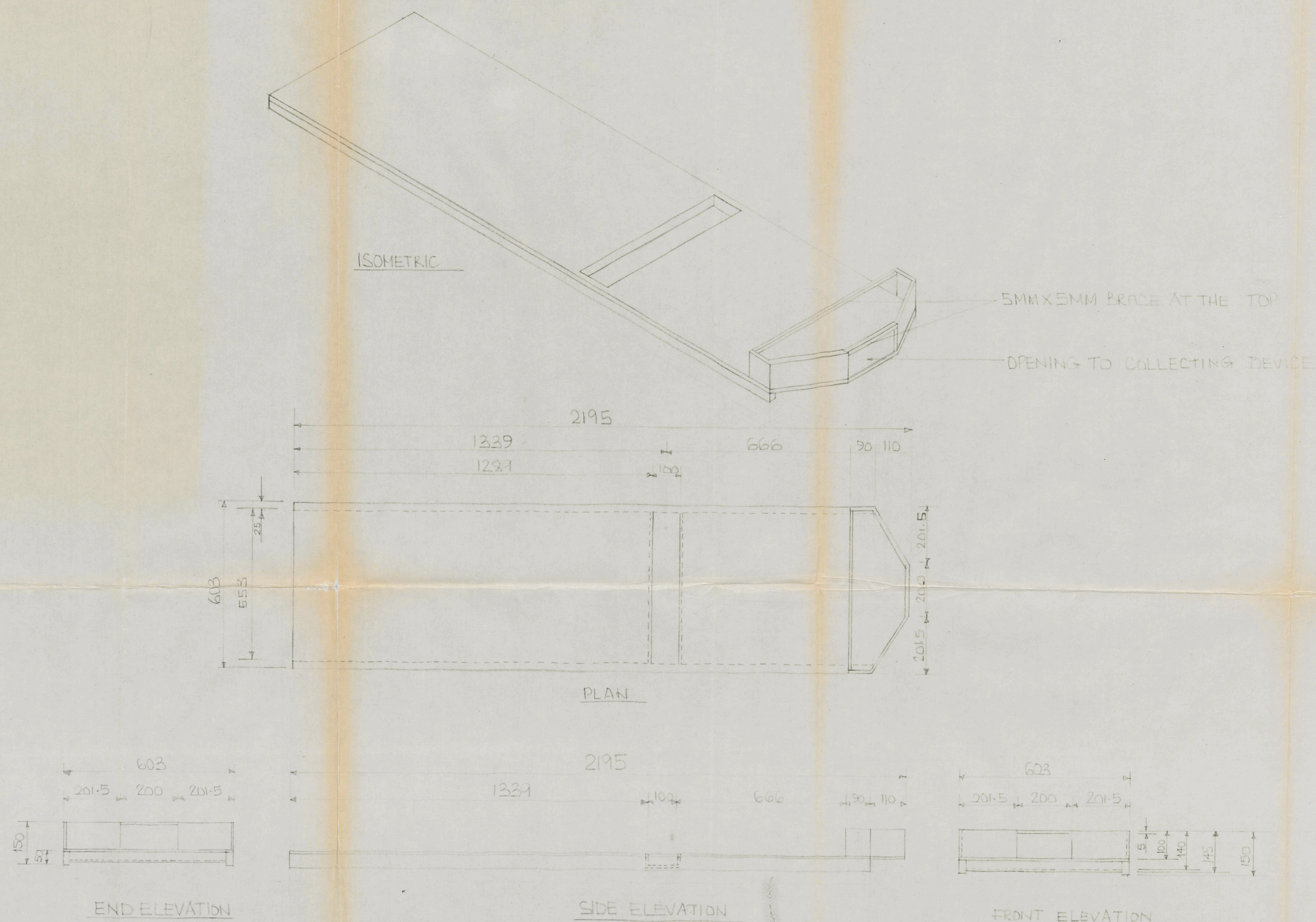


NOTES

1. 8'x 4' PLYWOOD (WATERPROOF) TO BE USED
2. WATERPROOF GLUE TO BE USED FOR ALL GLUING WORK
3. MOBILE BED TO FIT SEDIMENT TRANSPORT FLUME
4. 4 NO. MOBILE BEDS TO BE MADE

NATIONAL COLLEGE OF AGRICULTURAL ENGINEERING SILSOE BEDFORD			
MATERIAL	5MM PLYWOOD (WATERPROOF)		
TOLERANCE	+1MM		
~~FIRST~~ THIRD ANGLE PROJECTION			
SCALE	DRAWN BY	CHECKED BY	APPROVED BY
1:10	C. QUANSAH	[signature]	[signature]
PROJECT NAME	SEDIMENT TRANSPORT IN FLUMES		
PART NAME	MOBILE BED		
PART NUMBER		SHEET 1 OF 1	

Appendix 27



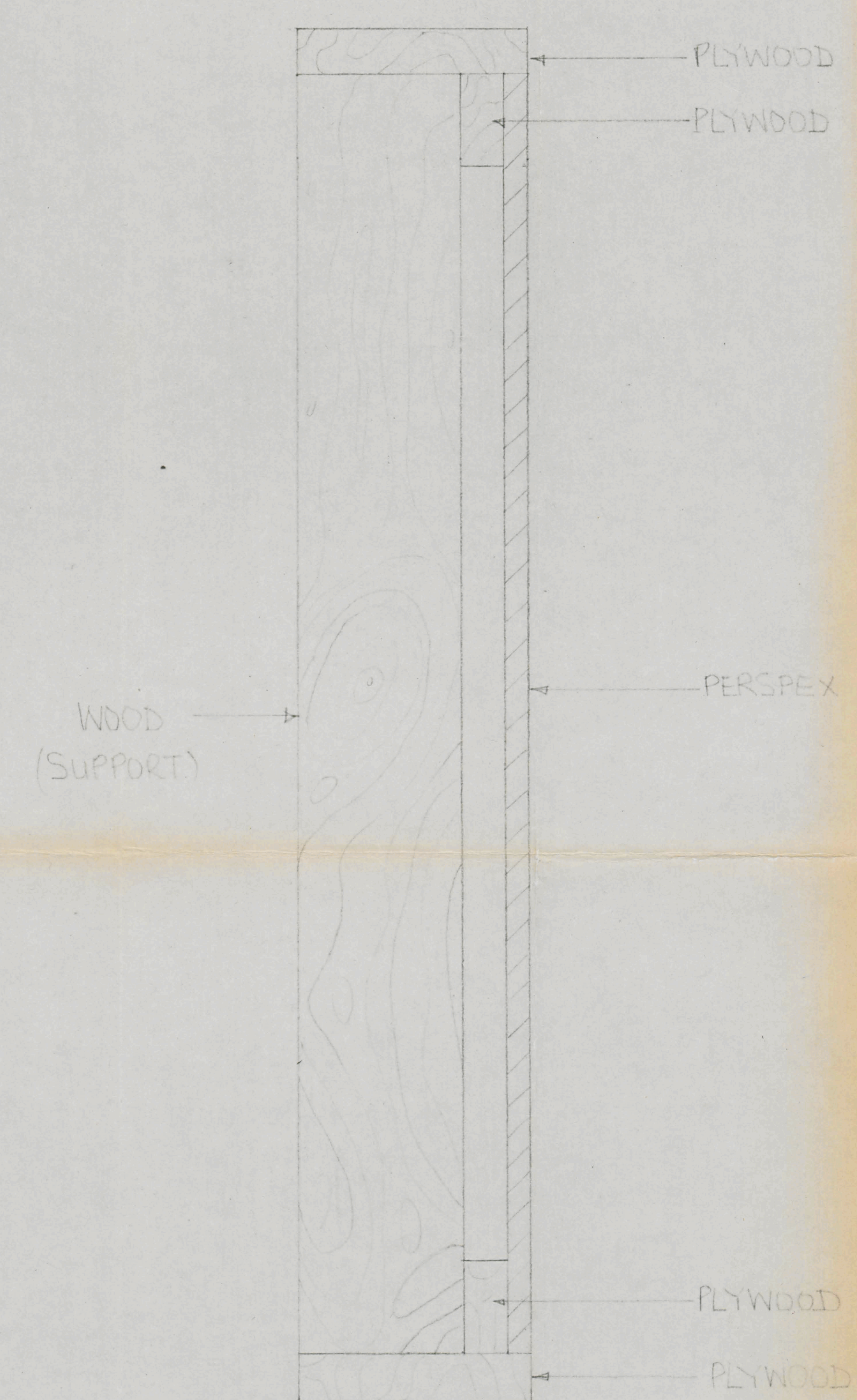
NOTES

1	8'×4' PLYWOOD TO BE USED
2	WATERPROOF GLUE TO BE USED IN ALL GLUING WORK
3	MOBILE BED TO FIT SEDIMENT TRANSPORT FLUME
4	4 NO. MOBILE BEDS TO BE MADE

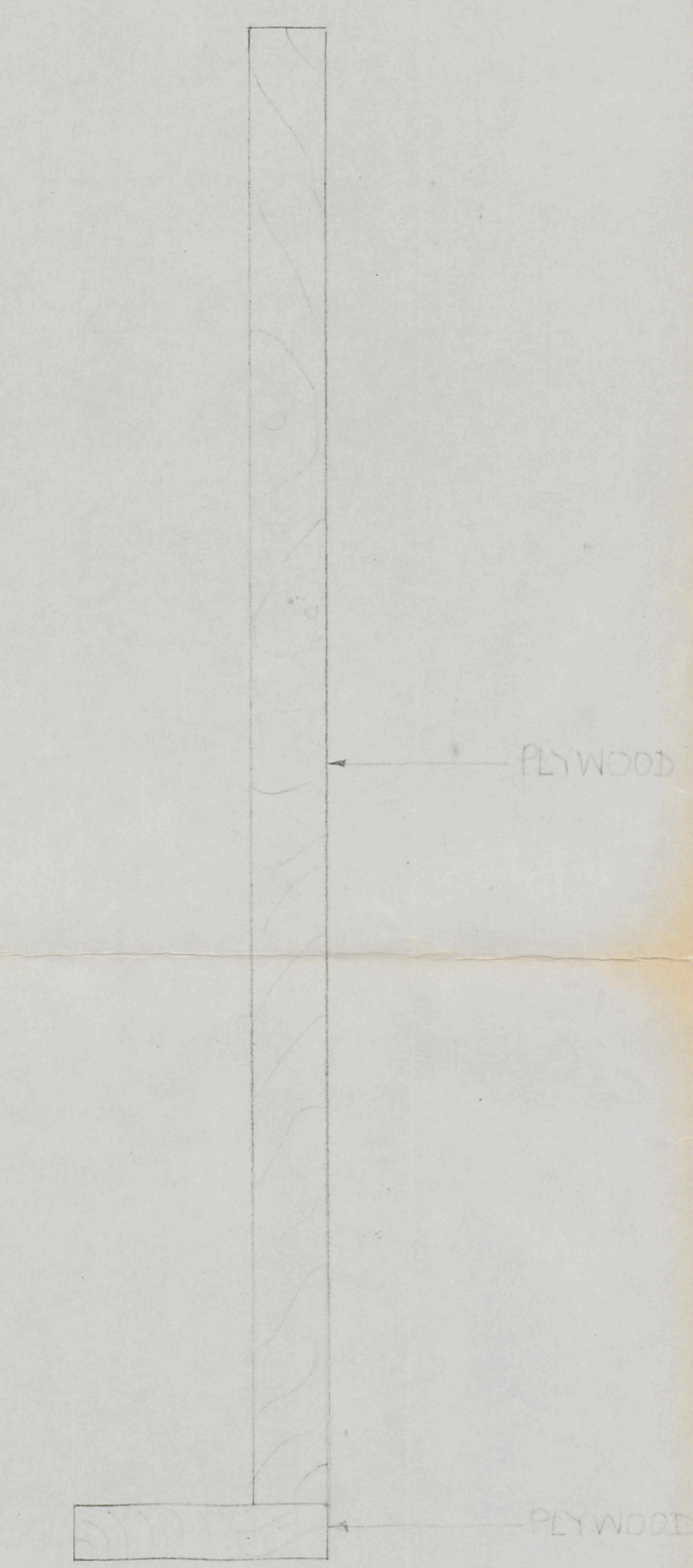
Appendix 26

NATIONAL COLLEGE OF AGRICULTURAL ENGINEERING
SILSOE BEDFORD

MATERIAL 5MM PLYWOOD (WATERPROOF)			
TOLERANCE ± 1 MM			
FIRST ANGLE PROJECTION			
SCALE	DRAWN BY	CHECKED BY	APPROVED BY
1:10	G. QUANSAH	[signature]	[signature]
PROJECT NAME SEDIMENT TRANSPORT IN FLUMES			
PART NAME MOBILE BED.			
PART NUMBER		SHEET 1 OF 21	



SECTION A-A



SECTION B-B

NATIONAL COLLEGE OF AGRICULTURAL ENGINEERING SILSOE BEDFORD			
MATERIAL PLYWOOD WOOD AND PERSPEX			
TOLERANCE			
~~FIRST~~ THIRD ANGLE PROJECTION			
SCALE	DRAWN BY	CHECKED BY	APPROVED BY
1:1	C. QUANSAH	[signature]	[signature]
PROJECT NAME SEDIMENT TRANSPORT IN FLUMES			
PART NAME FLUME HEIGHT EXTENSION			
PART NUMBER 1		SHEET 2 OF [illegible]	

Appendix 24b