

Chapter 8

RESULTS

8.1 Splash Cup Study

The splash cup losses per drop for each drop size and splash cup size combination are shown in Table 8.1. In Figure 8.1, the data is presented as plots of splash cup loss per drop versus splash cup diameter and versus drop kinetic energy.

8.2 Soil Tray Study

The masses of soil collected in the upslope and downslope collecting areas (trays 1 and 2, and 5 and 6 respectively, Figure 7.1), together with the total losses from the soil tray are shown in Table 8.2 (after Bush, 1981). From these were calculated the total splash loss in g m^{-2} and the net downslope component splash transport in g m^{-1} . These are plotted against soil tray slope in Figure 8.2 (after Bush, 1981).

TABLE 8.1: *Splash loss per drop for a range of drop diameter/splash cup combinations (g)*

Drop diameter (mm)	Splash cup diameter (cm)		
	3.1	9.0	15.3
4.7	0.050	0.030	0.027
	0.052	0.026	0.024
5.6	0.109	0.066	0.066
	0.114	0.058	0.052

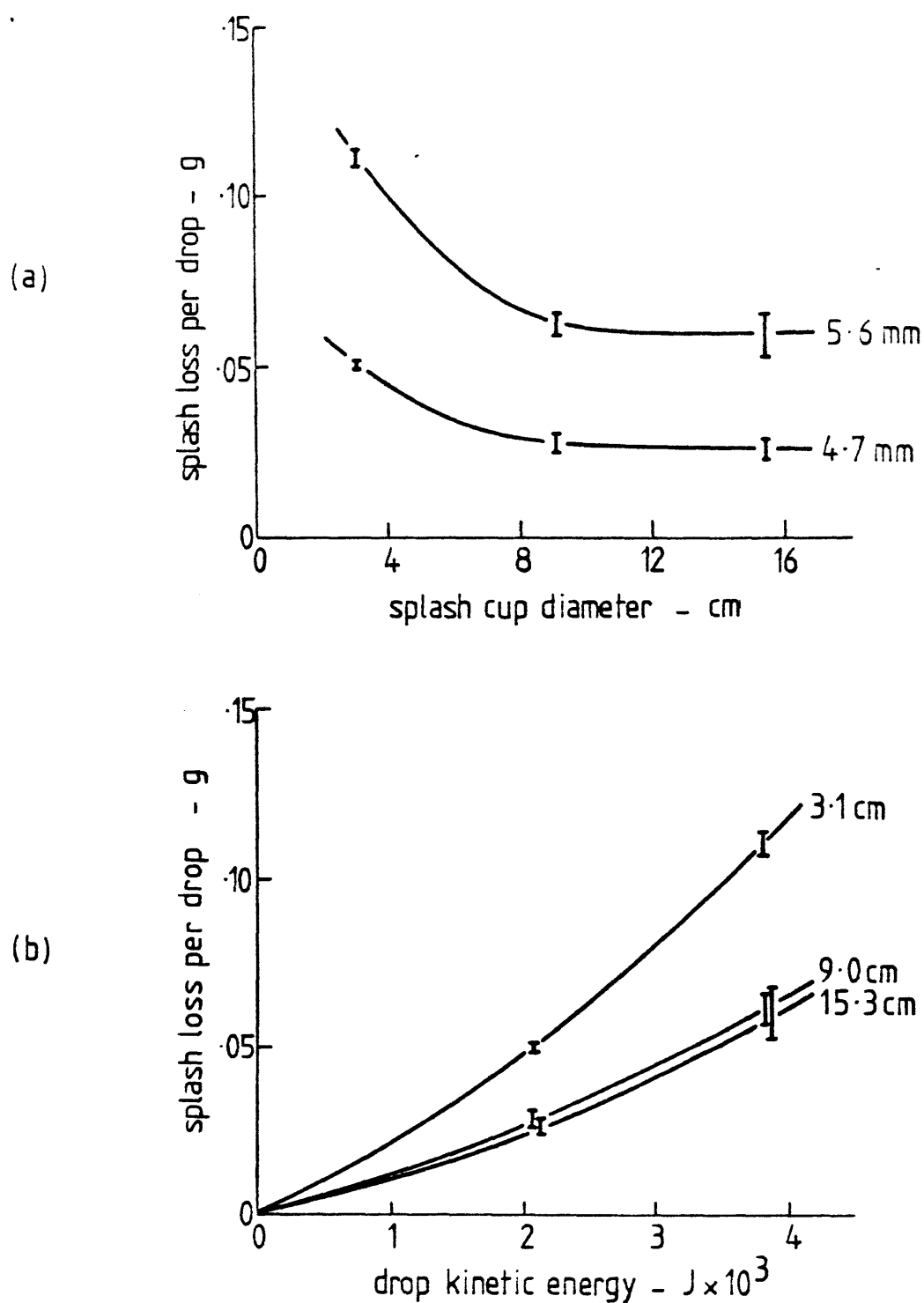


FIGURE 8.1: a) The effect of splash cup diameter on splash loss per drop for two drop sizes.
 b) The splash loss per drop versus drop kinetic energy relationship for three diameters of splash cup.

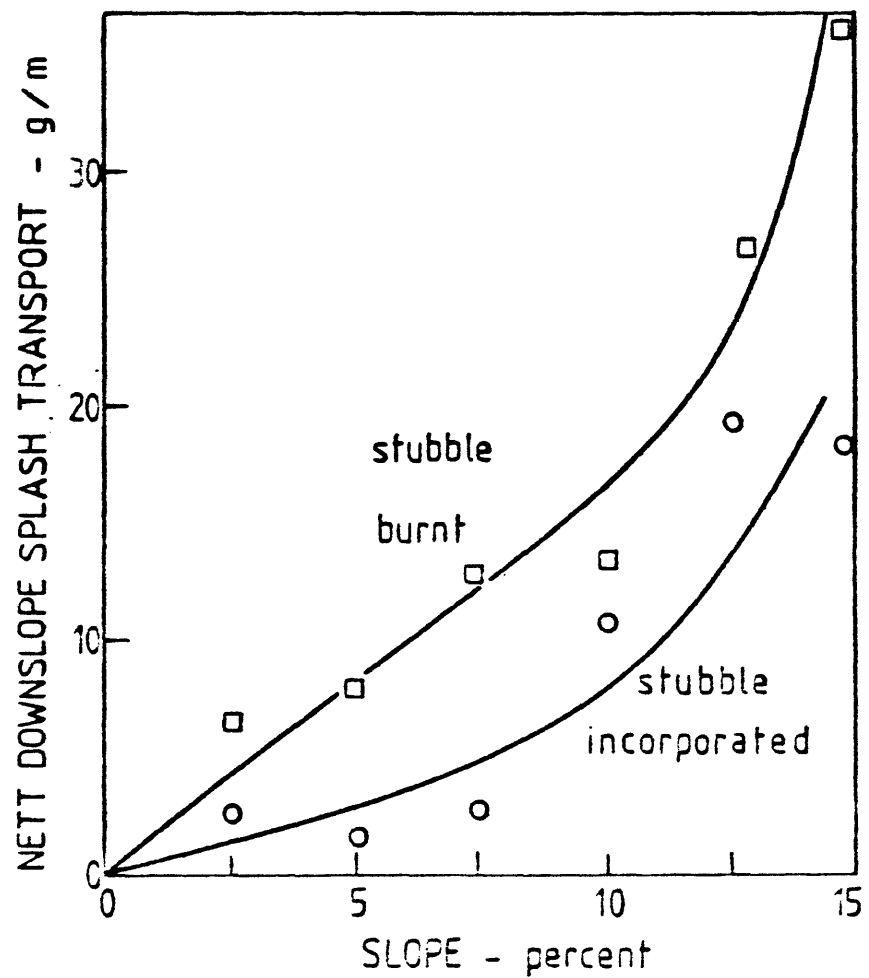
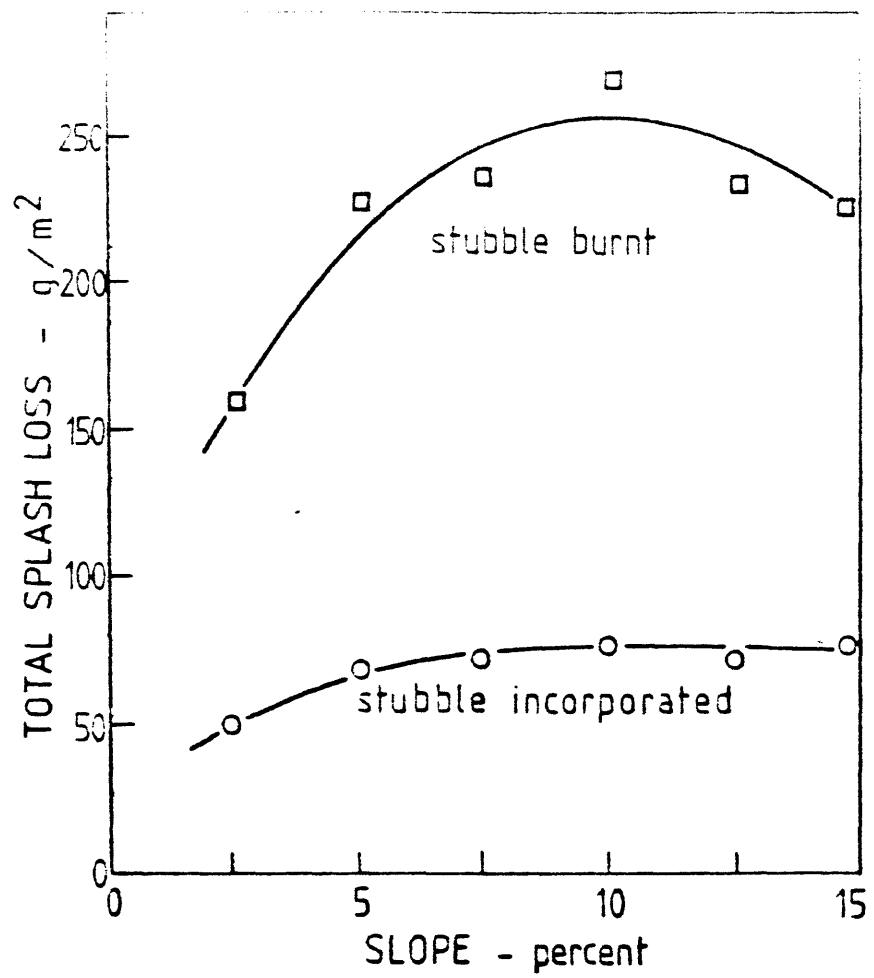


FIGURE 8.2: Slope relationships for total splash loss and net down-slope component splash transport. Gunnedah black earth, 110 mmh for 10 min. (after Bush, 1982).

TABLE 8.2: *Masses of oven dry soil (g) in upslope collecting traps (1 and 2 in Figure 7.1), downslope collecting trays (5 and 6 in Figure 7.1) and all collecting trays (1 to 6 in Figure 7.1). Upper figure of each pair is for stubble burnt treatment, while lower figure is for stubble incorporated*

Collecting tray	Slope (%)					
	2.5	5.0	7.5	10.0	12.5	15.0
Upslope	13.3	21.6	21.2	25.3	19.1	17.1
	3.5	5.2	5.2	6.0	5.1	4.9
Downslope	15.2	23.7	25.1	28.3	27.0	27.3
	4.2	5.6	6.0	9.1	11.0	12.1
All trays	47.0	68.5	71.5	78.3	70.6	67.3
	12.5	17.3	18.0	22.1	22.5	24.3

8.3 Splash Trap Study

Measurements were made with the two splash board array and the three modified Bollinne splash trap array from 21-7-81 till 28-9-82. Erosion events were frequently comprised of more than one rainfall event as shown in the records listed in Appendix 1. This was due to some rainfall events being too small to cause appreciable splash transport, or in some cases, due to inability to service the plot between rainfall events. As evaporation from the directional rain-gauge in dry spells between rainfall events would affect the calculation of rainfall inclination and direction, the lack of agreement between directional and daily read rain-gauge totals for summer erosion events with substantial dry spells between rainfall events was taken as an indication that the calculated rainfall inclination and direction might be in error. Table 8.3 lists daily read and directional rain-gauge data with erosion events numbers 5, 14 and 26 being marked as suspect for the reasons mentioned above. Variation between daily read and directional rain-gauge totals when there was no opportunity for evaporation from the directional gauge was taken as between-site variation. Table 8.4 lists the calculated downslope component

TABLE 8.3: *Daily read and directional rain gauge data*

Erosion event number	Total rain fall from daily read gauge (mm)	Total rain-fall from directional gauge (mm)	Direction of rainfall inclination (deg. E of magnetic N)	Angle of rainfall inclination (deg. from horizontal)
1	10.4	12.1	230	68
2	20.5	21.4	247	49
3	19.0	20.2	252	48
4	13.5	8.0	245	50
5*	154.8	137.1	286	67
6	3.8	1.7	221	56
7	23.4	21.0	088	83
8	10.4	10.0	161	50
9	8.9	8.5	093	80
10	4.0	3.8	244	76
11	27.0	27.4	237	85
12	13.0	12.0	319	83
13	8.2	9.0	265	66
14*	115.3	107.1	027	76
15	30.8	26.1	259	68
16	7.8	7.8	053	65
17	37.0	42.0	033	83
18	42.5	38.1	068	77
19	42.7	45.9	077	77
20	17.6	16.2	303	86
21	14.6	15.8	239	75
22	35.5	38.8	254	60
23	41.4	40.1	093	85
24	78.3	83.6	116	82
25	20.6	20.2	294	73
26*	21.5	15.7	029	82
27	10.0	9.6	060	85
28	63.5	61.7	289	87

* value for rainfall direction and inclination may be in error due to evaporation from directional rain gauge.

TABLE 8.4: Downslope component splash transport (gm^{-1}), and resultant splash transport (gm^{-1}) and direction measured by the two splash board array and the three modified Bollinne splash trap array for erosion events numbers 1 to 22. The direction of the resultant splash transport is expressed in degrees east of magnetic north. The downslope direction for the plot is 164.5°

Erosion event number	Downslope component		Resultant splash transport			
	Splash board	Modified Bollinne	Splash board array		Modified Bollinne array	
			Magnitude	Direction	Magnitude	Direction
1	5.1	4.1	3.8	084	3.9	081
2	60.7	33.7	103.2	082	63.1	066
3	26.4	13.0	31.6	083	28.9	062
4	10.1	17.7	4.4	152	7.8	165
5	197.1	325.7*	84.7	158	137.9*	136*
6	4.2	2.7	2.1	184	1.4	035
7	14.2	10.1	7.4	224	2.2	220
8	11.6	5.9	23.8	344	27.1	012
9	65.9	62.1	44.8	240	73.2	246
10	28.9	22.7	20.1	105	10.7	102
11	22.5	21.1	11.6	247	3.3	236
12	11.6	9.2	8.7	216	4.5	211
13	51.8	39.8	54.6	096	37.4	093
14	448.4	312.1	348.2	194	153.8	190
15	85.0	50.8	94.8	099	39.0	089
16	5.1	4.5	--†	--†	1.1	298
17	63.4	48.4	24.7	227	7.0	214
18	28.1	22.8	28.8	238	17.0	238
19	26.4	22.8	16.9	211	14.5	237
20	52.1	46.3	31.4	124	18.6	145
21	31.1	32.6	19.2	130	11.0	143
22	37.0	32.4	18.7	101	9.6	090

* result affected by runoff inflow into trap.

† no result due to accident during trap servicing.

TABLE 8.5: Downslope component splash transport (gm^{-1}), and resultant splash transport (gm^{-1}) and direction measured by the two splash board array, the three modified Bollinne splash trap array, the four pipe splash trap array and the three pipe splash trap array for erosion events numbers 23 to 28. The direction of the resultant splash transport is expressed in degrees east of magnetic north. The downslope direction for the plot is 164.5°

Erosion event number	Downslope component		Resultant splash transport			
	Splash board	Splash transport Modified Bollinne	Splash board array		Modified Bollinne array	
			Magnitude	Direction	Magnitude	Direction
(a)						
23	109.0	149.0	52.0	179	66.5	201
24	--†	79.0	--†	--†	88.8	319
25	86.6	72.6	78.7	141	42.4	151
26	72.3	90.0	57.3	193	47.3	206
27	18.7	16.2	11.0	233	7.0	245
28	162.8*	105.4	74.0*	171*	12.6	241
	Downslope component		Resultant splash transport			
	4 pipe array	Splash transport 3 pipe array	Four pipe array		Three pipe array	
			Magnitude	Direction	Magnitude	Direction
(b)						
23	106.8	141.0	46.8	148	45.8	158
24	141.6	143.5	107.4	266	111.0	252
25	83.9	113.9	70.7	134	79.3	140
26	63.2	72.6	23.3	179	25.4	186
27	19.4	33.5*	8.7	213	16.0*	179*
28	134.2	418.4*	17.8	266	294.1*	158*

* result affected by runoff inflow into trap.

† no result due to accident during trap servicing.

splash transport from the upslope facing trap of each array, and the calculated resultant splash transport rate for each array. A full listing of splash trap catches is given in Appendix 2.

As discussed in Section 9.3, it became apparent during the course of the splash trap study that wind during rainfall plays an important part in determining the direction of the resultant splash transport. As the splash boards and the modified Bollinne splash traps were not designed with this effect in mind, the pipe splash traps were then designed to minimise disturbance to wind flow over the plot. These were in use after erosion event number 22. The rainfall events comprising erosion events numbers 24 to 28 are listed in Appendix 1. Table 8.5 lists the calculated downslope component splash transport from the upslope facing splash trap of each of the four arrays: the splash board array; the modified Bollinne array, the four pipe array, and the three pipe array. The magnitude and direction of resultant splash transport is also given for each array.

8.4 Tracer Study

No results are presented for this study as a number of practical difficulties were encountered with the method. These are discussed in Section 9.4.

Chapter 9

DISCUSSION

9.1 Splash Cup Study

The smallest size splash cup (3.1 cm diameter) was able to be used successfully with a minimum of abandoned runs due to drops striking the edge of the cup. This was due largely to the relatively small drift during fall of the large drop sizes used. A splash cup of this size has also been used successfully by Moeyersons and De Ploey (1976).

Figure 8.1(a) shows that there is a significant relationship between the measured splash loss per drop and the diameter of the splash cup, the general form of which is as predicted by Farrell *et al.* (1974) and by this author in Section 5.2.1 (Table 5.1). It is of considerable import that the splash loss measured with a 3.1 cm cup is nearly twice that measured with a 9.0 cm cup (which is very slightly larger than the standard splash cup). The effect this has on the splash loss/kinetic energy relation is plotted in Figure 8.1(b). It can be seen that each size of splash cup produces a different relationship.

The significance of this small study lies not so much in the actual values or relationships measured, but more in its support of the theoretically justified contention that there is a need for extreme caution if the splash cup is to be used in experimental work that forms the basis of erosion prediction techniques. It is essential that it be understood that in determining "detachment"/kinetic energy relationships, there are impact variables such as splash angle and ejection velocity that also can be expected to vary with kinetic energy and these variables affect the proportion of total detachment that appears outside the splash cup to be measured as splash loss.

The successful use of a splash cup smaller than the standard splash cup, in this study and by Moeyersons and De Ploey, together with the smaller splash cup's ability to provide a better estimate of the total detachment that took place on the cup surface would seem ample justification for its inclusion in the range of techniques currently being used in erosion research.

9.2 Soil Tray Study

The user of the soil tray/collecting tray layout described in Section 7.2, Mr Alan Bush, found the design generally satisfactory in its practical aspects. The design does not differ greatly in this respect from the many that have been used in the past. It does, however, differ significantly from past designs in that the source/collecting area geometry has been chosen on the basis of rigorous analysis of the effect of this geometry on the relationship between the collecting rate and the resultant and component splash transport rates that would occur in the rectangle if it were surrounded by a similar soil surface and not isolated in the laboratory.

The study undertaken by Bush was partly to compare the effect of stubble incorporation and stubble burning on splash erosion. This aspect lies outside the scope of this thesis and is not discussed in any detail here, other than to point out that the significant difference between the two treatments shown by the total loss measurements (Figure 8.2(a)) is not nearly so significant for the net downslope component splash transport measurement (Figure 8.2(b)). This illustrates the contention that will be made subsequently - that many relationships determined by soil tray studies are subject to configurational artefact.

At the author's suggestion, the study undertaken by Bush also included the effect of slope as this aspect has received frequent attention in the past. Published relationships between various measurements of splash erosion and slope of soil tray are summarised in Figure 9.1. The relationships determined by Bush between slope and total splash loss, and slope and net downslope component splash transport, are shown in Figure 8.2. Two characteristics can be used to categorise these curves: (i) the direction of convexity of the curve, *i.e.* up or down; (ii) whether the curve passes through the origin or not. These characteristics can in most cases be related to the source/collecting area configuration used to determine the curves.

To aid in the understanding of this relationship, it is useful to consider the collecting rates from various source/collecting area configurations as either transport dominated or detachment dominated. In Chapter 5, it was shown that the collecting rate for a very small source area was very nearly equal to the detachment rate on the source area, while the collecting

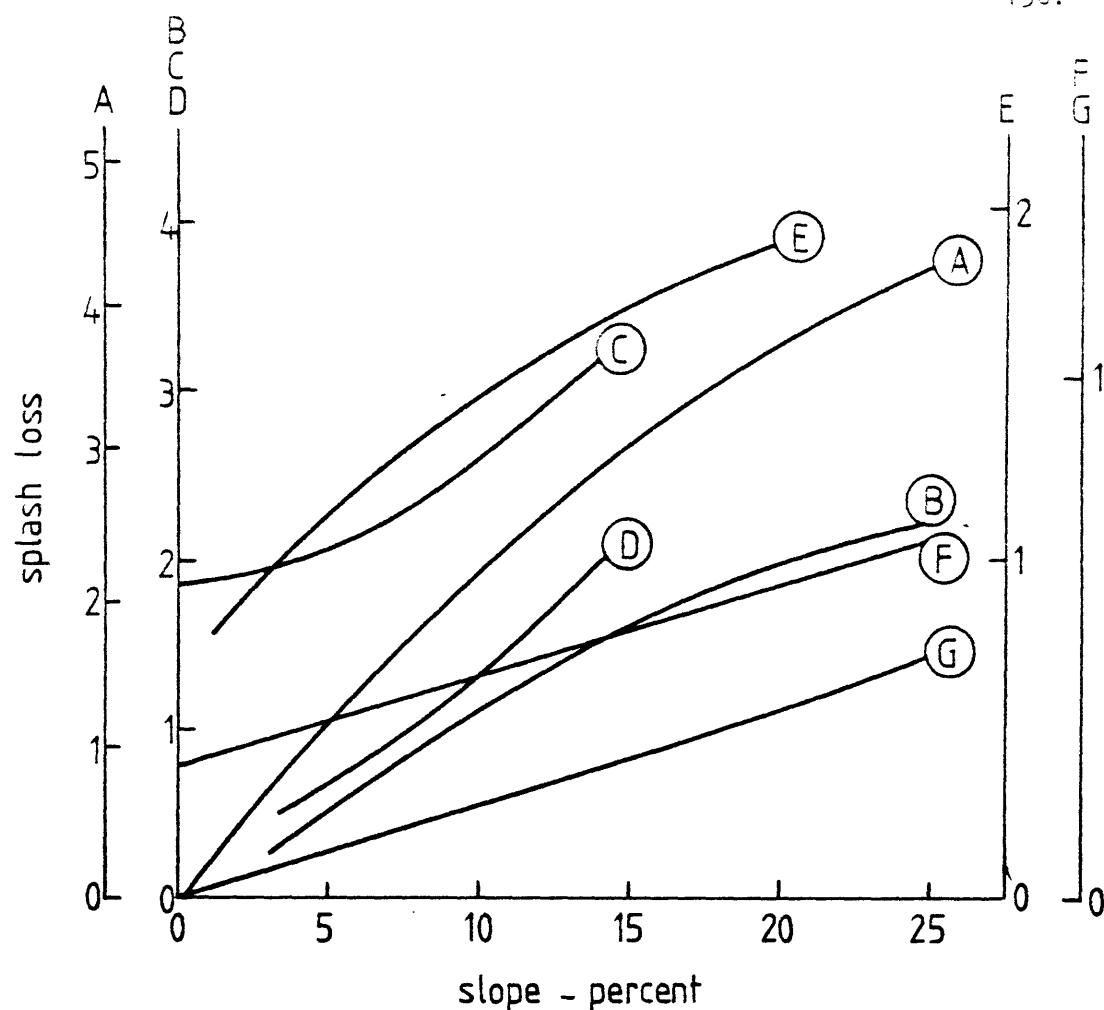


FIGURE 9.1: Published relationships between slope and various measurements of splash erosion.

A Moeyersons and De Ploey (1978), "splash transport rate", $\text{cm}^3\text{cm}^{-1}\text{year}^{-1} \times 10^{-2}$

B Farmer and Van Haveren (1971), "soil splash in bottom pan", $\text{g} \times 10^{-2}$

C Quansah (1982), "mean weight of soil detached", $\text{kg m}^{-2} \times 10$

D Quansah (1982), "mean weight of soil transported", $\text{kg m}^{-2} \times 10$

E Lattanzi *et al.* (1974), "soil loss", $\text{kg m}^{-2}\text{h}^{-1}$

F Moseley (1973), "total movement", $\text{g} \times 10$

G Moseley (1973), "net downslope movement", $\text{g} \times 10$

rate from the downslope end of a sufficiently long soil tray (single boundary type 1 or 3 configuration) was equal to the downslope component splash transport rate (a corresponding equality holds for the upslope end of the soil tray). Thus configurations that meet, or nearly meet, these source/collecting area geometrical requirements have a collecting rate that is respectively either detachment dominated or transport dominated. Note that the detachment rate and the transport rate are two different but related quantities. If, as a hypothetical example, the detachment rate on a soil surface is $2 \text{ kg m}^{-2} \text{ h}^{-1}$ and all particle displacements are downslope and 0.2 m in length, then the downslope component splash transport rate is $0.4 \text{ kg m}^{-1} \text{ h}^{-1}$. So a suitably small source area under these conditions would show a total loss rate close to $2 \text{ kg m}^{-2} \text{ h}^{-1}$, while the collection rate from the end of a suitably long soil tray (single boundary type 1 or 3 configuration) would be $0.4 \text{ kg m}^{-1} \text{ h}^{-1}$. Thus it is possible to get completely different collecting rates depending on how the source/collecting area geometry affects the degree of transport or detachment dominance of the collecting rate. Similarly, the slope/collecting rate relationship and the slope/splash erosion relationship derived from it will be affected by the degree of transport or detachment domination of the collecting rate.

It is also appropriate at this stage to reiterate the factors that are involved in the observed phenomenon that net downslope splash transport increases with increasing slope. These factors are given in Section 3.3 as:

- for a given trajectory downslope range is greater than upslope range - termed the "range effect";
- a greater mass of particles is displaced with a downslope component than is with an upslope component - termed the "detachment partitioning effect";
- a greater total mass of particles is displaced at steeper slopes - termed the "total detachment effect".

The other factors mentioned in Section 3.3 cannot so readily be related to source/collecting area configurations.

The source area in the configuration used by Moseley (1973) is relatively small having a downslope length of 10 cm. This, combined with

the narrow collecting boards, could be expected to result in a total collecting rate (the "total movement" of Moseley) that is a fair estimate of detachment, insofar as there is insufficient source length for the transport rate to be reflected in the collecting rate. Thus curve F of Figure 9.1 is a reflection of the "total detachment" slope effect. The source area used by Quansah (1982) is slightly larger, so the total loss (the "mean weight of soil detached" of Quansah) is probably not wholly detachment dominated. Curve C of Figure 9.1 (from Quansah's data) is nevertheless mainly a reflection of the "total detachment" slope effect. Moseley also measured separately the mass of particles detached with upslope and downslope components and expressed the difference as "net downslope movement". Thus curve G in Figure 9.1 expresses the combination of the "total detachment" and "detachment partitioning" slope effects. This effect is also probably expressed in curve D of Figure 9.1 although with the larger source area used by Quansah, it may not be wholly a detachment effect. The slope/net downslope component splash transport relationships shown in Figure 8.2(b) are the only ones, of the relationships being considered, to be determined with a fully transport dominated collecting rate, so that the curves of Figure 8.2(b) show the way in which the net downslope component splash transport increases with slope. As such these curves reflect the combination of the "total detachment", the "detachment partitioning" and the "range" effects.

Thus taking the work of Moseley, Quansah and Bush as a whole, it can be seen that the slope/total detachment relationship is - linear or slightly convex downwards and does not pass through the origin. The relationship between slope and the difference between upslope and downslope directed detachment is also slightly convex downwards but passes through the origin. The slope/net downslope transport relationship is more strongly convex downwards and it is probable that the increased convexity reflects the multiplicative effect of the additional mechanisms favouring downslope displacement.

Unfortunately, very few of the published configurations have source/collecting area geometries that enable collecting rates to be meaningfully related to some part of the splash transport process. Many studies have used total loss measurements which, except in the case of very small source areas, cannot be denoted detachment or transport dominated. The same applies to the configurational inverse, the internal collecting area (see p.96). Examples of slope/total loss relationships are the curves of Figure 8.2(a), and curve

E of Figure 9.1. These are all convex upwards and do not pass through the origin. In addition, some authors (*e.g.* Farmer (1973) and Luk (1977), both of whom used total loss measurements from medium-sized soil trays) have been unable to discern any consistent trend in their total loss/slope measurements. The analysis of total loss measurement (p.78) suggests that the total loss is a slightly decreasing function of slope (shown by substitution of numerical values in equation 5.9), but as this is for the simplified representation of the splash transport process which takes account only of the "range" effect, the combination of all the slope effects may, in fact, result in a convex upwards total loss/slope relationship.

Two curves in Figure 9.1 do not fall in with the general categorisation discussed above. They are curve A of Moeyersons and De Ploey (1976) and curve B of Farmer and Van Haveren (1971). The former is for a splash transport rate (which here would be termed net downslope component splash transport) calculated from two sets of laboratory data: the autoradiographic data of De Ploey and Savat (1968), and the mean saltation distance determined from the spatial splash distribution for single drop impacts (Moeyersons and De Ploey, 1976). The mean saltation distance, as pointed out in Section 2.3, cannot strictly be used with the detachment rate to obtain a transport rate, rather the length of the position vector representing the centre of mass of the splash displacement vectors should be used, as indeed was done by these authors in later publications. The different method of determination of splash transport rate may be responsible for the atypical nature of this slope/splash transport rate relationship. It should be pointed out, however, that of the soil tray studies considered here, that of Moeyersons and De Ploey is notable for its generally rigorous analytical treatment of the splash transport process.

The second atypical curve is that of Farmer and Van Haveren (1971) - curve B, Figure 9.1. From the published description of the source/collecting area configuration (see Figure 5.3), the downslope end constitutes a single boundary type 3 configuration, and, as such, the collecting rate in the downslope collecting area should equal the downslope component splash transport rate. Thus the curve for the slope/downslope component splash transport relation should not pass through the origin (it should, of course, do so for the slope/*net* downslope component splash transport relation). Curve B of

Figure 9.1, although it extends only as far as 3% slope, resembles the other curves that do pass through the origin. Since for the tray at zero slope, there must be a finite splash transport component in the direction that becomes downslope when the tray is tilted, the only explanation that can be offered for curve B's tendency to pass through the origin, is that either the published description of the method is incomplete, or this author has misinterpreted the published description.

The most significant aspect of the soil tray study is considered to be the fact that with no additional complexity in experimental design or additional effort in operation, it is possible to measure quantities that are directly related to the rate at which splash transport would occur were the soil sample not in the abnormal isolation of the soil tray. Furthermore, these measurements are free of the configurational artefact that effects total loss measurements and the relationships derived from them. That it is possible to relate such artefacts to the source/collecting area configuration producing them is of passing interest only.

It is clearly evident that the majority of soil tray studies have measured ill-defined quantities that are some indeterminate mixture of detachment and transport rates. While it is admitted that there is a useful role for empiricism in erosion research, it is felt that empiricism has in the past obfuscated our understanding of the inter-rill transport process.

The example of the conclusion of Lattanzi *et al.* (1974) that areas of zero slope would suffer appreciable inter-rill erosion has already been given (Section 2.1). One further example will suffice to illustrate the point. The study of Young and Weirsmas (1973) used a laboratory plot bed with two pre-formed rills (Figure 5.3) to determine the quantity of soil transported in splash and shallow flow off the plot end compared to the quantity transported by similar means into the rills. No account appears to be taken of the fact that splash and flow over the end of the plot occur over the plot width while supply to rills occurs over the plot length. The quantities are expressed in terms of the total for the length involved rather than per unit length. Thus it is not surprising that with a plot length of 4.52 m and a width of 1.52 m that the supply to rills was found to be several times greater than the supply off the plot end. It is considered that the concluding statement of Young and Weirsmas that 80-85% of soil loss originating in

the inter-rill area was transported to a rill before leaving the plot, while correct for the configuration used, conveys a misleading impression of the quantities of soil transported cross-slope and downslope on inter-rill areas. If Young and Weirsmas data is adjusted to allow for the different rill length and plot width, a figure of approximately 28% instead of 80-85% is obtained. This figure is more in line with the percentages of soil movement that would be expected in cross-slope and downslope directions.

9.3 Splash Trap Study

All the splash trap designs tested were found to be easily established in the plot and serviced after erosion events. The pipe traps were found to be superior in these aspects as the small excavation needed for their placement facilitated removal and replacement with a minimum of disturbance to the plot. The most serious problem encountered was runoff inflow during more intense rainfall events when deposition at the lower edge of the aperture raised the soil level sufficiently to allow overland flow to enter the trap. This problem could usually be detected by visual inspection at servicing, and also showed up as abnormally high trap catches (Appendix 2). The problem was invariably associated with traps facing upslope.

Given the considerable care in ensuring the uniformity of conditions on the plot, it was expected that the two measurements of downslope component splash transport would be reasonably consistent, within the limits of the normal variability of a natural process. This was not the case - of the erosion events from 21-7-81 to 4-1-83 (excluding events numbers 5, 24 and 28), twenty-one showed that the downslope component splash transport measurement by the splash board exceeded that of the modified Bollinne splash trap, while the opposite occurred only for four events (Tables 8.4 and 8.5). The overestimation by the splash board relative to the modified Bollinne splash trap is considered to be due to splashed particles falling directly into the collecting trough without first being intercepted by the vertical surface, *i.e.* the trough is registering the detachment as a horizontal aperture (see p.104) as well as the component transport by means of the vertical intercepting surface. When the splash board was designed, it was felt that, on the grounds of the small area of the collecting trough relative

to that of the intercepting surface, the direct infall would not be significant. This, however, appears not to be the case. Detailed analysis of the infall phenomenon using the simplified representation of the splash transport process has been published by this author (Reeve, 1982; Appendix 4). This showed that the degree of overestimation by the splash board reflected in the plot measurements was similar to that predicted by theoretical considerations. It should be pointed out, however, that although the agreement between theory and experiment is attractive, rigorous experimental verification would require that the two measurement methods be tested in a number of different positions on the plot to exclude the possibility of within-plot variation of soil conditions. As the splash board design was subsequently discarded for other reasons, this was not done.

As the plot has a slope of 17.6%, it was expected that the steepness of the slope would cause the resultant splash transport to be generally directed downslope. It was found, however, that there was considerable scatter. For the erosion events numbers 1 to 22 (excluding 5 and 14), the resultants for fourteen events had some downslope component, while those of six events had an upslope component (Table 8.4). If the direction of the resultant splash transport (from the modified Bollinne array) is plotted against the reciprocal bearing of the rainfall direction determined by the directional rain-gauge (*i.e.* the direction of the horizontal velocity component of inclined rainfall) as shown in Figure 9.2, it is apparent that the two directions are fairly strongly correlated. With the size of the modified Bollinne traps used to obtain these resultant splash transport directions, it was felt there could be an appreciable rainshadow on the downwind side of the downwind trap of the array, so that while the trap facing upwind was collecting splash from all of the soil surface within splashing distance, the trap facing downwind might be collecting splash from only that part of the soil surface beyond the rainshadow cast by the trap during inclined rainfall. This would naturally bias the resultant splash transport direction towards the downwind direction. To avoid this rainshadow effect, the pipe traps described in Section 7.3 were installed on the plot.

The data collected from the six erosion events for which the pipe traps were in place gave a preliminary indication of the success of the traps in avoiding the rainshadow effect. For each event, the splash traps facing

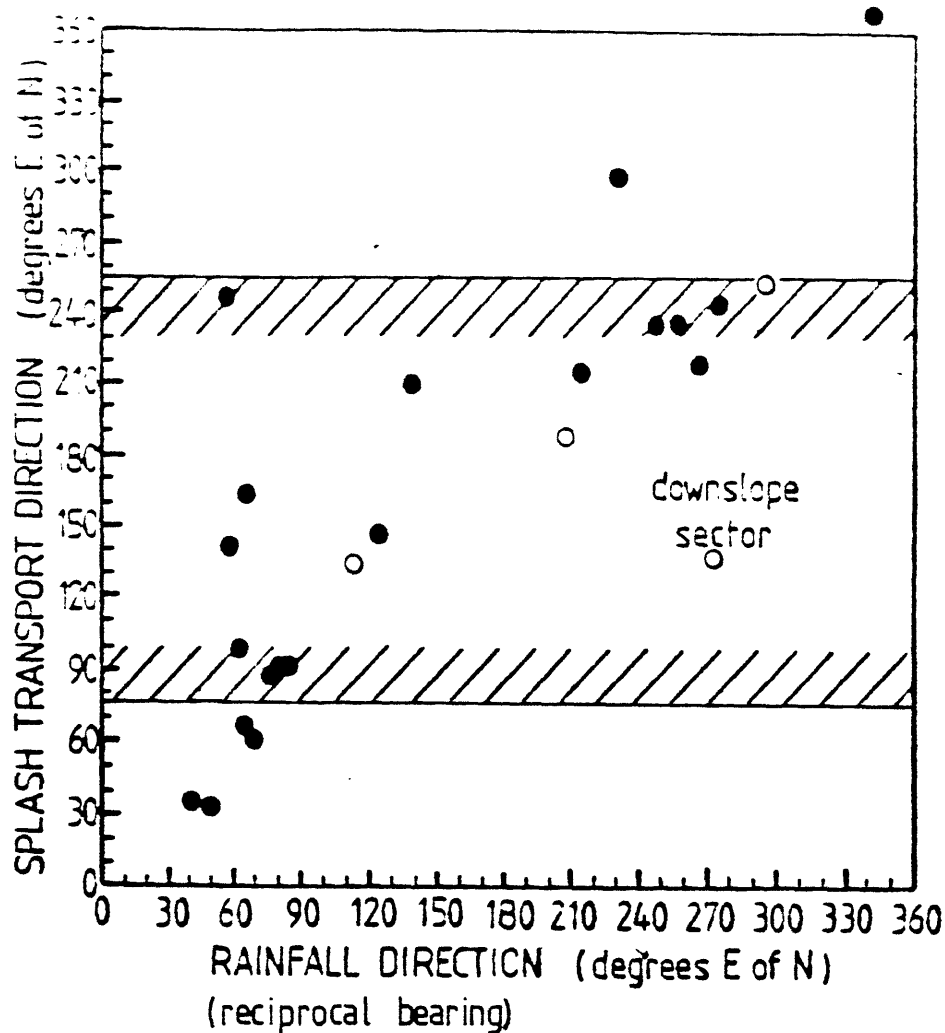


FIGURE 9.2: Direction of resultant splash transport plotted against reciprocal bearing of rainfall direction (i.e. the direction of the horizontal velocity component of inclined rainfall). Solid circles - erosion events numbers 1 to 22, excluding 5 and 14; open circles - erosion events numbers 23 to 26.

the rainfall direction can be considered as upwind facing traps, while those facing the reciprocal bearing can be considered as downwind facing traps. In Table 9.1, for both upwind and downwind facing traps, the component splash transport rate registered by the larger traps (splash board and modified Bollinne) is compared with that registered by pipe traps facing the same direction. It can be seen that, while for upwind facing traps the component splash transport registered by the larger traps is not consistently greater or less than that registered by the pipe traps, for downwind facing traps, the pipe traps, in all but one case, register a higher value for the component splash transport than do the larger traps. This is taken as clear experimental evidence that the pipe trap design has a reduced rainshadow effect compared to that of the larger splash boards and modified Bollinne traps.

There have been, to date, as far as the author is aware, no other studies of this nature, so precise comparison with other work is not possible. Bollinne (1978) used 5.2 cm diameter splash funnels flush with the soil surface to record a "detachment" rate of $30 \text{ t ha}^{-1} \text{ year}^{-1}$. The analysis previously mentioned (see p.104) shows that such a funnel will record exactly the detachment rate only for those particles with displacements greater than 5.2 cm. For displacements less than this, the reduction of the effective contributing region results in a collection rate not related directly to the detachment rate, but that is (by analogy with the configurational inverse - the splash cup) less than the detachment rate on the undisturbed part of the soil surface. Thus Bollinne's figure of $30 \text{ t ha}^{-1} \text{ year}^{-1}$ could be expected to underestimate the detachment rate.

If downslope component splash transport for the twelve months covered by erosion events numbers 1 to 21 is summed (using modified Bollinne splash trap data except for erosion event number 5 where the splash board figure is used - Table 8.4) the total downslope component splash transport amounts to 953 g m^{-1} . Assuming the length of the position vector representing the centre of mass of the downslope splash displacement vectors is of the order of 0.2 m (see, for example, the splash distribution of Reeve and Perrens, 1980), the annual splash detachment for downslope displacements is therefore, of the order of $5 \text{ kg m}^{-2} \text{ year}^{-1}$ (downslope component transport being equal to the product of the above mentioned length of position vector

TABLE 9.1: Comparisons between component splash transport measurements by large splash traps and pipe traps facing upwind, and between component transport measurements by large splash traps and pipe traps facing downwind ($g\ m^{-1}$)

Erosion event number	Upwind facing traps		Downwind facing traps	
	Larger	Pipe	Larger	Pipe
23	117.5	92.6	72.6	98.4
	111.4	88.7	98.7	102.3
24	181.3	203.2	79.1	143.5
25	72.6	113.8	25.6	22.9
	56.0	67.4	24.9	31.6
26	90.0	72.8	36.0	43.6
	72.3	63.2	21.8	40.7
	56.7	57.7	29.5	51.9
27	19.1	20.3	11.2	15.8
	20.6	20.0	10.3	13.6

and the downslope directed detachment). If approximately equal amounts of splashed particles have upslope and downslope components, then the total detachment is $10\ kg\ m^{-2}\ year^{-1}$ or $100\ t\ ha^{-1}\ year^{-1}$ which compares reasonably well with Bollinne's figure of $30\ t\ ha^{-1}\ year^{-1}$ given the likely under-estimation by his method, the lesser slope (6.5%) and the less intense European rainfall.

As far as the effect of wind in directing splash transport is concerned, the results presented here are regarded as the first quantitative field measurements of splash transport that show this effect. While the modified Bollinne splash trap measurements probably exaggerate the degree of

the effect, the later pipe trap measurements nevertheless show that this effect is significant (only one of the four pipe trap determined resultants is not correlated with the reciprocal bearing of the rainfall direction - Figure 9.2). The wind effect on splash transport has been shown to be reflected in post-event tracer distributions for two events by Coutts *et al.* (1968a) although these authors did not calculate the resultant splash transport from the distribution.

9.4 Tracer Study

A number of serious practical difficulties were encountered in the proposed tracer method. These were:

- the number of soil cores required to give a reasonable estimate of the post-event tracer distribution from a pre-event point application. As described in Section 7.4, the determination of the distribution along only upslope, cross-slope and downslope lines required 44 soil cores. Given the importance of wind effects discussed above, it cannot be assumed that the distribution is symmetrical about the downslope direction, so the distribution would need to be determined along at least four intermediate lines resulting in a soil core requirement of 88 soil cores per resultant transport determination per erosion event. A reduction in the number of cores could be achieved by using pre-event placement in a band across slope, but this method, as shown in Section 5.3.2, determines only the components in upslope and downslope directions. Thus it is apparent that the size of the sample of the distribution should be matched to the case with which the concentration of marked particles can be determined. In the case of determination by point-counting and hand traversing under a binocular microscope, at least 20 minutes and 500 points were found necessary for each core, resulting in an unacceptable labour component of at least 30 hours for the bare minimum delineation of the post-event tracer distribution for one resultant transport determination.

- for pre-event point placement, there is an unavoidable conflict between: (i) the need to have the pre-event core of marked soil as small as possible to make the area of origin of marked particles as near to a point as possible, and (ii) the need to provide sufficient marked particles to provide a measurable post-event distribution. The core size of 5 cm was found to supply too few marked particles for the visual counting method attempted. This problem may not apply as much to pre-event line placement of marked soil.

It is apparent from the above that the limit to visual counting was probably achieved by Kirkby and Kirkby (1974) who used small painted pebbles on a semi-arid pediment. If the tracing is to extend to sub-macroscopic soil particles, then the radioactive labelling as used by Coutts *et al.* (1968a,b) is virtually the only method where measurement of tracer concentrations is rapid enough to make it feasible to take a large number of soil cores to determine the post-event tracer distribution. One major drawback, however, of radioactive tracers is that once the labelled soil has been dispersed by several erosion events, the plot is no longer usable for this method until radioactive decay lowers activity levels to background. For Fe^{59} , for example, the half life of 45 days would mean a plot "resting period" of at least one year between applications of the method. This virtually precludes the use of radioactive tracers for routine plot measurements. On the other hand, the fact that the method, in common with all tracer methods, suffers no boundary problems, and can include measurement of flow displacements as well as splash displacements recommends it as an absolute reference measurement method.

9.5 General Aspects

The $\delta\theta$ and $\delta\theta\delta r$ methods of analysis developed in Chapters 4 and 5 have been shown to be extremely useful in examining how the collecting rates of various measurement methods relate to the detachment and transport rates that are required to be measured. They are also considered to be a definite improvement on Farrell's method (Farrell *et al.*, 1974; Savat and

Poesen, 1981) as the integral expressions developed are far simpler. Thus this study has been able to consider a wide range of measurement methods, whereas those of Farrell *et al.* and Savat and Poesen were limited to a few specific cases. It must be pointed out, however, that the author in no way lays claim to being the first to use these methods in the general sense. Such methods are the foundation of the analysis of physical systems with continuously distributed properties and have been in use since Newton's day. The methods have an extremely wide scope of application as the "applications of integration" chapters of any calculus text will show.

The application of these methods of inter-rill transport is very much dependent for its success upon the appropriate representation of the process. Thus the concept of inter-rill transport developed in this study, that of a drop impact induced particle displacement process, is probably somewhat of a departure from the concepts more widely held. Its validity, however, must be assessed in the light of the contribution it can make to improving both the technological and the conceptual bases of erosion prediction techniques. The concept introduced in this study is not without its parallels in other disciplines, *viz.* hydrology. Zaslavsky and Sinai (1981) proposed a similar concept for the transport of water in droplet splash. Their analysis follows exactly that for the simplified representation of inter-rill transport, and their equation for the downslope transport rate of water in droplet splash (derived by vector calculus) is exactly equivalent to equation 4.19 of this study. This author's concept and analysis of the inter-rill soil transport process was developed concurrently but independently of the analogous version developed by Zaslavski and Sinai. Documentary evidence of this assertion is provided in Appendix 3.

The concept of inter-rill transport developed in this study has two significant implications for erosion modelling. Firstly, the practice, in models that have separate inter-rill and rill components, of assuming that the rate of supply to rills is the same as the detachment rate on the inter-rill areas is open to question. Examples of these models are given in Section 2.4. Insofar as a rill acts as a sink for splash or flow transported material, a narrow rill can be represented as a small horizontal sampling aperture (see pp.96,104). Similarly, one side of a rill can be treated as the boundary over which splash passes into a modified Bollinne

splash trap, i.e. if all the material passing the inter-rill/rill boundary falls in the rill, then this boundary has the characteristics of the vertical sampling aperture or intercepting surface analysed above (see p.101). Thus the supply rate to a very narrow rill would be close to the detachment rate on the inter-rill surface. As the rill width increases the supply rate approaches the sum of the component transport rates in directions perpendicular to each side of the rill. Just as for laboratory collecting rates, the rill supply rate can be detachment dominated or transport dominated, or something in between. In this light, equating the rill supply rate only to the detachment rate is regarded as unjustified over-simplification.

The second implication is with reference to the concepts of "detachment limited" and "transport limited" inter-rill erosion. It is probably a useful concept of erosion processes in a general way to suggest that the erosion rate of a resistant material is limited by the strength of the material and the energy of the erosive agent (detachment limited), while for an unresisting material it is limited only by the energy of the erosive agent reflected in its transporting ability (transport limited). Extension of the concept to inter-rill erosion measurement and modelling, however, may lead to a false impression of the relative contributions of the various mechanisms involved. Regardless of whether the process is "detachment limited" or "transport limited" the rate of transport of soil off an inter-rill area is a function of the detachment rate *and* the magnitude and direction of particle displacements. Thus if the rate of transport is correctly defined, there is no need for the modelling practice (*e.g.* Meyer and Wischmeier, 1969; Onstad and Foster, 1975) of setting the supply rate from inter-rill area to whichever is the smaller of the "detachment rate" or the "transport rate". The supply rate off an inter-rill area has been shown to be a function of the boundary configuration at the point of supply (narrow or wide rills) which determines the degree of detachment or transport domination of the supply rate. The transport rate on the inter-rill surface is a function of the detachment rate and the magnitude and direction of particle displacements. It is the interactions of these last three variables with the resistance of the soil and the energy of the agent of erosion that determines the supply rate for a "detachment limited" or "transport limited" erosion situation, or any other type of situation that could be visualised.

A further general implication of the study as a whole is with regard to measurement boundary problems. The measurement methods developed in this study provide techniques of measuring: (i) the splash detachment rate under laboratory conditions; (ii) the component or resultant splash transport rate under field or laboratory conditions. The analysis of Chapters 4 and 5 showed that the advantages of these methods would apply also to the measurement of the detachment rates and the component and resultant transport rates of those particles transported wholly in drop disturbed, shallow overland flow, if and only if, the boundaries between source and collecting area are not associated with significant zones of anomalous flow behaviour. Improvement of this aspect of measurement technique is considered to be virtually essential to upgrading the measurement bases of deterministic inter-rill erosion models.

The final general implication of this study concerns the role of statistical analysis in inter-rill erosion research. The measurement approach to the inter-rill erosion process in the past has been that of the classical "black box" approach. The mechanisms of transport by omnidirectional particle displacement have been relegated to the inside of the "black box" where they have remained as the unknown or immeasurable part of the inter-rill transport process. Research into the workings of the "black box" has concentrated upon measurement of the way in which variation of inputs (such as rainfall kinetic energy, soil slope, soil moisture, etc.) affect the outputs which include the transport of soil in splash and flow. As there are many unseen interconnections of input factors and some apparently random effects within the "black box" and many different ways of measuring the outputs, a sound statistical approach to interpretation of the results of measurement has been appropriate. The theory developed in this study has brought out of the "black box" the mechanisms of transport by omnidirectional particle displacements. Through the precise definition of transport rates, and the specification of methods to measure these, the effect on measurement results of such ill-defined and dimensionally illogical quantities as "total movement", "net downslope movement" or "weight of soil transported" (see Figure 9.1) is removed. Removal of this configurational artefact from measurement means there is one less source of variation and thereby a decreased requirement for statistical analysis. The field measurements of splash transport in this study show variation between splash trap

Chapter 10

CONCLUSIONS

This study was undertaken in order to:

- develop a conceptual framework for the inter-rill transport process;
- analyse quantitatively the mechanics of the process;
- apply this analysis to inter-rill erosion measurement methods as a means of assessing the validity and utility of the methods;
- test those methods which can be shown analytically to provide valid estimates of inter-rill process rates.

The following conclusions have been made:

1. Inter-rill transport of soil by rainsplash and shallow drop-disturbed flow can be usefully represented as a system of drop impact induced particle displacements. In this system, the mass of particles displaced, *and* the magnitude and direction of particle displacements determine the rate of transport of soil particles.
2. Successful analysis of this system depends upon strict definitions, free of pedological or experimental connotations, of transport rate and detachment rate. The component transport rate in a particular direction should be defined as the mass per unit time, of soil particles with displacement components in that direction, crossing unit length of a line on the soil surface perpendicular to that direction. It has units $ML^{-1}T^{-1}$. The detachment rate should be defined as the mass, per unit time per unit area of soil surface, of soil particles being set in motion. It has units $ML^{-2}T^{-1}$.
3. The splash transport process is usefully conceptualised as a simplified representation that assumes radially uniform displacement of mass about each drop impact. Analysis of this representation shows that the component splash transport rate is a function of the detachment rate *and* the impact variables such as ejection velocity and splash angle that determine the magnitude and direction of particle displacement.

4. The full inter-rill transport process including splash and flow transport is usefully represented by a distribution function giving the disposition of mass of displaced soil particles about the drop impact point. The component inter-rill transport rate is readily expressed in terms of this function.

5. Applying the representations of the inter-rill transport given in 3 and 4 to measurement methods shows:

- a) a splash cup diameter as small as is practicable gives the best estimate of detachment rate;
- b) it is an inevitable consequence of the inter-rill transport process that the distribution of resultant transport rates on a section of soil surface is drastically altered when the section is held in isolation as in a laboratory soil tray. Despite this, the single boundary types 1 and 3 source/collecting area configurations have collecting rates that are directly related to the component transport rates that would apply *if the sections of soil were once more surrounded by a similar soil surface*. The configuration for total loss measurement from a soil tray does not have this desirable characteristic;
- c) it is likewise an unavoidable consequence of the inter-rill transport process that the resultant transport rates on a soil surface are distorted in the vicinity of a field splash trap that is acting as a sink for splashed material. The splash board and two types of splash trap developed in this study, the modified Bollinne trap and the pipe trap, have collecting rates that are equal to the component transport rate in the direction appropriate to the trap orientation;
- d) the resultant and component transport rates can be determined from post-event tracer distributions.

6. Testing of these measurement methods for splash transport in laboratory and field shows:

- a) a splash cup diameter as small as 3.1 cm can be used for detachment measurement. Kinetic energy/splash loss relationships are affected by the size of splash cup used.

- b) measurement of upslope and downslope component splash transport using a soil tray with a single boundary type 3 configuration at each end is no more difficult or time-consuming than total loss measurement. Comparison of slope/net downslope component splash transport relationships from this study with published slope/splash erosion relationships suggests the latter are subject to configurational artefact;
- c) measurement of component splash transport rates in the field is feasible using splash traps with vertical sampling apertures. Measurements with such traps show that wind and inclined rainfall have a significant effect on the resultant splash transport direction. Splash traps should therefore have a minimum effect on air flow over the plot and the pipe traps, due to their narrow section, meet this requirement;
- d) tracer measurements are unsuitable for continuous routine monitoring of inter-rill transport. Their freedom of boundary effects warrants their use in special cases as an absolute reference measurement.

The set of measurement techniques developed in this study enable the same strictly defined process rates to be measured regardless of whether the inter-rill erosion process is taking place under field or laboratory conditions. This is considered to represent a significant advance in the measurement technology available for use in soil erosion research and, it is hoped, might aid in the improvement of erosion prediction techniques. The inter-rill erosion concept and the methods of analysis developed in this study may be of use in such prediction techniques in enabling the conceptual framework to more closely match the realities of the process.

Chapter 11

LIST OF SYMBOLS

a	soil tray length
b	soil tray, splash trap width
c_i	collecting rates
$f(\theta)$	function describing the limit of splash about a drop impact
$f_t(\theta)$	function describing the limit of the post-event marked particle distribution
g	gravitational acceleration
i	drop impact frequency
j	dimensional restriction, source/collecting area configuration
k	dimensional restriction, source/collecting area configuration
ke	kinetic energy
m	mass displaced per drop impact
$m(r, \theta)$	mass distribution of splash about a drop impact
$ns_{\theta, \theta+\pi}$	net component inter-rill or splash transport rate in direction θ
p	perimeter length of soil tray
r	distance radially outwards from centre of cylindrical coordinates
r_i	a particular value of r
s	splash loss
s_{θ}	component inter-rill or splash transport rate in direction θ
$t_p(r, \theta)$	post-event mass distribution of marked particles about pre-event point placement
$t_b(x)$	post-event mass distribution of marked particles upslope and downslope of pre-event line placement
v	ejection velocity of splashed particles
w	rational substitution variable
x	independent variable, Cartesian coordinate system
y	dependent variable, Cartesian coordinate system
z	dependent variable, cylindrical coordinate system
B	$\frac{2v^2 \cos^2 \alpha \tan \alpha}{g}$, from range line equation
C	$\frac{2v^2 \cos^2 \alpha \tan \beta}{g}$, from range line equation

I_i	value of an integral
M	mass of splashed particles given by $m(r, \theta)$
P	proportion of total splash detachment lost from splash cup
R	radius of splash cup or splash funnel
S	resultant inter-rill or splash transport rate
T	mass of marked particles given by $t_p(r, \theta)$ or $t_b(x)$
V	drop fall velocity
α	splash angle
β	angle of slope of soil surface
θ	angular displacement of r in cylindrical coordinate system
θ_i	a particular value of θ
θ_c	critical value of θ , single boundary configuration

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APPENDIX 1

Daily rainfalls making up the erosion events monitored on the splash erosion plot at Newholme Field Laboratory. Rainfall figures are from the daily read rain gauge 200 m south-west of the plot.

Date	24 h rainfall (mm)	Erosion event number	Date	24 h rainfall (mm)	Erosion event number
22- 7-81	10.4	1	26-11-81	10.4	8
25- 7-81	19.8	2	30-11-81	0.6	9
27- 7-81	0.7		1-12-81	7.9	
			2-12-81	0.4	
29- 7-81	19.0	3	4-12-81	4.0	10
4- 8-81	4.5	4	14-12-81	11.2	11
9- 8-81	5.9		15-12-81	15.2	
10- 8-81	0.4		16-12-81	0.6	
13- 8-81	2.7		18-12-81	13.0	12
21- 8-81	4.2	5	20-12-81	8.2	13
26/27- 8-81	4.8		22-12-81	3.7	14
28- 8-81	7.2		24-12-81	20.0	
31- 8-81	0.4		25-12-81	9.4	
1- 9-81	0.7		26/27-12-81	3.0	
13- 9-81	2.4		8- 1-82	5.9	
21- 9-81	3.0		14- 1-82	11.6	
24- 9-81	2.4		15- 1-82	25.5	
25- 9-81	8.0		16- 1-82	6.0	
27- 9-81	32.5		17- 1-82	8.6	
28- 9-81	0.7		18- 1-82	1.1	
4-10-81	11.0		19- 1-82	1.5	
12-10-81	18.6		20- 1-82	5.0	
13-10-81	22.9		21- 1-82	4.8	
14-10-81	1.8		24- 1-82	9.2	15
16-10-81	0.6		27- 1-82	3.2	
18-10-81	10.2		1- 2-82	22.6	
19-10-81	18.7		2- 2-82	5.0	
20-10-81	1.5		5- 2-82	1.1	16
21-10-81	0.7		15- 2-82	6.7	
22-10-81	1.6		24- 2-82	14.1	17
23-10-81	0.9		25- 2-82	19.2	
10-11-81	1.1	6	28- 2-82	0.4	
11-11-81	2.7		1- 3-92	3.3	
13-11-81	1.9	7			
14-11-81	2.2				
20-11-81	4.9				
21-11-81	10.7				
22-11-81	3.7				

Date	24 h rainfall (mm)	Erosion event number	Date	24 h rainfall (mm)	Erosion event number
3- 3-82	8.2	18	30- 9-82	2.9	24
4- 3-82	23.0		1-10-82	0.6	
5- 3-82	9.6		10-10-82	50.2	
6- 3-82	1.7		11-10-82	14.4	
10- 3-82	26.3	19	12-10-82	10.2	25
11- 3-82	13.2		15-10-82	1.2	
12- 3-82	0.4		16-10-82	1.3	
13- 3-82	0.5		30-10-82	9.9	
14- 3-82	1.8		1-11-82	8.2	
15- 3-82	0.5		10-11-82	1.2	
16- 3-82	0.9	20	18-11-82	1.8	26
19- 3-82	1.7		2-12-82	1.4	
29- 3-82	1.6		3-12-82	3.0	
1- 4-82	0.6		4-12-82	2.5	
4- 4-82	0.6		13-12-82	1.8	
5- 4-82	11.4		15-12-82	1.4	
6- 4-82	0.8	21	16-12-82	8.4	27
27- 4-82	2.4		19-12-82	6.4	
6- 5-82	1.6		20-12-82	3.6	
9- 5-82	2.6		25-12-82	0.8	
30- 5-82	3.0		26-12-82	6.3	
31- 5-82	4.2		29-12-82	1.0	
1- 6-82	0.8	22	30-12-82	14.0	28
11- 6-82	5.0		31-12-82	11.0	
13- 6-82	4.0		1- 1-83	10.2	
15- 6-82	1.0		2- 1-83	2.0	
16- 6-82	0.5		3- 1-83	18.2	
21- 6-82	1.4				
22- 6-82	6.3	23			
15- 7-82	0.9				
16- 7-82	0.7				
19- 7-82	8.4				
20- 7-82	2.4				
25- 7-82	4.9				
17- 8-82	2.6	23			
18- 8-82	0.8				
19- 8-82	0.8				
9- 9-82	4.8				
19- 9-82	4.0				
20- 9-82	0.6				
21- 9-82	12.2				
22- 9-82	4.0				
23- 9-82	1.0				
24- 9-82	1.2				
27- 9-82	9.4				

APPENDIX 2

Splash trap catches (g) for erosion events numbers 1 to 28. The direction that the aperture or intercepting surface of the trap was facing is given in degrees east of north. Note that a trap aperture facing in direction θ is measuring the component splash transport rate per width of the trap in direction $\theta - 180^\circ$.

Erosion event number	Modified Bollinne array			Splash board array			
	Direction faced by aperture			Direction faced by intercepting surface			
	344.5°	224.5°	104.5°	344.5°	164.5°	254.5°	74.5°
1	1.24	1.78	0.45	1.52	1.33	1.66	0.55
2	10.11	23.66	2.02	18.21	13.96	33.35	2.69
3	3.90	10.63	0.86	7.93	6.56	11.81	1.32
4	5.31	2.94	2.98	3.04	1.79	2.83	2.23
5	79.69*	55.22	32.18	59.12	34.63	52.08	37.79
6	0.81	1.26	0.89	1.27	0.69	0.55	0.64
7	3.03	2.34	2.97	4.27	3.18	1.85	3.19
8	1.78	11.17	6.84	3.49	10.78	9.96	8.14
9	18.61	7.82	22.88	19.76	16.74	7.38	26.21
10	6.81	6.95	3.68	8.68	5.66	10.33	4.17
11	6.32	3.50	7.15	6.74	5.21	3.47	14.01
12	2.76	1.26	2.40	3.49	1.90	1.51	3.21
13	11.95	14.43	2.18	15.55	9.71	20.38	3.46
14	93.64	40.53	63.47	134.53	44.03	60.39	103.76
15	15.23	18.73	5.69	25.51	13.91	36.70	8.43
16	1.35	1.44	1.71	1.53	0.74	1.60†	0.81†
17	14.51	12.22	14.06	19.03	15.87	13.61	17.44
18	6.83	2.53	8.18	8.44	6.17	3.36	10.59
19	6.83	3.10	7.88	7.91	4.47	4.64	8.35
20	13.90	9.67	7.56	15.63	8.49	16.44	10.28
21	9.79	7.42	6.01	9.33	4.57	9.89	6.66
22	9.72	10.53	7.32	11.10	8.60	13.42	8.40
	Modified Bollline array			Splash trap array			
	344.5°	224.5°	104.5°	344.5°	164.5°	254.5°	75.5°
23	44.68	21.77	35.33	32.71	17.59	29.60	33.42
24	23.72	41.03	54.40	41.18†	24.64†	26.92†	37.51†
25	21.78	11.20	7.68	26.00	4.33	16.79	7.46
26	27.01	10.80	21.75	21.68	6.53	8.86	17.01
27	4.87	3.35	5.73	5.62	4.40	3.10	6.18
28	31.61	28.61	32.86	48.85*	26.81	38.97	41.62
	3 pipe trap array			4 pipe trap array			
	344.5°	224.5°	104.5°	344.5°	164.5°	254.5°	74.5°
23	4.37	3.05	2.87	3.31	1.92	3.17	2.75
24	4.45	2.33	6.30	3.71	4.39	2.41	5.67

... continued

Erosion event number	3 pipe trap array			4 pipe trap array			
	344.5°	224.5°	104.5°	344.5°	164.5°	254.5°	74.5°
25	3.53	1.85	0.71	2.60	0.71	2.09	0.98
26	2.25	1.35	1.69	1.96	1.26	1.61	1.79
27	1.04*	0.49	0.63	0.60	0.42	0.42	0.62
28	12.97*	4.53	3.30	4.16	4.27	3.51	4.05

* mass affected by runoff inflow.

† mass affected by accident in trap servicing.