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11.1. ANALYTICAL PROCEDURE.

During the 1959/60 and 1960/61 rainy seasons simultaneous measurements were made of various forms of erosion, using the methods described in Chapter 10, and of rainfall characteristics, using the methods described in Part II. In this period there were 77 rain showers, of which 62 were recorded separately, as sometimes there was insufficient time to change the apparatus between showers. In some cases data is missing from one or more of the recordings owing to electrical power failure in severe thunderstorms, or other mechanical or human faults. Showers when the total rain was less than 0.05 inches were excluded from the analysis. The net number of pairs of observations remaining for comparison is from 30-50 in most cases, and gives a good sample of all types of storms.

The analysis consisted of trial and error correlation between the recorded erosion and the rainfall parameters, but with emphasis on the search for causative relationships rather than purely statistical associations. For example, it is conceivable that in such a mass of data a mathematical association could occur between amount of erosion and wind velocity, but this would be meaningless unless it could also be shown that the wind caused the erosion. If the high winds were recorded in severe storms, such an association could easily occur, but the essential problem is what property of the storm caused the erosion?

In such analysis the question arises of what degree of correlation between two independent variables may be accepted as an adequate explanation of the relationship between them. In the present exercise the control conditions are progressively relaxed as additional variables are introduced, so the variation will tend to increase. No hard and fast rules may be laid down but it was considered that in the case of the splash cups, with strict control, a regression equation should account for at least 80% of the variation before it could be accepted as adequately explaining the relationship, i.e. in simple linear regressions the correlation coefficient should be better than 0.9. At the other end of the scale i.e. field plots with many variables, multiple regressions are to be expected, and one
which accounts for 50 - 60% of the variation would be satisfactory.

The procedure followed was to first plot the dependent variable, soil loss or run-off, against each of the possible rainfall parameters such as quantity of kinetic energy. Where associations occurred the least squares regression equation was calculated in the form

\[ Y \text{ (soil loss)} = a + b X_1 \]

After the main factor had been identified, if the residual variation was appreciable, secondary variables were tested in the forms

\[ Y = a + b X_1 X_2 \text{ or} \]
\[ Y = a + b X_1 + c X_2 \]

In numerical analysis, the methods of Snedecor (172) were used, and for multiple correlations the graphical methods of Ezekiel (173).

11.2. SAND SPLASH CUPS.

The weight of sand splashed out of the cups after each storm was corrected using the procedure established in Chapter 10, and plotted against all reasonable rainfall indices for the same storm. When the association was strong, least squares regressions were calculated and the correlation coefficients are shown in Table 11.1. This trial and error procedure was started at the end of the first season, and since a very positive result was obtained, the full mathematical analysis was only repeated after the second season using the best estimators.

The first index used, the total amount of rainfall in the storm, showed, as would obviously be expected, an association between heavy falls and high splash losses, but the correlation coefficient of the regression equation, \( r \), is only 0.75 which is low considering the precisely controlled conditions of the experiment.

The second storm characteristic selected was the total kinetic energy of the storm. This was computed for each storm by extracting from the intensity record the amounts of rain falling at various levels of intensity, and multiplying by appropriate values of 'kinetic energy per inch' from Fig. 8.19. The correlation is considerably improved with \( r = 0.856 \) showing that the total energy of the rain gives a much better measure of its ability to cause splash erosion than the quantity of rain does.

It is logical to expect that when rain falls at low rates, or with small drops of low terminal velocity, these drops would have insufficient energy to splash sand out of the cups. When observation confirmed this, a special series of tests were carried out to study this effect. Splash cups were exposed for 2 minute periods in low intensity rains with small drop sizes, and whenever the intensity
TABLE 11.1.

CORRELATION OF SAND SPLASH WITH RAINFALL CHARACTERISTICS.

\[ Y \text{ (sand splash in gms.)} = a + b X_n \]

<table>
<thead>
<tr>
<th>Independent Variable</th>
<th>Correlation coefficients ((p)).</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Present Experiments</td>
</tr>
<tr>
<td></td>
<td>(n = 20)</td>
</tr>
<tr>
<td>(X_1) TOTAL RAIN</td>
<td>0.750</td>
</tr>
<tr>
<td>(X_2) TOTAL K.E.</td>
<td>0.856</td>
</tr>
<tr>
<td>(X_3) K.E. &gt; 1</td>
<td>0.939</td>
</tr>
<tr>
<td>(X_4) K.E. &gt; 0.5</td>
<td>0.868</td>
</tr>
<tr>
<td>(X_5) K.E. &gt; 1.5</td>
<td>0.841</td>
</tr>
<tr>
<td>(X_6) RAIN &gt; 1</td>
<td>0.874</td>
</tr>
<tr>
<td>(X_7) K.E. &gt; 1 + WIND</td>
<td>0.955</td>
</tr>
<tr>
<td>(X_8) (K.E. &gt; 1) x (I_{15})</td>
<td>0.906</td>
</tr>
<tr>
<td>(X_9) (K.E. &gt; 1) x (I_{30})</td>
<td>0.926</td>
</tr>
<tr>
<td>(X_{10}) (K.E. &gt; 1) x (I_{60})</td>
<td>0.900</td>
</tr>
<tr>
<td>(X_{11}) (TOTAL K.E.) x (I_2)</td>
<td>0.895</td>
</tr>
<tr>
<td>(X_{12}) (TOTAL K.E.) x (I_3)</td>
<td>0.875</td>
</tr>
<tr>
<td>(X_{13}) (TOTAL K.E.) x (I_5)</td>
<td>0.861</td>
</tr>
</tbody>
</table>

Confidence limits of \(r\)

\[
\begin{align*}
  n = 20 & (0.854 < 0.939 < 0.975 (p = 0.05)) \\
  n = 31 & (0.87 < 0.939 < 0.981 (p = 0.01)) \\
  n = 59 & (0.891 < 0.958 < 0.964 (p = 0.01))
\end{align*}
\]

- \(I_{15}\) is 4 x the maximum amount of rain in any 15 minute period.
- \(I_{30}\) is 2 x the maximum amount of rain in any 30 minute period.
- \(I_{60}\) is 1 x the maximum amount of rain in any 60 minute period.

- \(I_2\) is the maximum intensity sustained for a period of 2 minutes.
- \(I_3\) is the maximum intensity sustained for a period of 3 minutes.
- \(I_5\) is the maximum intensity sustained for a period of 5 minutes.
remained constant throughout the exposure period the splash loss was measured. The results are shown in Fig. 11.1. and it is clear that although there is considerable scatter, the general effect is that there is a threshold level of intensity at which rain becomes erosive. The least squares regression is

\[ Y = 0.96 I - 0.02 \]

giving an average value of \( I = 0.85 \) at \( Y = 0 \), i.e. the critical level of intensity is 0.85 inches per hour. The scatter is to be expected because it was shown earlier that at low intensities there is considerable variation in drop size distribution and hence in kinetic energy. The intensity level dividing erosive and non-erosive rain will thus vary from storm to storm. It will also vary if the splash of different sands or soils is being measured, or if the surface conditions varied. Meteorological data on the quantity of rain at various intensities is recorded in the intensity classes: less than 0.1, 0.1 to 0.25, 0.25 to 0.5, 0.5 to 1.0, 1.0 to 2.0 and more than 2.0 inches per hour, so it would not be practical to use the figure 0.85 inches per hour. The rate of 1 inch/hour was provisionally selected and the kinetic energy computed of that amount of each storm which fell at intensities greater than 1.0 inches/hour. This gave a correlation coefficient of 0.939, showing that a good measure of ability to cause splash erosion is given by this parameter which for convenience in referring to it will be designated K.E. > 1. To check whether the arbitrary choice of 1.0 instead of 0.85 materially affects the accuracy, similar calculations were made using K.E. > 0.5 and K.E. > 1.5 i.e. ignoring the energy of the rain falling at less than 0.5 and 1.5 inches/hour respectively. For K.E. > 0.5 \( r = 0.868 \), and for K.E. > 1.5 \( r = 0.841 \) showing that the level of intensity selected as the threshold level is not very critical, and that 1.0 inches per hour is the best of those tested.

Although the idea of a threshold level, below which rain is not erosive, does not appear to have been previously investigated there is some confirmation from the work of Hann (202). When studying the effect of drops of various sizes, he deduced by extrapolation that drops smaller than 2 mm. diameter would not cause splash erosion. Rain composed entirely of drops of this size would have a kinetic energy of 535 ergs x 10^7/cm^2/inch, which is the energy corresponding to that of natural rain at 0.85 inches per hour. Undue importance should not be attached to the fact that this agrees precisely with the value obtained in the present experiments, because Hann's figure of 2 mm. diameter was only an estimate obtained by extrapolation, and drop sizes of 2.1 and 1.9 mm. diameter correspond to 1.0 and 0.7 inches/hour. The precise value of the threshold level of energy for given conditions is of less importance than the fact that the
FIG. 11.1. CRITICAL INTENSITY OF EROSIONAL RAIN.
association between energy and splash erosion is considerably more precise when the non-erosive part of the rain is excluded from the calculations.

The parameter $\text{K.E.} > 1$ thus gives a practical and accurate assessment of erosivity, and accounts for 88% of the variation in the regression equation, but before accepting this as the final answer some other possibilities should be explored.

Since ignoring the effect of the kinetic energy of rain which falls at intensities less than 1 inch per hour materially improves the correlation with splash loss, it is logical to apply the same argument to the quantities of rain. Using $X$ as the quantity of rain at intensities more than 1 inch per hour, $r = 0.874$. This is a considerable improvement on $r = 0.75$ for total rain, but significantly less than for $(\text{K.E.} > 1)$, and so confirms both that the rain at less than 1 inch per hour is ineffective, and that energy is a better measure than quantity.

When rain is accompanied by wind the terminal velocity is increased, and hence the kinetic energy also increased. A greater amount of sand will therefore be splashed out of the cups. To eliminate this variable factor in the comparison of splashed sand and kinetic energy, the measured values must be adjusted to a common condition. The mean angle of inclination of the rain was simultaneously measured as described in Chapter 6, so an adjustment may be made. The inclined rain has a terminal velocity which is greater than the still air velocity by the factor $\frac{1}{\cos \theta}$, where $\cos \theta$ is the angle of inclination with the vertical, and the kinetic energy is similarly greater by the factor $\frac{1}{\cos \theta}$. Applying this correction factor to the calculated values of $(\text{K.E.} > 1)$ for each storm, and computing the regression of splash loss on this value, the correlation coefficient is improved to $r = 0.955$. It was pointed out in Chapter 6 that this assessment of the wind effect is not very precise, as only the composite rain vector is determined by the three gauge instrument. In spite of this weakness, the partial elimination of variation due to wind does increase the efficiency of the estimator of erosivity.

There remains one further parameter which should be investigated because it has been found to be of importance in America. This is the so-called "30 minute intensity" or $I_{30}$ mentioned in Chapter 9. Although the parameter is quite empirical, there is good reason for predicting that under field conditions the correlation will be improved by the introduction of a second factor of this nature. The amount of soil splashed or detached will be determined by a function of energy, but how much of the splashed soil is washed away will depend on the volume or rate of surface run-off. A factor which provides some assessment of the run-off-producing capability of the storm may logically
be expected to improve the prediction of field erosion from rainfall data. In Wischmeier's studies in America all possible measures of the intensity/duration relationship were tested, and for the field scale erosion with which he was working, the $I_{50}$ index was found to improve considerably on the estimate based on energy values alone. At this stage of the present experiments, dealing with simple splash erosion, it is not expected that a run-off factor will be important, but in order to explore all possibilities, indices of the $I_{50}$ type were tested at all stages from splash only to field scale erosion. In the present experiments the maximum fell in any thirty minute period of each storm was calculated and converted to inches per hour. Similar expressions were also obtained for 15 and 60 minute periods, and the method was tested using $I_{15}$, $I_{30}$ and $I_{60}$ in turn as a multiplier of $(K.E. > 1)$. The respective correlation coefficients were $0.906$, $0.926$ and $0.900$. $I_{30}$ thus appears to be the best, but in all cases the correlation is reduced to less than that with $(K.E. > 1)$ alone. There is thus no advantage in introducing a run-off factor at this stage, but the method will be tested again when studying the soil losses measured in surface run-off.

A marked feature of the thunderstorm rain of Central Africa is the large variations in intensity over short time periods. It was considered possible that these variations were being masked by considering 15, 30 and 60 minute periods, and so another characteristic was tested - the maximum intensity sustained for periods of 2, 3 and 5 minutes. These were each combined with the total kinetic energy, but the correlation was not significantly better than with total kinetic energy alone, so this approach was not pursued with the more accurate estimators $(K.E. > 1)$ and $(K.E. > 1 + \text{wind})$.

All the previous calculations were carried out using the results of the first season only, and since it is very clear that the best estimators are $(K.E. > 1)$ and $(K.E. > 1 + \text{wind})$ the calculations were repeated on these, using additional data from the second year. The data and regression equations are tabulated in Appendix B, and shown in Fig. 11.2. The correlation is improved by the additional data in each case; for $(K.E. > 1)$ $r$ increases from $0.939$ to $0.958$, and for $(K.E. > 1 + \text{wind})$ from $0.955$ to $0.977$. The improved efficiency due to applying the wind correction is not quite significant at the 5% level when measured by the correlation coefficient, but it does reduce the positive intercept from 0.65 which is just significant, to 0.43 which is not. Since the regression on $(K.E. > 1)$ without the wind correction accounts for 92% of the variation, this is very satisfactory, and while recognising that there is a slight improvement when variations due to wind are adjusted, it would not be worthwhile to do so in practical calculations of erosivity. It was shown in Chapter 8 that both momentum and kinetic energy have very similar
FIG. 11.2 RELATION BETWEEN SPLASH EROSION & \( \sigma \).
relationships with intensity, and so momentum could equally well be used as the intermediate link to compute erosivity from intensity.

Free (176) also carried out some of these calculations on the data obtained from his soil pans, and the correlation coefficients are shown in Table 11.1. For those indices tested the pattern is very similar. The regression equations are not given by Free so it is not possible to test whether the correlation would have been improved by applying the concept of minimum energy values. Free also transposed his data to the logarithmic form and suggested that splash erosion was proportional to E.E. 0.9 for sand, and K.E. 1.45 for soil, but no arguments are given for preferring this form of relationship.

To summarise the results of this section, all rainfall characteristics which might be expected to influence splash erosion have been tested as estimators of erosivity. Several of these, alone and in combination, give good correlations (in fact all those described are statistically significant), and the test of those, which gives a very precise fit to the experimental data, is the kinetic energy of the rain at intensities heavier than one inch per hour. The next step is to test this when splash erosion is combined with surface flow.

11.3. SOIL TRAYS

The next stage in the progression from the particular to the general is to consider the soil and water losses from the miniature run-off plots or soil trays. It would theoretically be preferable to relax only one variable at a time i.e. to make only one change, but this would require an impractically large number of intermediate stages. In the soil trays there are in fact two variations. Firstly, soil is substituted for the standard sand, and secondly, the size of the test area is increased from 7 square inches to 420 square inches. The soil loss measured is a combination of splash erosion and transportation, in that the amount of soil loosened or detached will depend on erosivity while the amount of detached soil actually carried off will depend on the surface flow. The additional soil loss due to scour of the run-off water will be small in comparison with the detachment by splash erosion. This is logical from theoretical considerations of the energy values involved, as was discussed earlier, and also has been demonstrated in previous experiments. Free (150) found that the ratio of wash-off to splash varied between 1 to 50 and 1 to 90, and Mihara (21) describes splash as being "greater by two or more orders of magnitude". The object is to study the relation between the two processes and see whether they may be described quantitatively. The trays were exposed to storms simultaneously with the splash cups and rainfall studies, so the same rainfall parameters may be correlated with the soil and water losses.
11.3.1. Run-off from Soil Trays.

Since the soil moisture in the trays is held constant, the volume of run-off should be a linear function of the volume of rain. This prediction is confirmed by the data shown in Fig. 11.3, and giving the least squares regression.

\[ Y \text{ (run-off in inches)} = 0.78 \times Y \text{ (Rain in inches)} - 0.07 \]

The correlation is very good at \( r = 0.95 \), and both constants may be logically explained. The amount of run-off is less than the total rain because some rain is lost as surface splash and some is absorbed by the soil. The splash is naturally proportional to the amount of rain, hence the constant 0.78 i.e. 22% is lost as splash, 78% measured as run-off. The amount absorbed is independent of rainfall and an expected value may be calculated. The volume of soil above the water table is 0.25 cubic feet, and assuming a specific yield or macro-pore-space of 10% the volume of rain to fill this (i.e. to raise the soil from field capacity to saturation) is equivalent to a depth over the soil surface of 0.1 inch, which agrees very well with the value of 0.07 obtained experimentally.

11.3.2. Soil Loss from Soil Trays.

The next step is to see how the soil loss is influenced by the introduction of run-off as the transporting medium for the splashed soil. Following the sequence used in the analysis of splash erosion from the sand cups, linear regressions were calculated on the total amount of rain, and on the quantity of rain at intensities greater than one inch per hour (Table 11.2). For total rain the correlation coefficient is 0.790 (corresponding with 0.750 for splash only), and for \( (\text{Rain} > 1) \) \( r = 0.845 \) (corresponding with 0.856). The pattern is very similar, and a threshold between non-erosive and erosive rain is again demonstrated. Using the estimator total kinetic energy, \( r \) becomes 0.860, and for \( (\text{K.E.} > 1) \) \( r = 0.919 \). Clearly the amount of soil detached by splash action is still the primary factor controlling the amount of soil washed off.

It was suspected earlier that the value 1.0 inches/hour which was adopted as the threshold level at which rain becomes erosive may be on the high side as the experimental value was 0.85. If this is so there would be some contribution to erosion from that part of the rain falling at intensities of less than one inch per hour. To test this, multiple regressions were calculated of the form

\[ Y \text{ (soil loss)} = a + bX_1 + cX_2 \]

where \( X_1 \) is the main factor i.e. \( (\text{K.E.} > 1) \), and \( X_2 \) is a subsidiary factor related to the rain at less than one inch. Values tested as \( X_2 \) were the amount of such rain, the kinetic energy of such rain, and the amount as a percentage of the total rain. In none of these is the correlation significantly improved, confirming the hypothesis that this arbitrary choice of threshold value is not introducing any error.


**TABLE 11.2.**

**CORRELATION OF SOIL LOSS FROM SOIL TRANCHE WITH RAINFALL CHARACTERISTICS.**

\[ Y \text{ (soil loss in gms.)} = a + b X_n \]

<table>
<thead>
<tr>
<th>X</th>
<th>r (n = 29)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Rain ( X_1 )</td>
<td>0.790</td>
</tr>
<tr>
<td>Rain ( &gt; 1 ) ( X_2 )</td>
<td>0.845</td>
</tr>
<tr>
<td>Total K.E. ( X_3 )</td>
<td>0.860</td>
</tr>
<tr>
<td>K.E. ( &gt; 1 ) ( X_4 )</td>
<td>0.919</td>
</tr>
<tr>
<td>(K.E. ( &gt; 1 )) + wind ( X_5 )</td>
<td>0.891</td>
</tr>
<tr>
<td>(K.E. ( &gt; 1 )) ( x T_{30} )</td>
<td>0.867</td>
</tr>
</tbody>
</table>

Confidence limits of \( r \):

- \( n = 29 \)
  - \( 0.793 \pm 0.919 \rightarrow 0.970 \) (p = .01)
  - \( 0.833 \pm 0.919 \rightarrow 0.962 \) (p = .05)

**TABLE 11.1.**

**CORRELATION OF RUN-OFF FROM FIELD PLOT.**

\[ Y \text{ (Run-off in inches)} = bX + a \]

<table>
<thead>
<tr>
<th>X</th>
<th>Correlation Coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>( a ) For all storms where run-off occurred ( (n = 23) )</td>
<td></td>
</tr>
<tr>
<td>Total rain ( X_1 )</td>
<td>0.809</td>
</tr>
<tr>
<td>Rain ( &gt; 0.5 ) ( X_2 )</td>
<td>0.892</td>
</tr>
<tr>
<td>Rain ( &gt; 1.0 ) ( X_3 )</td>
<td>0.858</td>
</tr>
<tr>
<td>Rain ( &gt; 1.5 ) ( X_4 )</td>
<td>0.855</td>
</tr>
</tbody>
</table>

| \( b \) For storms when the ground was saturated at the beginning of the storm \( (n = 8) \) |
| Total rain \( X_0 \)   | 0.968                    |
| Rain \( > 0.5 \) \( X_6 \)| 0.981                    |
| Rain \( > 1.0 \) \( X_7 \)| 0.982                    |
| Rain \( > 1.5 \) \( X_8 \)| 0.975                    |
Next applying the correction which eliminates variation due to inclination of the rain caused by wind, this reduces the efficiency of the estimator at \( r = 0.891 \). The regression equations are

\[
Y = 0.612 X_1 + 22.96 \quad \text{and} \quad Y = 0.557 X_2 + 21.24
\]

where \( X_1 \) is \((K.E. > 1)\) without the wind correction and \( X_2 \) is with the wind correction. The data is tabulated in Appendix 9 and shown graphically in Fig. 11.4. The difference is not significant, and while it is not clear why eliminating the wind variable makes a slight improvement in the case of splash alone, and a slight deterioration in the case of splash plus wash, nevertheless the main conclusion is confirmed - that wind affects do not materially affect the erosivity.

The efficiency of the best estimator so far is slightly less \((r = 0.919)\) than for splash alone \((r = 0.977)\). This may be because the control conditions are less exact, or may indicate that there is a secondary influence at work which is related to surface flow. The introduction of the \( I_{30} \) index as a multiplier of \((K.E. > 1)\) reduces the efficiency \((r = 0.867)\) as it did for splash alone. Since the secondary influence (if it exists) is more probably related to surface flow than to the incident rainfall, it should be partly independent, and so a search was made for a secondary variable to apply to the model

\[
Y = a + b (K.E. > 1) + c X_n
\]

Eskial’s graphical method was used in which the possible secondary variables are plotted against \( y - \hat{y} \), the difference between the measured value and the value estimated from equation (1). An association between these departures and the values of any index shows that it is worth pursuing as a secondary variable. Factors tested in this way included the average energy of the storm, the average intensity, the 15, 30 and 60 minute ‘intensities’, the quantity of run-off, the percentage of run-off, the effect of proceeding rainfall, the proportion of erosive rain to total rain, the proportion of non-erosive rain to total rain, and several combinations of these factors. In none of these cases was there any indication that the regression on \((K.E. > 1)\) would be improved by the introduction of a second factor.

The conclusion is that for the miniature run-off plots the amount of total erosion is mainly determined by the splash erosion, which is in turn determined by the kinetic energy of the rain. The detailed study of the subsidiary influences of run-off is better pursued at the next stage which is consideration of the soil and water losses from field size run-off plots.

11.4 FIELD SCALE PLOT.

At the next stage in the sequence there are again two changes in the control conditions. The plot used was much larger (approximately 450 square feet), and the water content of the soil was not controlled.
FIG. 11.4. RELATION BETWEEN EROSION FROM SOIL TRAYS & (K.E. $> 1$).

$Y = 0.62X + 22.9$
The length of the plot was the same as that of the field scale plots used for crop experiments, that is the distance between conventional contour ridges on this soil type and slope, (in this case 90 feet), so no extrapolation is required to apply the results to farmed land. The soil was similar to that of the run-off trays, with an initially loose surface, later compacted by the rain, and kept free from vegetation. In the absence of any moisture control the soil dried out between storms to a varying degree depending on the amount of rain and the intervals between storms.

11.4.1 Run-off Losses from Field Scale Plots.

The first step was to test the direct correlation between run-off and quantity of rain on each of the days when run-off occurred (Table 11.1). At $r = 0.809$ there were obviously other factors which should be considered. Some of the rain will infiltrate into the soil during each storm, and the correlation was tested ignoring the rain below various intensity levels. In each case the correlation was improved, the best ($r = 0.892$) being total rain at intensities greater than 0.5 inches per hour. This implied that the average rate of infiltration is 0.5 inches/hour, but sufficient variation remains to show that this is not the whole explanation. When similar tests were made on those run-offs which occurred immediately after a run-off producing storm, i.e. those when the soil was saturated or nearly so, the correlation was very good with all values of $r$ better than 0.968. This confirms the expectation that the unaccounted variation in run-off is due to the varying degree of saturation when different time intervals occurred between rains. Several simple measures of this factor were tested, such as whether rain fell on the preceding day, or days, and the total amount falling on the preceding day, two days, three days etc., but the inclusion of these did not materially reduce the variation, and a more precise measure of the moisture status was evidently required. Several methods have been developed by hydrologists for calculating an "antecedent soil moisture index" (A.S.M.) from rainfall records (Hartman et al. 203, Thames and Ureio 204). The procedure used in this case uses the features from several methods. The basic principle is to carry a running total of rainfall to date, with amounts subtracted to allow for evaporation and transpiration between rains. When this index rises above a certain level, run-off should occur, and the amount of run-off is a function of the surplus, or the rise above this level. The method requires the selection of three variables: the critical level above which run-off will occur, corresponding to soil saturation; the shape of the depletion curve for evapotranspiration losses between rains; and the proportion of the surplus which becomes run-off.
The shape of the best depletion curve depends largely upon the type of vegetation. With a heavy growth the transpiration will be more important than evaporation, and a nearly constant rate of depletion is suitable, with an initial loss due to interception. In this case, with bare ground, only evaporation occurs, and the evaporation from an initially saturated surface will decrease rapidly after a day or two. The evaporation curve which by trial and error was found to be most suitable is shown in Fig. 11.5, and using this to estimate losses between rains, the critical level of A.S.M. at which run-off occurs is 200 (units are hundredths of an inch). The calculated index of moisture is plotted throughout the season in Fig. 11.6. After each run-off the index starts again at 200. Although this method is somewhat empirical it is evidently very accurate since there is only one case where run-off occurs and is not predicted, one case where run-off is predicted but does not occur, and in the other twenty-two cases run-off occurs when predicted from the A.S.M. index.

To estimate the quantity of run-off the least squares regression was calculated (Appendix 10) of the recorded amount of run-off on the 'surplus' i.e. the value of A.S.M. minus 200. The equation is

\[ Y = 0.61X - 0.04 \] (inches)

The 'b' value is naturally lower, as there is more infiltration on the large plots than on the small ones with a water table just below the surface. The small intercepts are not statistically significant in either case. The high correlation (r = 0.948) shows that using this method a very good estimate may be made from rainfall records of both when run-off would occur, and the quantity. The amounts of run-off predicted by applying this equation are also tabulated in Appendix 10 and shown graphically in Fig. 11.7, in comparison with the recorded values. was tested

As an entirely independent check the method using the data of the first part of the 1961/62 season. The running plot of the soil moisture index is shown in Fig. 11.8, and the comparison of actual run-off and predicted run-off in Fig. 11.9. There are discrepancies for first few weeks of the season when predicted run-off did not occur, but this was due to the plot having been cultivated just before the rains, and the loose surface texture allowed abnormally high infiltration rates. Once the surface had been compacted again the predicted run-off agreed well with the actual run-off. On all 17 occasions when run-off is predicted, it did occur, and the total amounts are 4.64 inches actual and 3.84 inches estimated. From this additional data (Appendix 11) the regression of run-off on A.S.M. surplus is
FIG. 11.5. DEPLETION CURVE FOR ANTECEDENT SOIL MOISTURE INDEX (A.S.M.)
FIG. 11.7. PREDICTED AND ACTUAL RUN-OFF 1960/61.
FIG. 11.9. PREDICTED AND ACTUAL RUN-OFF 1961/62.
which agrees very well with the previous year's
\[ Y = 0.61 X - 0.04 \text{ (inches)} \quad (r = 0.948) \]
The equation from the pooled data of both years is
\[ Y = 0.61 X - 0.02 \text{ (inches)} \quad (r = 0.948) \]
When sufficient information is available to determine a
suitable moisture depletion curve, and to establish the relation between
surplus and run-off, the method allows fairly accurate estimation of both
occurrence and quantity of surface run-off from rainfall records.

11.4.2. Soil loss from Field Scale Plot.
As it has been shown both in the case of pure splash, and
for combined splash and wash-off erosion on the small soil trays, that
the main factor controlling erosion is the parameter \((K.E. > 1)\), this
is the obvious starting point for analysing the soil loss from the
field plot. The data is plotted in Fig. 11.10. and gives the least
squares regression
\[ Y = 0.083 X - 2.6 \quad (r = 0.943) \]
where \(Y\) is the soil loss in lb., and \(X\) is \((K.E. > 1)\) in ergs \(x 10^3/cm^2\).
The correlation is so good that this relationship is sufficiently
precise to estimate soil loss, but again the possibility of improvement
from subsidiary variables was considered. Variables closely related
to energy, and so tested as multipliers, were \(E\), the total rain, the
amount of rain at intensities greater than one inch per hour, and the
duration of the storm, but none of these improved the correlation.

It was found in the previous section that run-off was influenced not
only by the amount of rain, but also by the preceding rainfall, and so
as run-off is to some extent independent of the rain in a particular
storm, it was combined in a multiple regression of the form
\[ Y (soil loss) = f (energy) + f (run-off) \]
Listing variations from the regression equation on \((K.E. > 1)\)
against quantity of run-off, and against average rate of run-off, both
showed a positive association, suggesting that either might be useful
as the secondary variable. Eichel's graphical method of successive
approximations \((17)\) was used to obtain a correction term for both
factors. These are shown in Figs. 11.11. and 11.12. and are of very
similar form. The nature of the correction is quite logical.
When the quantity of run-off, or average rate of run-off, is small,
al the soil detached during the storm is not transported, giving
low recorded values of soil loss. When the volume, or rate, is high,
the run-off acts as an eroding agent and picks up extra soil as well
as that detached by the splash process. Either quantity or average
rate of run-off is equally efficient as an estimator of this secondary
Fig. 11.11. Soil loss correction for run-off rate.

Fig. 11.12. Soil loss correction for run-off amount.
effect. When allowance is made for the run-off effect, the regressions (Fig. 11.1) and Appendix I) become:

\[ Y_1 = 0.0775 - 1.0 \quad (r = 0.973) \quad \text{(run-off quantity)} \]

\[ Y_2 = 0.0774 - 0.1 \quad (r = 0.982) \quad \text{(run-off rate)} \]

The differences are not significant and both give a very satisfactory explanation of the relationship. For the conditions of these experiments, this method of introducing an allowance for the secondary effects of run-off is evidently more suitable than empirical multipliers like Wischmeier's "T" index.

An interesting variation of the run-off effect during the 1961/62 season. During unusually heavy November rains, a miniature gully formed on the bare plot (Plate 11.1). This concentrated the run-off water, and increased its velocity and scouring action. The secondary effect of the additional soil loss caused by scour was thus more important than when the run-off was in the form of sheet flow in previous years. However, the main relationship between soil loss and (K.E. > 1) was still dominant.

The conclusion is that soil loss from the field plot is very largely determined by the (K.E. > 1) factor, with a secondary variable, of minor importance, which depends upon the physical conditions controlling surface flow. This secondary variable only has a significant effect in the cases a) when there is so little surface flow that the detached soil is not all transported, and b) when the surface flow is canalized by surface conditions so that it has appreciable scouring action.

11.5. THE "DESIGN STORM" FOR A RAINFALL SIMULATOR.

The possibility was discussed earlier of establishing a "design storm" for a rainfall simulator by determining the type of rainfall which, in the long term, causes most erosion. A tentative solution to this problem is shown in Fig. 11.14. A linear relation has been established between erosivity per unit rainfall and the energy parameter (K.E. > 1). (Fig. A from Figs. 11.2 and 11.10.) The relation between (K.E. > 1) and intensity rises rapidly to approximately 3 inches/hour and then levels off. (Fig. B from Fig. 8.19.) The relationship of erosivity per unit rainfall to intensity therefore has the same form (Fig. C). Rainfall records show that the relation between quantity of rain and intensity is of the form shown in Fig. D. Combining Figures C and D gives the total erosion for any given intensity (Fig. E). At low intensity the increase in (K.E. > 1) is greater than the decrease in quantity of rain, so the product E x Q increases. At high intensities the opposite occurs and E x Q decreases. The peak of E x Q determines the critical level of intensity at which most erosion occurs. The exact value depends upon the shape of Fig. B, and may vary slightly, but it will be close to the point at which the (K.E. > 1)/intensity relationship changes, i.e.
FIG. 11.13. RELATION BETWEEN SOIL LOSS FROM FIELD PLOT (WITH CORRECTIONS FOR RUN-OFF) AND \( K.E. > 1 \).

\[
Y_1 = 0.077 X - 1.0
\]

\[
Y_2 = 0.0774 X - 0.1
\]
Plate 11.1. The bare soil plot of the mosquito gauge experiment. (Plot 20, Experiment 1/3). The small gully formed during November 1961, after considerable erosion in the previous eight seasons. The soil level is about 6 inches below the original level.
**FIG. 11.14. INTENSITY FOR GREATEST EROSIVITY.**

- **Intensity 0-3 in/hr.**
  
  \[ E = a I^b \quad (b \approx 0.3) \]
  
  \[ Q = c I^d \quad (d \approx 0.15) \]
  
  \[ E \times Q = c I^e \quad (e \approx 0.15) \]

- **Intensity > 3 in/hr.**
  
  \[ E = p - q \frac{dE}{dI} \quad \alpha \frac{-1}{I^2} \]
  
  \[ Q = \frac{dQ}{dI} \quad \alpha \frac{-1}{I^e} \]

\[ E \times Q \text{ increasing with } I \]

\[ E \times Q \text{ decreasing with } I \]
about 3 inches/hour (Fig. 8.10).

11.6. **Summary.**

The sequence of analyses has shown that working progressively from the simplest case of sand splash to that of soil loss on a field scale, the mechanical process is essentially the same. The effect described variously as the raindrop impact effect, splash erosion, or particle detachment is the primary agent in the erosion process, - primary both in time and in importance. The extent to which rainfall has the power to cause this effect is defined as the erosivity of the rain, and may be quantitatively estimated from a function of the kinetic energy of the rain. This is a major step forward and means that the amount of erosion can also be estimated from rainfall data, once the relationship is established between this potential ability to cause erosion, and the actual erosion which occurs for a particular set of soil conditions or soil erosibility.

Expressed mathematically, it has now been shown that

\[ \text{Erosion} = b (\text{K.E.} > 1) + a \]

and the a and b constants have been evaluated for each of the set soil conditions in the analytical experiments. As these conditions range from simple splash to field erosion it is highly probable (though not yet conclusively proven) that the form of the equation will apply to all conditions, that is all erosibilities. But the constants will be different for every set of soil conditions, and the quantity of erosion caused by a given erosive power will vary for different soil types, slopes, or vegetative covers.

In Part IV this information forms the basis for the design of an artificial rain making device which will allow the assessment of any erosibility under suitable constant erosivity. In Part V the information is applied to some of the results from the field scale experimental plots to estimate the erosibility of practical soil and crop conditions.
PART IV. RAINFALL SIMULATORS.

CHAPTER 12.

REVIEW OF PREVIOUS RAINFALL SIMULATORS.

12.1. HISTORICAL DEVELOPMENT.

At an early stage in the history of erosion and run-off research, it was appreciated that the results of field experiments could and should be augmented and amplified by studies using artificial rain, either in the field or in the laboratory. Since the early nineteen thirties many types have been developed and constructed, and although the literature contains more references to the design and operation of simulators than to results obtained from their use, nevertheless several machines have been successfully used for various specific purposes. The early interest in simulators arose from their potential use as infiltrometers, i.e. to study water intake rates, rather than to measure soil loss. Early types of infiltrometer measured the intake of water enclosed in an open-ended cylinder pressed into the soil surface. (Musgrave 205; Musgrave and Free 206). Refinements of this technique included the use of an outer cylinder to provide a buffer area (Nelson and Muckenhurn 207), devices to maintain a constant shallow head of water, and a metered water supply (Cox 208). This method is still widely used for practical field tests of infiltration rates for irrigation studies (Haise et al. 209). Realising that standing water with an appreciable head is an artificial condition, Pearse and Bertleson (210) applied the water in the form of a thin laminar flow at the top edge of a small sloping plot and measured the run-off in a collecting device at the lower edge. However, unless the water is applied as falling drops the effects of soil structure degeneration and surface sealing are not included, and only comparative infiltration rates may be obtained. In addition Free (211) and Hendrickson (212) showed that the turbid water from natural or simulated rain has much lower infiltration rates than the clear water normally used in ring infiltrometers. The next stage in the development of infiltrometers was therefore to apply the water as simulated rainfall, and after this had been done it was realised that such a device could equally well be used to measure soil erosion effects. The United States Soil Conservation Service and
Forest Service developed a number of spraying type simulators during the nineteen thirties. Some of these aimed at putting down known quantities of water, others controlled both quantity and intensity, and this led to discussions of the relative merits (Kohnke 21) and the first comparative tests in 1940 by Laws (13). Realising that the size and velocity of the drops has a profound influence on splash erosion, Laws went on to his classic studies of drop velocity (39) and of drop size distribution (119). Using this knowledge of the characteristics of natural rain, V.D. Young designed the Type F nozzle (Wilm 214) which was used extensively for many years, and only superseded a few years ago by the Meyer simulator (121, 215, 216, 217) which is based not only on suitable drop size and velocity, but also on erosive power.

Parallel with this development of spraying type simulators, mainly for field use, several other methods were introduced, usually for laboratory studies, or for a specialised purpose such as rapid field tests of relative soil erodibility. In the present investigation the object is to apply the new knowledge of subtropical rainfall to design a general purpose field simulator for local use, (the design requirements are given in Chapter 1)), but since design features of any simulator may be applicable to those requirements, it is convenient to review the more important earlier types according to the method of drop production rather than by considering their purpose.

12.2. SIMULATORS WITH INDIVIDUAL DROP FORMATION.

12.2.1. Thread Dropers.

The rainfall applicator of Ellison and Pomerene (218) was designed initially for laboratory studies on the nature of splash erosion, and enabled Ellison to carry out his pioneer studies in this field (14). Water was allowed to drip (later sprayed) onto a screen of open-mesh wire netting covered with muslin. At each pocket where the muslin was fastened into the wire mesh a length of cotton yarn was fastened underneath so that the water seeping through the muslin formed drops which fell from the yarn. Various thicknesses of yarn, wool, and other threads, were used to give different drop sizes, and the whole apparatus could be suspended from the laboratory ceiling at any chosen height. To give a suitable distribution of rain on the soil samples at floor level, the drop-forming tray was vibrated by a motor-driven rocker. This fairly successful design was also used by Woodburn (196) in laboratory studies of the effect of soil structure on splash erosion, and
by Goodman (219) to test the effect of chemical soil conditioners. A larger machine using this method of drop formation to rain onto soil tanks of 1/1,000 acre was used by Banu, Puranik and Ballal (220, 221), in India. Although Ellison's first simulator was designed for laboratory studies he later (217) designed a larger version mounted on a truck for field use. A telescopic frame carried the shower head and gave a drop fall of about 15 feet, and the rain could be applied to a plot 5 feet square. This design was successfully used in Texas to test both erosion and infiltration (Ellison 222; Sreenivas et al. 223). Osborne (224) obtained new data on ground cover with an improved version of the apparatus, also in Texas, and this same model was later transferred to Wyoming for infiltration studies of forest lands. (Hunt and Zingg 225; Barnes and Costel 226).

The main disadvantage of this apparatus, and indeed of any system which depends only on gravity to give the drops velocity, is that it is seldom practical to use heights of fall of the order of 25 feet, as is necessary to achieve the terminal velocity of natural raindrops. A second problem with field instruments is that screens must be provided to avoid interference by wind.

21.2.2. Nozzle Dropers.

As an alternative to forming drops on hanging threads, many workers have used small diameter tubes or nozzles from which individual drops of constant size are produced. The simplest variation consists merely of allowing single drops to fall from a burette, as used by McCalla (227) and Rei et al. (228) in laboratory tests of structure. Large drops of the order of 5 or 6 mm. diameter are formed and usually fall only a few feet. Vilensky (229) used a combination of tests to assess credibility using both single drops and a spray to measure aggregate breakdown. To measure the breakdown of structure under conditions approaching those of tropical rainfall, Pereira (230) required a high impact effect, and allowed drops of 6 mm. diameter to fall through 2 metres onto soil samples, assuming that extra large drops achieving 50% of their terminal velocity would have an effect comparable to smaller drops falling at terminal velocity. Ten jets, made from thick walled capillary tubing, applied rain at the rate of 6 inches/hour for ten minutes to small test cylinders a few inches across. A very similar principle was used by Adams (231, 232) for a portable simulator designed for field tests of soil erodibility in the undisturbed state. In this instrument one hundred nozzles in the shower head gave drops of 5,5 mm diameter from glass capillary
tubes in which a fine wire was inserted to give better control of drop size. The height of fall was only about 1 metre so that each drop had a kinetic energy equal to that of a drop of 3.44 mm diameter falling at terminal velocity. Two inches of rain were applied at the rate of four inches per hour to test areas 6 inches in diameter. A multiple nozzle dropper giving fairly uniform drops between 2.5 and 3.5 mm. diameter has been used recently in Russia (Sumash 23) on plots of several square feet (0.6 sq. metres), to provide comparative information on infiltration, permeability and run-off.

Wishing to have a range of drop sizes, as occurs in natural rain, van Heerden (20) used a combination of drawn out glass tubing and hypodermic needles in a laboratory simulator for tests on disturbed soil samples 6 inches x 3 inches, following the design of Ekern (65,202). Van Heerden used various combinations of nozzles to provide different intensities, and used a height of fall of 29 feet. The shower head was oscillated by pulling on ropes to give a changing drop distribution pattern. This problem of achieving uniform distribution from a fixed shower head onto a number of replicated samples was overcome by McIntyre in Australia (175, 197), and Rose (19) in Uganda, by mounting the soil samples on a revolving table under a stationary shower head. McIntyre used 5 mm drops falling a short distance; Rose, by using different sized nozzles of glass and plastic capillary tubing, was able to vary drop size and intensity as well as height of fall up to a maximum of 20 feet.

The disadvantage of all these instruments is that they substitute large drops at low velocities for the natural rainfall conditions of drops of various sizes all at terminal velocity. The same kinetic energy may be achieved, and several of the machines were specifically designed to do this, but it has only been established that splash erosion of soil is proportional to kinetic energy within the range of natural rain conditions. It is true that Ekern (65) extended this relationship beyond the range of natural drop sizes in the case of sand, but many workers, particularly Rose and McIntyre, have shown that the splash action on an aggregated soil with particles of various size is a very complicated process not capable of simple analysis. There is thus no evidence that the action of natural rain on a natural soil can be exactly duplicated by unnaturally large drops at unnaturally low velocities. Indeed it is unlikely that this relationship between kinetic energy and splash erosion will hold at all levels. Consider the extreme cases of 0.5 mm. drops travelling at 117 metres/second, and 10 mm.
drops travelling at 1.3 metres/second. Both have the same kinetic energy as a 3 mm. rain drop at its terminal velocity of 8 metres per second, but the momentum is very different and it is unlikely that they would have the same effect when striking a natural soil. Some of the laboratory simulators described above are perfectly adequate for comparative tests of specific soil properties, but it is preferable that a simulator which is to be used for tests of soils in natural conditions should reproduce as closely as possible all the relevant features of natural rain, including drop size and velocity.

12.3. SPRAY SIMULATORS.

The first attempts to reproduce falling rain on field plots used commercial sprinkler irrigation nozzles. Lowdermilk (234) and Nichols and Sexton (235) sprinkled field plots of 1/1,000 acres from pipelines surrounding the plots and fitted with "Skimmer" nozzles every foot. High pressures were used, resulting in fine droplets, and although these experiments demonstrated previously unknown results, such as the beneficial effects of surface mulch, the results were rather variable. At the other extreme Duley (236, 237) used unnaturally large drops from hand-held watering cans. Believing that suitable drop size and velocity would not be achieved by hit and miss trials, the American Soil Conservation Service started in 1936 a methodical programme of testing existing nozzles. This programme produced several simulators which were developed to the stage of field testing.

The first of these was the Type D-1 (Blaisdell 238) which used a commercial irrigation nozzle (Lown 239) and was used for field experiments in the late 1930's (Boutner et al 240). This was shortly followed by the Type E (Borst and Woodburn 241, 11), which was a fairly large apparatus requiring five man days to assemble, and applied rain on plots 72 inches by 6 feet in studies of the effect of land slope.

The Type F was, as mentioned earlier, the first simulator based on the drop size distribution of natural rain (Wilm 214). The basic principle was a battery of fixed Type F nozzles spaced evenly along each side of the plot, mounted a few feet above the ground and spraying upwards for an additional 7 feet, so that the total drop fall was about ten feet. High pressures of the order of 20 - 30 p.s.i. were used. Although standard specifications for use were issued by the Soil Conservation Service (241), the numerous investigators using this type of apparatus appear to have followed their own inclinations as to size and shape of plot, length of application and so on. Successful studies of infiltration characteristics were carried out on the soils of South Carolina by Peelo and others (243) and of Utah by Woodward (244). The instrument was also used by the Bureau of Reclamation (245).
and the Forest Service (246). It was used by Immard and Augustine (247) on an impervious plot to study the mechanics of run-off in regard to time of concentration and surface detention, and by Sharp and Holton to develop methods of graphical analysis of hydrographs both from small plots (248, 249) and from small watersheds (250). All of these studies were concerned primarily with relative infiltration, and the instrument does not appear to have produced much information on rates of soil loss.

The standard Type F apparatus, using a large number of nozzles, and plots up to 24 feet x 6 feet, was rather cumbersome to transport and erect, and several scaled-down variations were produced using the same type F nozzles and smaller plots. The Type FA of the Soil Conservation Service used three nozzles and a plot 12 inches by 30 inches. (Diebold 251, 252; Reid 253) and was really the substitution of Type F nozzles for fog nozzles in the earlier North Fork simulator of the Forest Service (Rowe 254). The North Fork machine put down high intensities of up to 12 inches per hour on plots 12 inches x 30 inches but with very small drops. Other variations were the Rocky Mountain infiltrometer (Dortignac 255, 256) which also used three Type F nozzles on a plot 12 inches by 30 inches, and the Intermountain infiltrometer (Packer 257), in which two banks of seven Type F nozzles sprayed onto an area of 9 square feet, within which were fitted three plots, each 2 feet by 6 feet, allowing simultaneous replication.

Among other systems worthy of note are those of Hendrickson (212), who sprayed muddy water in order to assess the sealing effects of the suspended material present in run-off from arable lands, and of Kennedy (258) who introduced a novel idea for plot boundaries on large but temporary plots. A tractor-drawn mouldboard plough carried a roll of cotton belting which was fed from a roll into the plough furrow so that the lower half of the belting was buried. The upper half was supported on stakes. The intention was to avoid the insertion by hand of the conventional plot boundaries of wood or metal strips. This operation is normally very tedious and time consuming when large plots are involved, or large numbers of replications with small plots, but no reports are known of the successful application of Kennedy's method.

A technique used to apply water to large plots is to have pipes running the full length of the plot, with spraying nozzles at set intervals, and to distribute the water across the plot by rotating the whole pipe, as is sometimes done in commercial irrigation systems. This method was used in the laboratory by Neal (161) on plots 12 feet by 3.63 feet by 2 feet deep with pipes raised
4 feet above ground level so that the total drop fall was 8 feet, and very similar apparatus was used ten years later by Woodruff (259). The idea of oscillating pipes has also been applied to field plots by Craddock and Pearsam (260), who used 1/200 acre plots (33 feet by 6.6 feet) on very steep slopes. In all of these only the average intensity was controlled, and drops were small from high pressure nozzles. More recently the method of rotating pipes was used by Weeks and Colter (261), with better nozzles, to test the effect of chemical soil conditioners upon soil aggregate stability.

Few machines are reported which are able to apply simulated rain over large areas. Kringleid and Shakori (262) used commercial irrigation sprinklers of the "Rainbird" type to apply rain to areas of several acres, but were primarily concerned with the design of contour ridges rather than with soil effects, so even distribution within the plot was not essential. The most efficient and most recently designed simulator, that of Meyer (215), is constructed in units each covering an area 15 feet by 18 feet, but up to twelve units may be operated together so that they cover a total area of 75 feet by 36 feet. This was a design requirement of this apparatus, so that it could be used on large permanent run-off plots, of which there are very many in the United States, but even although the machine was built for maximum portability it requires a 22 foot flat-bed trailer to transport it. Since in Africa the number of permanent plots is not sufficient to warrant a simulator designed to operate on them, and since transportability to areas with poor roads is a major requirement, the Meyer simulator does not fulfill local needs, but as it is the product of very careful and detailed research it is worth considering in some detail. After extensive tests of many types of nozzle, Meyer selected one, available commercially, which gives a flat fan distribution and a suitable drop size distribution at low pressure. Since the rate of application was far in excess of precipitation rates, intermittent spraying was necessary, and since the application was highly localised, movement of the nozzles was necessary. Also, to eliminate weak distribution at the fan edges, the sprays had to overlap. These difficulties were all overcome, and the apparatus consisted of an overhead framework carrying carriage which traversed the plot with reciprocal motion. The nozzles sprayed directly downwards to achieve suitable velocities, and intermittent spraying was controlled by solenoid valves, with intensity adjusted by the period of spraying. No wind shielding was required at wind velocities of up to 10 m.p.h. A petrol engine provided power for the carriage movement, a powered irrigation pump was required for the water supply.
and 12 volt accumulators provided for the electric circuits. The kinetic energy of the artificial rain was approximately 537 ergs x 10^3/cm^2/inch of rain applied. This is about 75% of the value of natural rain at 1/4 inches per hour (the intensity used for most tests). In brief, this simulator is excellent for the conditions it was designed to meet, but it is too big, complicated, and cumbersome, to comply with the present specifications.

12.4. COMPARATIVE TESTS OF SIMULATORS AND OPERATING TECHNIQUES.

Few studies are reported in which results from rainfall simulators are critically and quantitatively compared with results under natural rain conditions, and it remains to be seen to what extent absolute measurements may be made. This will probably be established by the use of Meyer's simulator on permanent run-off plots which have many years' records. However, Adams, Pereira, Rose, and many others, have shown that good comparative assessments of soil structure and credibility are obtainable from both laboratory and field studies. Similarly, infiltration properties have been qualitatively assessed by Maugrave (205), Reid and Love (251), Peale and Beals (263) and others, with the results confirmed by independent measurements using other techniques. The only known report of serious incompatibility of results from a simulator with those from natural rain is that of Woodburn and Kossolyn (198), but Rose (19) has shown that this might easily be accounted for by errors in experimental techniques.

Turning to comparative tests of different types of simulators, Law's tests of early nozzle types (13) led to the design of the Type F. As soon as several models using Type F nozzles were in use, Wilm (264) carried out a critical comparison of three of them, the Type F, Rocky Mountain and North Fork, in comparison with the Pearson "square foot" flow infiltrimeter (210). From careful statistical analysis of a large number of tests, Wilm concluded that differences in true infiltration at different sampling sites accounted for more variation than errors due to the instruments or operation, and that all the machines tested could give satisfactory estimates of relative infiltration rates. He also found that it was important to maintain accurate control of variables such as intensity and initial moisture, or where control is not practical, to record all data on such factors, so that by analysis the errors so introduced may be reduced.
Another subject which has aroused considerable discussion is the effect of the size of test plot, and this is associated with the question of whether a buffer area is desirable round the plot. With flooding type infiltrometers there is obviously a danger that without a buffer strip some of the water will spread out in a cone below the surface into drier surrounding areas. Dudley and Domingo (265) showed that the intake on non-buffered plots could be as much as 75% higher than on buffered plots, but felt that given adequate buffering small plots would give results as satisfactory as those from large plots. Marshall and Stirk (266), reviewing opinion on the subject, quote several other workers who supported buffer areas, (Kashinsky 267, 268; Mungrove 269; Cox 208). Others felt that adequate comparative results could be obtained without them (Lewis 270; Penneyfather 271; Burghy and Luthin 272). To resolve the question of plot size and buffer areas, Marshall and Stirk carried out tests with both flood and spray application of water, each with and without buffer areas. Their conclusions were that without buffer zones, the minimum infiltration rate decreased as plot size increased, but that a correction could be applied based on the amount of water retained below the plot after completion of the test - in effect by measuring the loss due to lateral movement. Since this involves extensive soil sampling it would be inconvenient to apply. They found buffer zones round flooded plots reduced lateral movement, but were inconvenient, and did not reduce the variation between tests - i.e. just as many replications were required. However, with sprayed plots a buffer zone was simple to apply, reduced lateral movement, and improved the consistency of the results. Difficulties were only likely to arise in soils with pronounced soil layers of varying permeability. Small sprayed plots with adequate buffer areas were as effective as large sprayed plots, and gave the least variation of all the combinations.

Two features of operating technique are the measurement of the rainfall applied and the initial moisture conditions. Some small simulators have had a collecting pan which was placed over the whole of the test area, so that intensity could be measured before and after the test run. This obviously does not allow for variation during the run, nor is it desirable to interrupt the run for spot checks. The better system is one which allows continuous sampling. The Rocky Mountain infiltrometer had a battery of twelve one inch diameter raingages spaced over the \( z \) square feet plot, and they were suspended from wires on a frame, so that using two interchangeable sets an almost continuous sampling was possible during consecutive five or ten minute periods. This also allowed
checks of distribution over the plot. Truly continuous sampling was achieved in the Type F infiltrometer by narrow trough rain-gauges extending the length of the test plot on either side. The disadvantage of this method, that different intensities in the centre of the plot will not be recorded, is overcome in the Meyer simulator by having the trough collector diagonally across the plot. This appears to be the best solution although a point which appears to have been overlooked is that the troughs must be designed to eliminate splash. Meyer's troughs of 1 inch aluminium channel must allow considerable losses from splashing drops, and a section similar to that of a tropical-type rain gauge would seem to be required, i.e. 4 inch vertical sides above a 90° V.

The second point, that is the best initial moisture content of the soil, is not in dispute. All the comparative tests on this question show that variation between replicated test runs is materially reduced by some degree of pre-wetting. Two common procedures are to saturate the soil 24 hours before the test, which then takes place at something like field capacity, or alternatively to apply a given quantity at a fixed time before the test e.g. 1 inch at 4 inches per hour, four hours before the test (Wilm 264). As Pawirm has shown (230) that few soil techniques developed for the soils of temperate climates are suitable for tropical soils, the question of the best pre-wetting technique for Central African soils must certainly be established locally.
CHAPTER 13.

DESIGN OF A NEW RAINFALL SIMULATOR.

13.1. INTENDED USES.

The object of designing a simulator for use in Central Africa has been briefly mentioned earlier, and the design requirements should now be considered in detail before describing the development of an instrument which satisfies these requirements. It is the intention that the machine will be used mainly in the field, as studies on disturbed soil samples are usually less satisfactory, and the major use will be to determine, on as quantitative a basis as possible,

a) the relative erodibility of various soil types,
b) the effects of different cultural, rotational, and tillage operations on the erodibility of individual soil types.
c) It is anticipated that a simulator that can satisfy these requirements by reproducing as accurately as possible the characteristics of sub-tropical rainfall will also at the same time provide information on the infiltration capacities of the soils being tested.

13.2. SPECIFICATIONS.

1. Since it has been established that the erosivity of natural rain is a function of kinetic energy, the simulated rain must reproduce as closely as possible the kinetic energy of natural rain.

2. The kinetic energy should correspond to the type of rain causing most erosion - that is an intensity of about 3"/hour.

3. Since the relationship between erosivity and kinetic energy has only been established within the limits of drop size and velocity occurring in natural rain, the simulated rain must also reproduce these as closely as possible.

4. If the primary requirements of 1, 2 and 3 above cannot be achieved at a continuous intensity of 3 inches/hour, intermittent application will be required to reduce the average intensity to 3 inches/hour, but the application should be as near
continuous as possible, (It is most probable that drop size and velocity of natural rain at 3 inches/hour can only be achieved artificially at higher rates of intensity.)

5. The artificial rain should be as uniform as possible over the test plot in regard to drop size, velocity, kinetic energy, and intensity.

6. Since for maximum utilisation several instruments will be required, they must be reproducible in standard form.

7. Since the machine will be used in remote and inaccessible areas, it must be as light as possible, and capable of easy erection and assembly.

8. Since water may not be readily available at some sites, the instrument must use small test plots.

9. Since it may be operated in remote areas by non-specialist or unqualified operators, the design must be as simple, robust, and reliable, as possible.

10. For operation in remote areas it must be provided with its own independent source of any power required.

Summarising these points,

1) The rain should be uniform, and have the drop size, velocity, and kinetic energy, of natural rain at 3 inches/hour.

2) The apparatus must be small, light, portable, simple, robust, reliable, and self-sufficient in power.

13.3. DESIGN.

The design of the instrument involved a great deal of trial and error experimentation, and included many trials of methods and ideas which were found to be impracticable or in conflict with some part of the design specification. To detail all the cul-de-sacs partly explored, but later abandoned, would serve little purpose, and instead only the positive steps which led to an adequate design will be described.

13.3.1. Method of Drop Application.

As the heights necessary for drops to achieve velocities approaching terminal values are impracticable in the field, gravity droppers are excluded, and some type of pressure spray directed downwards will be used. Exploratory tests showed that irrespective of the operating pressure or type of nozzle, drops of 4 - 5 mm diameter can only be produced from nozzles having quite large orifices or jet openings, and that such nozzles pass such large quantities of water that very high intensities of rain are produced. This means that
some form of intermittent application is required. This conclusion is confirmed by the work of Meyer (121). Three methods of achieving this are possible: rotary movement of the nozzle, reciprocating movement of the nozzle, and intermittent flow through a stationary nozzle. The method of rotary movement of the nozzle was selected on the grounds of simplicity, and was found to be successful. The rain applicator consists essentially of a commercial rotary lawn sprayer turned upside down, so that the spray has a downward initial velocity before accelerating under gravity, and the lateral component of velocity gives a reaction which drives the nozzle arm round. Since nozzles giving suitable drop sizes give excessive intensities, a single nozzle was used instead of the standard form of one at each end of the rotating arm.

13.3.2 Type of Nozzle.

Several previous workers have carried out extensive tests of commercially available nozzles, particularly Blaisdell (238) and Meyer (121), but in both cases the drop size distribution of the selected nozzle did not follow that of natural rain as closely as desirable, the usual difficulty being the lack of large drops in the range 4.0 - 6.0 mm. diameter. In the present investigation tests of many commercial nozzles gave the same result, and eventually a simple nozzle was designed which can be made cheaply and simply in any workshop. This nozzle is made from a short length of \( \frac{1}{2} \) inch diameter brass rod, and some of the main variations tested are shown in Fig. 13.1. A water jet, passing through an axial \( \frac{1}{2} \) inch hole, impinges on a flat machined face and spreads out in a flat fan. Various angles were tested (numbers 1 and 2 on Fig. 13.1.), and 45° was found to give the best results. Recessing the milled face beyond the axial hole (No. 3) caused a rough uneven edge on the fan, a chamfer as in No. 4 had no effect. The addition of a \( \frac{1}{2} \) inch gap (No. 5), before the jet impinges on the flat face, gave a smoother more uniform spread, and this design was selected.

13.4 Testing.

13.4.1 Variable Operating Conditions.

Fig. 13.2 shows how the nozzle was mounted on the arm of the rotary spray so that adjustments of several variables could be made. The variable quantities, any of which could affect some aspect of the rain produced are:

1) operating pressure,
2) height of fall,
3) speed of revolution,
4) test area receiving rain,
5) setting angles  $\theta$ and $\phi$.

$\theta$ is the angle of twist in the plane D-D about the axis A-A.

To test all combinations of these variables in a factorial design would be impracticable, so a suitable range of values was established for each, in a progressive series of tests.

13.4.2. Measurements during Tests.

The testing consisted of measurements, during ten minute runs, of

a) intensity of rain,
b) drop size,
c) erosivity, and
d) uniformity.

The target was a 6 ft. square shallow metal tray on the laboratory floor, which could be centred exactly under the rotating spray, and on which were marked radial lines with fixed positions numbered 0 to 7 at six inch increments along each radius. (Plate 13.1.)

a) Intensity.

Intensity was measured by recording the volume of water caught in glass jars of approximately 3 inches diameter, placed at each position along the marked radial line. The volume in cc. caught in 10 minutes divided by 18.4 gives the intensity in inches per hour. When the distribution is not uniform the average intensity is computed by weighting the intensity recorded for each annular segment according to its area. For example, a large variation in intensity at the central position has little effect on the average intensity over the whole area as the area of the central 6 inch diameter circle is only 0.6% of the whole area, but the area of the outer annulus from radius 3'3" to 3'9" is 25% of the whole, so a suitable distribution there is much more important. The test results show both the actual amount of rain at each position, and then the weighted average amount over progressively increasing areas.

b) Drop Size and Distribution.

Drop size was measured by the flour pellet technique described in Chapter 5, and using the calculation procedure of Chapter 8. Flour pans were exposed briefly at several different radial positions while using each of the various possible nozzle pressures. The pellets were dried and sieved, and the mass (volume) of water in each of ten drop diameter size classes was calculated. This information was plotted as a cumulative percentage curve, from which was read off the increments for class intervals of 0.25 mm. diameter. This gives a 24 step
Measuring the distribution of both quantity of artificial rain, and its erosivity.

A test rig for measuring the effect of alternative heights.

A test rig for trying out alternative nozzles and spraying heads.
The distribution curves for a given nozzle pressure vary slightly at different radial distances as shown in Fig. 13.3, so to get a composite picture of the overall effect, averages were calculated for each pressure, weighted according to area covered, as in the case of intensity. The result is shown in Fig. 13.4. This shows that at all the tested pressures, the drop sizes produced all fall within the range of natural rain, and that all the drop sizes of natural rain are included, except that at 5 p.s.i. the largest drops of 5.4 - 6.0 mm. diameter are missing. In the extremely low size range, the fact that drops up to 0.25 mm. diameter are not produced by the nozzle is irrelevant, as these contribute nothing to erosivity, and negligible quantities to volume. (In fact it is quite possible that some of these minute drops are produced, but not recorded, because the pellets pass through the smallest sieve used.) At any of these pressures the drop sizes are therefore acceptable because they conform to the range of sizes occurring in natural rain. At pressures around 5 p.s.i. the concentration of 1.5 - 2.5 mm. diameter drops is greater than is desirable, and at 3 p.s.i. the distribution is closest to that of 3 inches/hour rain. In the 2 p.s.i. range there is an unduly large concentration of larger drops, (3.5 - 5.5 mm. diameter), but since the general tendency of all artificial rains in exploratory trials and other simulators has been unduly low values of erosivity, it is probable that this oversizing of drops will be helpful in giving suitable erosivity. If the design requirements of drop size distribution and erosivity are incompatible, the requirement of suitable erosivity is over-riding, provided that the range of drop sizes agrees with the range of natural drop sizes.

c) Erosivity.

Erosivity was measured using the standard splash cups technique described in Chapter 11. The splash cups were placed at radial positions corresponding to those used for the intensity jars, but on a different radius so that there would be no interference.

To determine average splash rates, a weighted average was computed, allowing for the different areas represented, as in the case of intensity and drop size distribution. The calculation of the required erosivity at various intensities is shown in Table 13.1.

13.4.1. Control and Effect of Variables.

Preliminary tests showed that, as anticipated, the adjusted variables have interacting and sometimes conflicting effects, but the main results of each were established.

1) Pressure. Water pressure was controlled by adjustment of gate
FIG. 12. DROPP SIZE DISTRIBUTION AT VARIOUS PRESSURES - AVERAGE OVER WHOLE TEST AREA.
### Table 11.1. Calculation of Design Intensity and Erosivity.

<table>
<thead>
<tr>
<th></th>
<th>Intensity (ins/hr.)</th>
<th>Energy/Inch (ergs x 10^3 per cm²)</th>
<th>Rain in 10 mins. (ins.)</th>
<th>Energy in 10 mins. (ergs x 10^3/cm²)</th>
<th>Corrected splash in 10 mins. (gms.)</th>
<th>Rain in measuring jars in 10 mins. (cc)</th>
<th>Corrected Erosivity (gms/100 cc)</th>
<th>Measured splash in 10 mins. (gms)</th>
<th>Measured Erosivity (gms/100 cc)</th>
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**Notes.**
- Col. 2 from Fig. 8.19
- Col. 6 is Col. 3 x 110.4 (vol. in cc of 1 inch in jar 2.95 ins. dia.)
- Col. 7 is (Col. 5 + Col. 6) x 100
- Col. 8 from Col. 5 and Fig. 10.9.
- Col. 9 is (Col. 8 + Col. 6) x 100
- The erosivity in Col. 7 could also be derived from the equations:
  - Splash loss (gms x 10) = 0.156 K.E. + 4.3 (Eq. 11.2)
  - Kinetic Energy (ergs x 10^3/cm²/inch = 758.52 - 227.51 (Eq. 8.7)
which combine to give:
  - Erosivity (splash loss in gms/100 cc) = 11.17 - 2.15

The slight differences between values from this expression and those of Column 7 are due to the fact that equation 8.7 is an approximation of the energy/intensity relationship in Fig. 8.19.
valves from a high pressure mains supply, and measured on a pressure
gauge mounted immediately above the spraying head. Increase of
pressure, with other factors constant, causes a smaller median drop
size, and hence a lower erosivity, and a greater volume of water,
hence a higher intensity. The drop size distribution tests indicate
that the possible range is 0 - 5 p.s.i., with 2 - 3 p.s.i. as preferred
values.

2) **Height of Fall.** An angle-iron framework allowed the spraying head
to be raised or lowered from 0 - 16 feet. Increased height of fall
causes a greater impact velocity, and hence greater erosivity.
Since the drops fall in a parabolic arc, they cover a larger area
when falling from a greater height, but this effect is slight above
about 6 feet, as they are then falling almost vertically. The probable
range is thus from 6 feet upwards.

3) **Speed of Revolution.** To very speed of revolution for a given water
pressure, the wind resistance of a flat plate of thin sheet metal was
varied by rotating it about the vertical axis C - C (Fig. 13.2.). This
was merely a testing device, and a desired speed of rotation would be
achieved on a practical model by selecting a value of the radius arm R
to give the necessary torque. In the test model, R was adjustable
from 4 - 8 inches through the sliding fit of two concentric tubes. The
downward component of velocity is not influenced by speed of revolution,
but the not horizontal component is the initial speed of the water
leaving the jet minus the velocity of the jet. When the rotary
movement was reduced, independent of pressure, the drops sprayed out
farther and covered a larger test area. However, very low rotary speeds
gave less even distribution, as the total application consisted of a
small number of heavy bursts of rain. The range for further detailed
testing was found to be from 15 - 45 R.P.M.

4) **Test Area.** Measurements were taken over a test area of 7 feet
diameter, and the measurements relative to any smaller area could be
selected. Increasing the area rained on reduced the average intensity,
and the average erosivity, but the critical factor of erosivity per
unit quantity of rain was not affected. Areas of the order of 3 - 7
feet diameter appeared most suitable. Distribution over the small
central area is usually erratic, and so this area should be a small
proportion of the total area.

5) **Setting Angles of Nozzles.** The angle \( \beta \) (see Fig. 13.2.) is
slightly greater than 45\(^\circ\), so that the fan of rain is nearly vertical.
The fan bends back slightly below the flat face of the nozzle ( \( \alpha \) in
Fig. 13.2.) so 45\(^\circ\) would give a fan with an outward inclination of a
few degrees. As the nozzle is mounted at a radial distance of from
4 - 8 inches, the angle \( \gamma \), necessary to bring the fan back to the
centre of the test area, is \( \tan \frac{\gamma}{H} = \frac{R}{H} \) where R is the radial distance
(4 - 6 inches) and \( R \) is the height of fall.

Thus \( \phi = 45^\circ + x + \beta \)

\( \beta \) ranges from \( 1^\circ - 4^\circ \) for possible values of \( R \) and \( H \), and \( x \) varies from \( 2^\circ - 3^\circ \) with variations in pressure. The selected value of \( 50^\circ \) for \( \phi \) was found to be suitable for all ranges, and was accepted as a final value, with no subsequent adjustments.

Adjustments to the angle \( \theta \) were made by rotating the entire nozzle about the horizontal axis \( A - A \) and locking it in selected positions. Increasing the angle \( \theta \) has the effect of directing the water fan farther out in a radial direction, thus increasing the wetted test area, but it also increases the torque due to the jet's reaction, and so increases the speed of revolution. Exploratory tests showed that the value of \( \theta \) was not very critical and that the optimum range was \( 20^\circ - 40^\circ \). The problem of exact reproduction of many simulators will be easily overcome by using an assembly jig to locate the components precisely.

13.4.4. Test Results and Conclusions.

The results of the main sequence of tests which led to the progressive narrowing of the permissible range of each variable, and to the selection of the final design, are shown in Tables 13.2 - 13.4. Only those tests which led to positive improvements have been included, as no useful purpose would be served by including the mass of detail from tests which were merely repetitions, or which included values of variables which were later found to be out of the question. The positions 0 to 7 of the splash cans and the jars for measuring intensity are increasing multiples of 6 inches from the centre of the test area. The amount of rain is recorded as the volume in cc., caught during a ten minute test, and the design figure aimed for is 3 inches/hour or 55.4 cc.

The splash is the weight in grams of oven dry sand lost from standard splash cups in 10 minutes with the correction applied as developed in Chapter 10 (Figs. 10.8. and 10.9.). The design figure is 11 gm. measured (7.1 gm. corrected) which is the splash caused by the kinetic energy of \( \frac{1}{2} \) inch of rain (10 minutes) at an intensity of 1 inches per hour as computed in Table 13.1. Comparable figures for other intensities would be 7.8 gm. (measured) at 2 inches/hour, and 8.4 gm. (measured) at 4 inches/hour - all for ten minutes duration.

The erosivity is the sand splashed in gms. per 100 cc. of rain and the design figure is 20 gm. (measured). This figure is only slightly influenced by intensity as shown in Table 13.1. The weighted
### Table 13.2.

**Simulator Test Data (First Series)**

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<th>Height (Feet)</th>
<th>Pressure (psi)</th>
<th>R.P.M.</th>
<th>Radial Position (x 6 Inches)</th>
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<td>5) 6.8</td>
<td>7.0</td>
<td>8.0</td>
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<td>12</td>
<td>8 2 19 20</td>
<td>1) 10 235</td>
<td>160</td>
<td>180</td>
<td>90</td>
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<td>2) 2.1</td>
<td>19.0</td>
<td>15.1</td>
<td>8.8</td>
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<td></td>
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<td>3) 0.9</td>
<td>10.5</td>
<td>21.1</td>
<td>27.6</td>
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<td>4) 10 202</td>
<td>178</td>
<td>143</td>
<td>112</td>
<td>112</td>
<td>88</td>
<td>69</td>
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</tr>
<tr>
<td></td>
<td></td>
<td>5) 0.9</td>
<td>8.1</td>
<td>14.6</td>
<td>15.8</td>
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</tr>
</tbody>
</table>

**Notes:**

- **Horizontal rows:**
  1. Amount of rain (cc)
  2. Measured splash (gm)
  3. Measured erosivity (gm/100 cc.)
  4. Weighted average amount of rain over whole area up to each radial position
  5. Similar weighted average erosivity

**Design Figures:**

- 55.4
- 11.0
- 20.0
- 55.4
- 11.0
averages are calculated over progressively increasing areas when individual values are weighted according to the areas of bands of 6 inch width. Since the area of each band is a function of the mean radius, the weights correspond to the position numbers, except for the central circle which has a weight value of 1/6.

From the results of tests 5 - 8 (Table 13.2.) it appeared that

1) There is a marked decrease in erosivity as the pressure increases. This is to be expected in view of the smaller drop sizes at higher pressures, as established in the drop size measurements.

2) Even at the lowest pressure (2 p.s.i.) the erosivity is too low (Test 5), but as it is improved by the increase in height (Test 6), even more height is indicated.

3) There is too much concentration of rain in the inner part, with intensities too high at the centre, too low at the outside. This improved by greater height (comparing tests 5 and 6) and possibly by lower rotation speed (Tests 6 and 7).

The next group of tests 8 - 12 therefore used low pressures at 8 ft. Alternative values of the angle \( \theta \) were compared.

1) Changes of angle \( \theta \) have little effect on erosivity, but 30° gives more suitable (lower) intensities and better distribution. If this trend continues 35° or 40° would be better still.

2) The increased height reduces the intensity and improves the distribution but both effects should go further. The erosivity is increased, for the first time to values above those of the design figure but the distribution is poor, possibly due to the low speed of revolution (Test 12).

This led to Tests 13 - 17 using heights of 10 and 12 feet, and pressures of 1\( \frac{1}{2} \) and 2\( \frac{1}{2} \) p.s.i. The results (Table 13.3.) show that 12 feet and 1\( \frac{1}{2} \) p.s.i. (Test 15) gives the result very close to the design requirements. Tests 18 - 23 were then made to see whether the same result could be achieved using 2 p.s.i. instead of 1\( \frac{1}{2} \) p.s.i. at slightly lower rotation speed, and to test the similarity between duplicate runs. The duplicate runs agree reasonably, but the 45 R.P.M. raises the average intensity too much (because less of the drops are thrown out beyond position 7), and so the erosivity is too low. Even at the lower speed the erosivity is on the low side. Obviously the requirement is either still more height or the pressure below 2 p.s.i. The practical difficulties of working in the field with heights greater than 12 feet will obviously be considerable, so further tests were made at 1\( \frac{1}{2} \) p.s.i. (Tests 24 and 25). This design was accepted as the best possible combination of the variables and the results of the three runs are shown in Table 13.4.
### Table 13.1

**Simulator Test Data (Second Series)**

<table>
<thead>
<tr>
<th>Height (feet)</th>
<th>Pressure (p.s.i.)</th>
<th>Radial Position (x 6 inches)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>0</td>
</tr>
<tr>
<td>13 10</td>
<td>1.5</td>
<td>25</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>14 10</td>
<td>1.5</td>
<td>25</td>
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<tr>
<td></td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>15 12</td>
<td>1.5</td>
<td>25</td>
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<tr>
<td></td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>16 12</td>
<td>2</td>
<td>35</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>17 12</td>
<td>2</td>
<td>35</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>18 12</td>
<td>2</td>
<td>34</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1</td>
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<tr>
<td>19 12</td>
<td>2</td>
<td>32</td>
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<td></td>
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<td>1</td>
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<tr>
<td>Mean of 18</td>
<td></td>
<td>38</td>
</tr>
<tr>
<td>and 19</td>
<td></td>
<td>2</td>
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<td>21 12</td>
<td>4</td>
<td>44</td>
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<td>1</td>
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<tr>
<td>Mean of 21</td>
<td></td>
<td>94</td>
</tr>
<tr>
<td>and 22</td>
<td></td>
<td>2</td>
</tr>
</tbody>
</table>

**Notes:**

- **Horizontal Rows:**
  1. Amount of rain (cc)
  2. Measured splash (gm)
  3. Measured erosivity (gm/100cc)
  4. Weighted average amount of rain over whole area up to each radial position
  5. Similar weighted average erosivity

**Design Figures:**

- 55.4
- 11.0
- 20.0
- 55.4
- 11.0
### Table 3.4

**TEST DATA OF FINAL DESIGN.**

Height 12 ft.  Pressure 1.5 p.s.i.  $\theta$ 35°  R.P.M. 22-24

<table>
<thead>
<tr>
<th>Rainfall Position</th>
<th>TEST 0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Amount of rain (cc in 10 mins)</td>
<td>15</td>
<td>15</td>
<td>15</td>
<td>15</td>
<td>15</td>
<td>15</td>
<td>15</td>
<td>15</td>
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<tr>
<td>24</td>
<td>10</td>
<td>32</td>
<td>48</td>
<td>40</td>
<td>42</td>
<td>64</td>
<td>72</td>
<td>50</td>
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<tr>
<td>25</td>
<td>10</td>
<td>30</td>
<td>38</td>
<td>40</td>
<td>64</td>
<td>72</td>
<td>46</td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>11.7</td>
<td>11.3</td>
<td>12.0</td>
<td>11.7</td>
<td>14.0</td>
<td>16.7</td>
<td>16.0</td>
<td>17.0</td>
</tr>
<tr>
<td>2. Mean intensity (ins/hr)</td>
<td>0.66</td>
<td>1.73</td>
<td>2.61</td>
<td>2.87</td>
<td>2.39</td>
<td>3.67</td>
<td>3.70</td>
<td>2.56</td>
</tr>
<tr>
<td>3. Average amounts of increasing areas</td>
<td>15</td>
<td>15</td>
<td>15</td>
<td>15</td>
<td>15</td>
<td>15</td>
<td>15</td>
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<tr>
<td>Mean</td>
<td>11.7</td>
<td>11.3</td>
<td>12.0</td>
<td>11.7</td>
<td>14.0</td>
<td>16.7</td>
<td>16.0</td>
<td>17.0</td>
</tr>
<tr>
<td>4. Mean of intensity over increasing areas</td>
<td>0.66</td>
<td>1.52</td>
<td>2.13</td>
<td>2.16</td>
<td>2.27</td>
<td>2.74</td>
<td>2.97</td>
<td>2.91</td>
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<tr>
<td>7. Amount of splash (gm. in 10 mins)</td>
<td>15</td>
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<tr>
<td>8. Erosivity (splash/100 cc)</td>
<td>15</td>
<td>-</td>
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<td>-</td>
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<td>-</td>
<td>-</td>
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<td></td>
</tr>
<tr>
<td>9. Average erosivity over increasing areas (gms/100 cc)</td>
<td>15</td>
<td>-</td>
<td>-</td>
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<td>Mean</td>
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</tr>
</tbody>
</table>

Required design figures:

1) Amount of Rain 55.4 cc.
2) Intensity 3 inches/hour
7) Amount of splash (measured) 11.0 gm.
8) Erosivity (measured splash per 100 cc.) 20 gm.
13.5. **Assessment of Final Design.**

The next questions are "Over what test area will the best results be obtained?" and "Over this best area have the design specifications been adequately met?" The best area may be determined from Fig. 13.5, which presents graphically the data of lines 4 and 9 of Table 13.4. The range 5.5 feet to 7.5 feet diameter is clearly the optimum, and has average intensity and average erosivity of the order of 97 - 99% and 89 - 90% of the respective design figures. From 4.5 - 5.5 feet diameter the values are 91% and 83%, and the conclusion is that 6 or 7 feet diameter test areas will be best, but could be reduced to 4.5 feet, if convenience of operation offsets the slight reduction in efficiency. Field tests will be required to establish the optimum within this range, and also whether circular or square plots are most convenient.

Considering whether the design specifications have been adequately met,

1. **Kinetic Energy.** The simulator gives a very satisfactory reproduction of kinetic energy of 3 inch/hour rain, averaging 92% of the required erosivity over the test plot. The question of uniformity of distribution will be considered later.

2. **Drop Size.** The distribution of drop sizes does not exactly follow that of 3 inch/hour rain, in that a greater number of large drops is produced, but this is inevitable if the primary requirement of kinetic energy is to be met without impractically large heights of fall. The present drop size distribution is acceptable in that it includes all, and only, the size range of natural rain.

3. **Velocity.** The impact velocity of the drops of various sizes could only be determined precisely by high speed photography, but approximate values may be calculated. At 1.5 - 2 p.s.i., the drops leave the nozzle with sufficient velocity to rise vertically about 2.75 feet when the spray is directed vertically upwards. Neglecting the effect of air resistance, this means an initial velocity of \( \frac{2gh}{2} \) or 13 feet per second. In the spraying position some drops are projected vertically downwards on the inside edge of the fan, some in the middle of the fan at 35° (8) from the vertical, and the drops on the outer edge at 70° from the vertical. The vertical component of initial velocity will thus be

- at the inside edge: 13 feet per second
- at the centre: 13 cos 35° or 10.7 feet/sec
- at the outer edge: 13 cos 70° or 4.5 feet per second

To this is added the velocity due to acceleration under gravity during the fall of 12 feet. This may be read off directly from data curves of Laws (39) for drops of various sizes and the results are shown in
FIG. 13.5: EFFECT OF SIZE OF TEST AREA.
Table 13.5. There is a small outward component of velocity at the point of impact so the actual velocity, not quite vertical, is only slightly less than terminal velocity. This is compensated by the slight excess of 4 - 5 mm. drops (Fig. 13.4.), so that the total kinetic energy is very close to that of natural rain.

4. Frequency of Application. It has been necessary to invoke the condition that the intensity of 3 inches/hour may be achieved by intermittent application. The proportion of the time during which rain is actually landing on the target decreases as the radial distance increases, but at 20 or 25 R.P.M. the separate applications of rain are at the rate of one per 2.4 - 3 seconds. Changes in the soil water relations at the surface are unlikely to occur in this time, i.e. soil particles are unlikely to slake, and puddles of standing water unlikely to infiltrate appreciably, so this method of application may be assumed to have an effect comparable to continuous application.

5. Mechanical Specifications. Improvements in design and assembly for further field testing will be discussed later, but it is already clear that the mechanical requirements have been very adequately met. The shower head consists of readily available standard parts and a purpose-made nozzle which can be made easily. Accurate reproduction of many instruments can be easily arranged. The apparatus is extremely light and robust, and the only parts subject to wear are easily interchangeable. The apparatus is light, portable and easily erected. It uses small quantities of water, and the only power required is to provide a 15 foot head of water.

6. Uniformity of Application. The only requirement not fully met is uniformity of application over the test area. Both the quantity of rain and the average power per unit quantity of rain vary considerably over the test plot. The extremely low application on the central area of 1 foot diameter may be ignored as this constitutes a negligible portion of the total area, but beyond this the quantity and erosivity up to 4'6" diameter are too low, the outer part up to 6'0" diameter has values too high, and finally the extreme edge (Position 7 or up to 7 feet diameter) is slightly below average. It is impracticable to improve on this distribution as changes in any of the variable adjustments introduce other more undesirable characteristics. It is suggested that in fact this lack of uniformity is not at all important. Practical field tests will consist not of a measure of erosion under uniform rain, but a composite measure of erosion under slightly different rainfall intensities. As there is unlikely to be an interaction between the soil characteristics under investigation and erosivity (within the range provided by the simulator, which is still relatively small),
### TABLE 13.5.

**DROP VELOCITIES IN RAIN SIMULATOR.**

<table>
<thead>
<tr>
<th>Initial Vertical Velo (ft/sec)</th>
<th>1.0 mm</th>
<th>2.0 mm</th>
<th>3.0 mm</th>
<th>4.0 mm</th>
<th>5.0 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outer edge</td>
<td>4.5</td>
<td>14.2</td>
<td>19.0</td>
<td>22.0</td>
<td>23.8</td>
</tr>
<tr>
<td>Centre</td>
<td>10.7</td>
<td>14.2</td>
<td>19.5</td>
<td>22.5</td>
<td>24.7</td>
</tr>
<tr>
<td>Inner edge</td>
<td>13.0</td>
<td>14.2</td>
<td>20.2</td>
<td>23.3</td>
<td>25.1</td>
</tr>
<tr>
<td>Terminal Velocity</td>
<td>14.2</td>
<td>23.1</td>
<td>28.4</td>
<td>31.2</td>
<td>32.2</td>
</tr>
</tbody>
</table>
quantitative measurements should be equally valid. Gradients of soil characteristics may of course occur on test plots, but since the chance of such gradients following concentric circles may be ignored, qualitative or comparative results will not be prejudiced.

In order to give a picture of the proportions of the test area which are subjected to varying intensities, the percentage areas covered by class groups of intensity were calculated as shown in Fig. 13.6. An intensity distribution curve along a radius was drawn from the intensity histogram (line 2 in Table 13.4.) and the radial limits of intensity groups are carried to cumulative percentage of area curves drawn on the same base line for test areas of diameters 5, 6 and 7 feet. A similar exercise was carried out for erosivity, and the results are shown in Table 13.6. From these results a quantitative measure of the lack of uniformity emerges, and further information on the optimum test area.

Considering distribution of intensity, between 2.5 and 3.5 inches per hour is received by 48% of a 7 foot diameter test area, and 61% for a 5 foot diameter. However the next group of intensity on either side are more evenly spread at 7 feet (19% and 28%) than at 5 feet (23% and 5%), which reduced the inference that a 5 foot area is better.

Considering the distribution of erosivity, a larger proportion of the area is included at 7 foot diameter than at 5 foot in both cases of the range 20 ± 2 and 20 ± 4. Since erosivity is more important than quantity of rain, the conclusion is that a 7 foot test area is preferable unless, as mentioned earlier, practical considerations arising from field operation dictate otherwise. Given the 7 foot diameter area, 48% will receive the design intensity ± 0.5 inches/hour and 95% will receive the design intensity ± 1.0 inches per hour. Also 24% will receive the design erosivity ± 10% and 64% receive the design erosivity ± 20%.

The conclusions are 1) that lack of uniformity constitutes the only known weakness in this simulator, 2) that measures to improve uniformity will introduce other less desirable departures from the specification, and 3) that the hypothesis that the lack of uniformity will not mar the usefulness of the device should be verified by field testing.

13.6. PRACTICAL MODIFICATIONS AND FIELD TESTING.

The prototype simulator was built up on a commercial lawn sprinkler because the nozzle attachments allowed adjustment of the nozzles in several directions. The disadvantage is that the water seal in the bearing is not renewable, and after extended use, wear
FIG. 13. CONSTRUCTION FOR TESTING UNIFORMITY.
\[
\begin{array}{ccc}
\text{EROSIVITY GROUP} & \text{GME/100 CC} & 10 - 14 & 49 & 34 & 25 \\
& & 14 - 16 & 19 & 15 & 11 \\
& & 16 - 18 & 2 & 1 & 10 \\
& & 18 - 20 & 3 & 2 & 1.5 \\
& & 20 - 22 & 7 & 9 & 11 \\
& & 22 - 24 & 20 & 39 & 30 \\
\end{array}
\]
might change the friction and so alter the speed of rotation.

To avoid this the production model shown in Fig. 13.7, uses the barrel of a "Rainbird" irrigation spray, where the water seal and bearing surfaces are plastic "neoprene" washers, available in bulk and renewable in a matter of seconds. The adjustable plate to control air resistance and rotation speed is no longer required, and replaced by a fixed counterweight. The nozzle is soldered onto the other arm, using an assembly jig to ensure accurate setting angles. Control of pressure at the low operating pressure of 1.5 p.s.i. is achieved by a constant head tank which eliminates the need for valves and pressure gauges. A filter is introduced in this tank so that water of poor quality may be used in the field, but the risk of interference by grit is remote as the bearing is very adequately sealed, and the minimum internal diameter through the supply pipes and nozzle is ½ inch.

The provisional design for the whole field apparatus is sketched in Fig. 13.8. The central tubular support will be either telescopic or in jointed sections for ease of transport, and carries both the constant head water tank, and the arm supporting the spraying head. This arm may be rotated in a horizontal plane so that several replications may be made in a circular pattern around each position of the central mast, thus reducing movement and assembly operations. The rate of water supplied for a test area of 7 foot diameter is only about 1 gallon/minute for ten minutes, so only a small constant head tank is required, and may be supplied from a mains supply where available, or if not by a hand pump or small engine driven pump.

The operating details to be determined by field testing include:

1) Size, shape, and construction, of the test plot boundaries and collecting device.
2) Method of measuring and recording the quantity of surface run-off and soil loss.
3) Method for check measurements of intensity during operation.
4) Techniques for pre-wetting the test area.
5) Standard deviation in results of run-off and erosion, and hence the number of replications needed.
FIG. 13.7. SKETCH OF PRODUCTION MODEL RAIN APPLICATOR.
PART V.

FIELD EXPERIMENTS.

CHAPTER 14.

BRIEF REVIEW OF METHODS AND DESCRIPTION OF PRESENT EXPERIMENTS.

14.1. REVIEW OF FIELD EXPERIMENTS.

In Chapter 1 the historical development of field research stations was briefly sketched, showing how the first stations of the United States Department of Agriculture established in the 1930's led to the present network of experiments in America, and to similar field experiments in other countries. Little would be achieved by presenting a catalogue and description of the large number of stations now operating, but rather the principles and techniques used will be discussed before describing the field experiments now being reported.

14.2. EXPERIMENTAL DESIGN.

An important feature, common to all designs of field erosion experiments, is the difficulty of having enough plots. In agronomic experiments it is possible to use formal statistical designs suitable for accurate and detailed statistical analysis of the results, and experiments with dozens or even hundreds of plots are quite common. In erosion experiments this is usually impracticable because, in addition to the application of treatments and recording of yield just as in the agronomic experiments, there is also the large capital cost of the installation, and the high labour requirement of the erosion measurements. The effect is that most designs are limited to 10 or 20 plots, and only a handful of stations throughout the world have 50 or more plots. In most cases then, even the simplest formal designs such as factorials or Latin squares are impracticable, and replication is usually either omitted entirely or inadequate. This lack of precision in design is frequently excused by the argument that "If it needs statistical analysis to show the difference between two farming systems, then the difference is of no practical importance" - a specious argument which has led
(a) Small plots, usually of 1/200 to 1/50 acre, where field treatments (e.g. ploughing) are not practical, but all the run-off and soil may be collected in tanks or pits.

(b) Medium sized plots, usually 1/20 to 1/2 acre, where field treatments are applied as far as possible, and the run-off and soil loss are continuously sampled with a constant proportion stored.

(c) Field scale plots, usually 1/4 to 4 acres, which are farmed in the regular way. Run-off is recorded but soil loss is either not measured or limited to ad hoc sampling.

All three types are used in the research programme now being reported.

14.1.1. Flumes and Recorders.

The devices ordinarily used for gauging small flows of water are not suitable for use in erosion experiments. Any type of notch which requires a stilling pond and low approach velocity is liable to be silted up by deposition of the silt load.

Critical velocity flumes, such as the Parshall, avoid this problem but are not very sensitive at low flows. A flume was therefore designed especially for erosion experiments by the Soil Conservation Service of the United States Department of Agriculture, and has been adopted in almost all field experiments. These are known as "H" type flumes and consist of converging vertical side walls cut back on a slope so as to give a trapezoidal projection of the outlet (Plates 14.1 and 14.1). The advantages are that it may be made in various sizes to measure flows from a trickle up to 100 cusecs, and if constructed accurately to specification it does not require individual rating, as rating tables have been prepared from laboratory tests. Straight-through flow at the base of the flume prevents the deposition of silt or the trapping of rolling bed-load. Increased sensitivity at low stage allows the accurate measurement of the more frequent low flows, while there is sufficient capacity to pass the infrequent high flows.

A continuous hydrograph may be obtained from H flumes by fitting a float-operated depth-of-flow recorder at a float-wall on one side of the flume. The rating curves allow for the draw-down between the float-wall and the discharge point. In the present experiments special charts were printed so that depth of flow was recorded directly as rate of flow in cusecs.

14.1.2. Sampling Devices.

When plot sizes bigger than about 1/100 acre are used, the
size of the collecting tank required to catch the whole of the
run-off becomes unmanageably large, especially when tropical storms
are being catered for, and some method of sampling is required.
Again the Soil Conservation Service have designed a suitable
instrument called the Geib divisor (Plate 14.1.). This consists
of a rectangular flume, through which the run-off passes, and with
a series of vertical rectangular slots at the downstream end.
The soil and water passing through one slot is retained, giving an
accurate and constant fraction of the total. The sample may be
from $1/3$ to $1/12$ of the total depending on the number of slots,
and two or more divisors may be used in series for smaller fractions.
This device has also been very widely used, but in Rhodesia some
difficulty was experienced in having the flumes made with sufficient
accuracy, and alternative methods were also used. One consisted of a
series of ten $90^\circ$ V notches which were bolted up and machined to
ensure uniformity, and then fixed to a flat plate (Plate 14.2.).
A later type consisted of horizontal and vertical rows of $\frac{1}{2}$ inch
holes drilled in a stainless steel plate from a master template
(Plate 14.3.).

In experiments using field scale plots, where the flows
are too large to pass through Geib divisors, several samplers have
drawn off a small sample at right angles to the main flow. The
"Indian" sampler has a vertical row of circular holes drilled in
the side of an H flume, the holes being progressively larger
towards the top to give a fairly constant aliquot of the flow at all
stages. The "Hammer" sampler is simply a small rectangular notch in the
side of a rectangular flume. The early Glunara experiments in Rhodesia
used a small $15^\circ$ Dialetti notch to take a sample from the stilling
pond behind the large $90^\circ$ measuring notch. With great variations in
bed load and suspended load, and in the distribution of these loads
across the flume or channel, all these side sampling methods are
subject to considerable error in sampling soil loss, even if they
take a constant water sample.

Occasionally use has been made of mechanical sampling
devices which use the run-off water to operate a tilting-bucket
sampler, or water-driven rotary sampler. Such devices have found
little favour because of the difficulties of catering for a wide
range of flows, and of ensuring reliability in a machine exposed
to all weathers.

14.3.1. Frequency of Recording.

If the object of the experiment is only to measure annual
run-off and soil loss, the emptying of the tanks may be done on
an ad hoc basis as and when necessary. If individual records for
each storm are required, the procedure must allow for complete and
rapid emptying of all tanks. For annual recording the usual
technique is to allow the soil to settle, then to pump out or drain
out the water, and remove the soil to a common container for
subsequent drying and weighing. When a large number of plots are
to be recorded after each storm, it is impracticable to store the
whole of the eroded soil, and some form of sampling is required.
The technique developed for the Henderson experiments was based
on the use of a highly efficient flocculation agent. This is a
proprietary brand chemical which is added to each storage tank
after rain. The suspended soil flocculates, and settles within
an hour. The clear supernatant water is measured and drained off,
and the sludge emptied into metal drums, leaving the tanks ready
for the next storm. The sludge is later weighed and a subsample
taken for laboratory determination of percentage solids.

14.4. DESCRIPTION OF FIELD EXPERIMENTS.

Comprehensive accounts of the design and operation of the
experiments, and of the crop treatments have been published by the
writer as described on page XII. The present description is
therefore limited to those points which are relevant to the
discussions of results in the following chapter.

Two sizes of experimental plots are used, - small plots
of 1/100 acre, known as the minor experiments, and 1/20 acre plots
for the major experiments. Both types of experiment are conducted
on each of four soil types, clay loam, clay, poorly drained
shallow sand, and well drained deep sand. The layout of each site
is shown in Figs. 14.1. - 14.4.

For the major experiments, removable plot boundaries are
used so that tractor cultivation is possible (Plate 14.4.). The
run-off is caught in brick-lined collecting troughs and piped to
the storage tanks. On the clay loam soil (Series I) three tanks
are used with Geib divisors taking 1/7 samples (Plate 14.1.). This
design was improved for the clay soil (Series II) which has two
brick tanks and a ten notch divisor (Plate 14.2.). Further
improvements led to the design used on the sand soils (Series III
and IV) where the run-off is piped to a building which houses all
the tanks. In this case two corrugated-iron tanks are used
with a 1/15 divisor (Plate 14.5.). These variations are the result
of increased experience, and do not affect the common principle
which is to store an accurate and known fraction of the soil and
water from each plot.
Plate 14.1. The collecting tanks on Series I with H flume and Geib divisor.

Plate 14.2. The collecting tanks of Series II under construction.

Plate 14.3. The improved tanks and divisor used on Series III and IV.
Plate 14.4. The plot boundaries, of asbestos cement planks, are removable for tractor cultivation.

Plate 14.5. In the last experiments to be installed, the run-off from all the plots is piped to a central building, housing all the collecting tanks.
I. DEMONSTRATION PLOTS.
2. 6 COURSE ROTATION.
3. OFFICE AND LABORATORIES.
4. STORES AND WORKSHOPS.
5. EXPERIMENT ON 65% SLOPE.

6. - 3
7. - 2
8. - 1 - 4 1/2
9. - 1 - 3
10. - 4

FIG. 14.1. SITE PLAN SERIES I
FIG. 14.2. SITE PLAN SERIES II

1. OFFICE & STORE
2. EPT. 7 ON 3 1/2% SLOPE
3. EPT. 8 ON 3% SLOPE
4. METEOROLOGICAL STATION
1. **EXPT. 10 ON 5½ % SLOPE.**
2. **GRATED ROW PLOTS.**
3. **ANGLED ROW PLOTS.**
4. **METEOROLOGICAL STATION.**
5. **OFFICE AND STORE.**
6. **COLLECTING TANKS.**

**FIG. 14.3. SITE PLAN SERIES III**
For the first three years, 1953 - 1956, only the annual soil and water losses were recorded. Since 1956 separate measurements have been made after each storm which causes run-off. The analysis of results will be confined to the major experiments, except in the case of bare soil where data is taken from the mosquito gauze experiment described previously.
CHAPTER 15.

EROSIVITY AND FIELD EXPERIMENTS.

A vast amount of data has been recorded from the field experiments in the nine years of their operation. Much of this has been published in the form most suitable for its application in land use planning, and a detailed examination of all the material is outside the scope of this thesis. The present object is to demonstrate by a few chosen examples how the information on erosivity and the mechanics of erosion developed in Parts II and III may be used as a magnifying glass for the closer examination of the data. Any trends or patterns so revealed may then be subjected to detailed study under controlled conditions by the rainfall simulator. As all the inferences are provisional, statistical tests are not applied to the results of this chapter.

15.1. DETERMINING EROSIVITY FROM RAINFALL RECORDS.

It was shown in Chapter II that the erosive power of a storm may be estimated from the kinetic energy. When it is possible to extract from rainfall records the amounts of rain falling at various intensities, the kinetic energy may be calculated by multiplying these amounts by the appropriate values of energy per unit quantity of rain from Fig. 8.19. Using the detailed intensity records of the years 1953 - 1961 the value of (K.E. > 1) was computed for each storm, and summed to give monthly and annual totals. The intensity records allowed the estimation of amounts at all intensities, but since the energy per inch of rainfall only increases very slightly at high intensities, it was found that the result is not significantly less accurate if a mean energy value is applied to the amounts which fall in the intensity range of 1 - 2 inches per hour, and greater than 2 inches per hour. Sample calculations of this are shown in Table 15.1. This greatly increases the application of this method of calculating erosivity from rainfall records, because much information is available in this form from the standard recording rain gauges of Meteorological Departments.

15.1.1. Annual Variation of Erosivity.

In Fig. 11.13, it was shown that for individual storms
the erosivity as measured by \( K.E. > 1 \) was directly related to the soil loss from bare soil. Comparing the annual totals of erosivity with total annual soil loss an equally precise relationship holds (Fig. 15.1.). The positive intercept, implying that no erosion occurs until the annual erosivity is of the order of 4,000 ergs \( \times 10^3 \text{cm}^2 \), is probably due to the energy of short duration periods of rain, when the intensity momentarily becomes erosive but there is insufficient volume of run-off to carry away the soil. This secondary effect was evaluated in Chapter 11, and compensation for it can be made if the volume or rate of run-off is known, but the present object is to see whether annual soil loss could be predicted directly from rainfall records. The very good correlation of Fig. 15.1. shows that for bare soil such predictions would be quite accurate. The relation between total annual erosivity and total annual amount of rainfall (Fig. 15.2.) shows that considerable variation in erosivity can occur for a given annual rainfall, and that erosivity could not be predicted from the amount of total annual rainfall.

The clearcut relation between erosivity, or the potential ability of the rain to cause erosion, and the soil loss which does occur from the bare soil is materially modified when the land carries a crop. This is demonstrated in Fig. 15.3. While the annual soil loss from a maize crop follows the general pattern of the seasonal erosivity there are apparent discrepancies, particularly in the season of 1954/55. That this is not experimental error is shown by the fact that low soil loss was recorded from all the plots with maize crops. The explanation is that although the 1954/55 season had a high total erosivity, it was unusual in that nearly all the heavy rains occurred late in the season. By this time the maize crop was well grown and gave good protection to the soil, hence a low soil loss, although the bare soil continued to erode. Conversely in 1956/57, a concentration of erosive rain in the early months of the season gave a relatively high soil loss. The complicated nature of the interactions of rain, soil, and crop, will be demonstrated later.

15.1.2. Geographical Variation of Erosivity.

Data on rainfall intensities was obtained from the Meteorological Department for the years 1951 - 1956 at five meteorological stations in Southern Rhodesia and used to compute monthly and seasonal erosivity. A period of five years is too short to draw firm conclusions, but the results are used to show the type of information which may be obtained when sufficient data is available from the constantly expanding network of recording rain gauges.
FIG. 15.1. ANNUAL EROSION AND SOIL LOSS FROM BARE SOIL.
FIG. 15.2. ANNUAL EROSIVITY AND ANNUAL RAINFALL.
FIG. 15.3. VARIATIONS IN ANNUAL EROSIvITY & EROSION.
### Table 15.2

**Erosivity at Five Meteorological Stations in Southern Rhodesia 1951 - 1956.**

<table>
<thead>
<tr>
<th></th>
<th>Salisbury</th>
<th>Que Que (Undali)</th>
<th>Grand Reef</th>
<th>Port Victoria</th>
<th>Bulawayo</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Annual rainfall (inches)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>b) Average of 5 years</td>
<td>36.9</td>
<td>34.7</td>
<td>33.9</td>
<td>31.6</td>
<td>30.75</td>
</tr>
<tr>
<td><strong>Total Erosivity</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1951 - 1956</td>
<td>49,480</td>
<td>37,015</td>
<td>36,560</td>
<td>36,980</td>
<td>31,445</td>
</tr>
<tr>
<td>ergs x 10³/cm²</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Comparative erosivity</strong></td>
<td>100</td>
<td>74.8</td>
<td>73.9</td>
<td>74.7</td>
<td>63.6</td>
</tr>
<tr>
<td><strong>Erosive rain 51-56 (inches)</strong></td>
<td>72.7</td>
<td>54.8</td>
<td>53.7</td>
<td>55.2</td>
<td>46.5</td>
</tr>
<tr>
<td><strong>% Erosive rain</strong></td>
<td>39.4</td>
<td>31.6</td>
<td>31.7</td>
<td>34.9</td>
<td>30.2</td>
</tr>
<tr>
<td><strong>Average erosivity</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(ergs x 10³/cm²)</td>
<td>268</td>
<td>213</td>
<td>216</td>
<td>234</td>
<td>204</td>
</tr>
</tbody>
</table>

#### Seasonal Distribution of Erosivity

<table>
<thead>
<tr>
<th></th>
<th>November</th>
<th>December</th>
<th>January</th>
<th>February</th>
<th>March</th>
</tr>
</thead>
<tbody>
<tr>
<td>Salisbury</td>
<td>4,840</td>
<td>13,770</td>
<td>15,370</td>
<td>9,150</td>
<td>6,350</td>
</tr>
<tr>
<td>Que Que</td>
<td>3,060</td>
<td>11,180</td>
<td>6,630</td>
<td>13,710</td>
<td>2,440</td>
</tr>
<tr>
<td>Grand Reef</td>
<td>6,510</td>
<td>11,140</td>
<td>10,690</td>
<td>4,770</td>
<td>3,480</td>
</tr>
<tr>
<td>Port Victoria</td>
<td>5,550</td>
<td>10,520</td>
<td>8,980</td>
<td>8,880</td>
<td>3,050</td>
</tr>
<tr>
<td>Bulawayo</td>
<td>5,990</td>
<td>5,560</td>
<td>10,140</td>
<td>7,300</td>
<td>2,260</td>
</tr>
</tbody>
</table>
The results are tabulated in Table 15.2. Again there is a general association of higher erosivity with higher rainfall, but stations of similar average rainfall amount can have considerable difference in the seasonal pattern of erosivity. Comparing Salisbury and Bulawayo it is clear that in this five year period, Salisbury not only received more rain than Bulawayo, (which is to be expected from long term averages) but also a higher proportion of erosive rain. This disproves the widespread misconception that severe storms are relatively more frequent in regions of lower rainfall, and in the months of lower rainfall at the beginning of the season. The reason for this mistake is that a few heavy storms are more noticeable, when they are isolated, than a larger number of similar storms included in a greater total amount of rain. In general the frequency of high intensities increases as the average annual rainfall increases, so the average erosivity may be expected to be higher in high rainfall areas. There will probably be exceptions in certain areas of Rhodesia. For example the mountainous Eastern border has a very high rainfall, but since much of this is either monsoon type or orographic rainfall the average erosivity may well be lower. Again, the low-lying valleys of the south-east have very low average rainfall, but what rain does occur is mainly isolated storms associated with cyclonic disturbances off the Mozambique coast, and the average erosivity may be unusually high.

The variations in seasonal distribution of erosivity shown in Fig. 15.4, may also be significant if confirmed by further data. Bulawayo appears to have particularly low erosivity in the beginning of the season (November and December). On the other hand, at Grand Reef (Umtali) erosivity is high in the early months but low in February and March. This could be helpful in choosing the most appropriate time to carry out those reclamation works, such as gully control, which may be done either at the beginning or the end of the rainy season. The required conditions are enough rain to assist in establishing vegetation, without excessive damaging rain and run-off. The seasonal pattern suggests that the beginning of the season would be better in Bulawayo, but the end of the season in Salisbury and Umtali.

The modern system of land-use planning depends upon the classification of land according to its vulnerability to erosion. This would be much more efficient if allowance could also be made for the erosivity in different climatic regions, and this can now be done when sufficient information is available to map erosivity in addition to isohyets and isopleths.
AT 3 STATIONS IN S. RHODESIA.

FIG. 13.4. AVERAGE MONTHLY EROSION

- MILLER
- MILLER
- MILLER
- MILLER
- MILLER
- MILLER
15.2. SOME EFFECTS OF CROP COVER.

It has been shown (Hudson, 34) that relatively small differences in the density of the cover of a growing crop can cause large differences in the amount of soil loss. In comparisons of average and above average maize crops, the average soil loss was reduced by the good dense crop to a quarter of that from the average crop. In the mosquito gauge experiment the loss from bare soil is of the order of 100 times that from soil with 100% artificial protection. The reason is that raindrop impact is the main cause of erosion, and the extent to which the potential erosive power is allowed to expend its energy on the soil is entirely dependent on the extent to which the soil is covered. Although for convenience in publicizing the prevention of erosion, the stress is put on providing cover, the amount of erosion in fact depends not on the amount of soil covered, but on the amount of soil exposed to the rain’s erosivity. With most agricultural crops the small percentage of exposed soil is less than the covered soil. Vertical photographs of mature maize showed that with 10,000 plants per acre approximately 60% of the ground is protected, and 40% exposed. With 15,000 plants per acre 90% is covered, and 10% exposed. The soil loss is in the ratio of the exposed soil i.e. 4 to 1 not the covered soil, 1 to 4.

This explains why large differences in erosion are caused by relatively slight crop differences.

The effect of progressive changes during the season as the maize crop matures is shown in Fig. 15.5. The soil losses in individual storms from the same plot, growing maize each year, are plotted against the energy parameter (E.E > 1). In each of six years the storms have been grouped into "early" - the first one or two storms of the season, "middle" from mid-December to mid-January, and "late" in February and March. Three different relations appear. In the early storms, the soil loss is low because the soil is dry and uncompacted giving low run-off. This is a physical condition varying little from year to year, so there is no scatter. In December/January losses are much higher from storms of similar erosivity because the crop is only part grown, but the initial conditions no longer exist. There is the greatest scatter in this group because the crop growth in mid-season varies from year to year. Finally the end of the season storms give lower soil loss because the crop is providing good cover. The scatter is reduced because there is less variation in the density of the mature crop.
Fig. 15.5. The changing effect of crop cover during the season.
15.3. THE EFFECT OF SLOPE.

In the group of experiments on clay loam soil (Series I), identical crop treatments are applied to plots whose slopes are 6.5%, 4.5% and 3%. Taking as an example the plots growing continuous maize at average fertility, the soil loss from the three slopes may be compared. Fig. 15.6 shows the losses from the two flatter slopes plotted against that from the steepest slope, all during individual storms in the last half of the season. Although there is considerable scatter, the general relation is clear.

It is usually assumed (177) that the slope effect may be assessed by an expression of the form

\[ \text{Soil loss} = a x (\% \text{Slope})^b \]  

The constant \( a \) depends on crop treatment, and has the same value for each slope in this case.

From the equation (1) and from Fig. 15.6,

\[ \text{Soil loss (4.5\%)} = 0.65 \times (\text{Soil loss 6.5\%}) \]  

\[ (4.5)^b = 0.65 \text{ or } b = 1.18 \]  

Similarly from Soil Loss (3\%) = 0.4 \times (Soil loss 6\%)

\[ b = 1.17 \]  

Combining (2) and (3)

\[ \text{Soil Loss (4.5\%)} = 0.65 \times (\text{Soil loss 3\%}) \]  

Hence \( b = 1.19 \)

The close agreement between the three values of \( b \), suggests that this is a good evaluation for the effect of slope under these conditions. However, bearing in mind the strong probability of interactions between the variables, it is quite possible that both the \( a \) and \( b \) constants would vary for other crops, or other soils. This is one of the many cases, where the general trend may be established from the field plots, but the rainfall simulator is essential to obtain the final answer which covers all variations.

The relatively low value of \( b \), (or the relatively small differences in soil loss over large differences of slope), is explained by the fact that in the plot design some allowance is made for the effect of different slopes. The length of plots on each slope is the distance between conventional contour ridges, using the standard formula

Vertical Interval between contours = \( 4 \times \% \text{slope} \) (foot)

This gives a closer spacing and a shorter length of plot on the steeper slopes, and consequently less erosion per unit area as there is a shorter distance over which the run-off accumulates velocity. A precise evaluation of this effect of length of slope...
FIG. 15.6. THE EFFECT OF SLOPE ON SOIL LOSS.
is not required as the use of the contour spacing formula is standard on all arable lands in Rhodesia. An experiment was laid down to test the suitability of this formula, and showed that it does in fact give good results (Hudson, 33).

15.4. INTERACTION BETWEEN SOIL TYPE, SLOPE AND CROP.

An example should be considered of the complicated interactions which occur. The same crop treatment, average continuous maize, was grown on plots on the three sites with soils of clay loam, poorly drained shallow granite sand, and well drained granite sand. The slope differed slightly on the three sites so the soil loss figures were all adjusted to a common slope using the relation of the previous section i.e. erosion = (slope)^1.18. The adjusted annual soil loss is plotted against annual erosivity in Fig. 15.7, and appears to indicate that there is no significant difference between the soil types.

However when the same exercise is carried out using the soil loss from the plots carrying a very poor maize crop, there appears to be a considerable difference between the two sand soils (Fig. 15.8). Clearly there is an interaction between the variables; either the difference between the two soil types is significant for a bad maize crop but not for a good maize crop, or the slope effect is not the same for these two crops. On the evidence available from the field plots either, or both, are possible, and again the trends and indications need detailed study under controlled conditions using the rainfall simulator.

15.5. SOIL DEGRADATION.

For some soils it is assumed that after a considerable amount of the top soil has been lost by erosion, the exposed subsoil will be less resistant, and erosion will accelerate. Alternatively, in other soil conditions the lower soil may be harder and more resistant. Previously it was not possible to test these alternatives on the field experiments, but now that storms and seasons can be assessed quantitatively, comparisons per unit erosivity may be made. The data from the bare clay loam soil (Fig. 15.1) is suitable because it showed little scatter, and during eight years, several inches of topsoil have been removed. In Table 15.1 the erosivity and erosion are compared over eight years, and there is no sign of a change in erodibility.

However there are grounds for suspecting that a different
FIG. 15.8. INTERACTION EFFECTS OF SOIL & SLOPE.
### TABLE 15.1

TEST OF PROGRESSIVE DEGRADATION OF BARE CLAY LOAM SOIL, on 4% SLOPE.

<table>
<thead>
<tr>
<th>Year</th>
<th>Seasonal Erosivity</th>
<th>Seasonal Soil Loss</th>
<th>Effective Erosivity (i.e. &gt; 4000 ergs x 10^7/cm^2)</th>
<th>Soil Loss per 1000 ergs of effective erosivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>1953/54</td>
<td>10,500</td>
<td>65.1</td>
<td>6,500</td>
<td>10.0</td>
</tr>
<tr>
<td>1954/55</td>
<td>13,500</td>
<td>91.2</td>
<td>9,500</td>
<td>9.6</td>
</tr>
<tr>
<td>1955/56</td>
<td>10,100</td>
<td>60.5</td>
<td>6,100</td>
<td>9.9</td>
</tr>
<tr>
<td>1956/57</td>
<td>10,100</td>
<td>59.1</td>
<td>6,100</td>
<td>9.7</td>
</tr>
<tr>
<td>1957/58</td>
<td>6,000</td>
<td>22.1</td>
<td>2,000</td>
<td>11.1</td>
</tr>
<tr>
<td>1958/59</td>
<td>12,500</td>
<td>90.1</td>
<td>8,500</td>
<td>16.5</td>
</tr>
<tr>
<td>1959/60</td>
<td>4,200</td>
<td>3.3</td>
<td>200</td>
<td>16.5</td>
</tr>
<tr>
<td>1960/61</td>
<td>9,400</td>
<td>54.2</td>
<td>5,400</td>
<td>10.0</td>
</tr>
</tbody>
</table>
result might occur on the lighter sand soils. These soils have a very low proportion of the silt and clay fractions and organic matter, and it has been suspected for some time that this is selectively removed by erosion, leaving a soil which becomes progressively poorer in these constituents. Since these materials are important in binding together soil into aggregates or crumbs, their reduction could lead to greater vulnerability to erosion.

Under maize crops it is not easy to test this because the crop growth varies from year to year, but tobacco crops appear to be less variable, probably because the cover is less dense. Comparisons of the annual soil loss from two successive tobacco crops on previously virgin land are shown in Fig. 15.9, after making allowance for the different erosivities of different seasons. There is strong evidence of an increase in erosibility, as the erosion from second year tobacco is consistently three times that from first year tobacco. A similar comparison may be made of the losses from the same plots when tobacco was grown again after several years of grass. The losses in individual storms from first, second and third tobacco crops are shown in Fig. 15.10. The degradation after the first crop is marked, but less so than when the crop was grown on virgin land. This is quite logical, as the object of the rest period under grass is to build up resistance to erosion by increasing the bulk organic matter. A further slight increase in erosibility appears to occur in the third season when tobacco is grown. Again these are general trends and require further investigation.

15.6. CONCLUSIONS.

In this chapter several examples are given of how a quantitative measure of erosivity allows useful information to be extracted from the results of field plot experiments. The inherent weaknesses of field experiments are shown; there are too many interacting variables, and inadequate replication which arises from the necessity of including so many variables. The primary purpose of the field experiments is to provide practical answers to practical field problems, but by applying the knowledge of the mechanics of erosion, additional information may be extracted which was previously concealed among the mass of data. Since the same knowledge of erosivity allows the design of a rainfall simulator, the trends and indications which emerge from the field experiments may be subjected to detailed examination, in controlled experiments whose results may be subjected to proper statistical examination.
FIG. 15.9. THE EFFECT OF SUCCESSIVE TOBACCO CROPS ON VIRGIN LAND.
FIG. 15.10. THE EFFECT OF SUCCESSIVE TOBACCO CROPS
SUMMARY OF THE NEW CONTRIBUTIONS TO THE KNOWLEDGE OF SOIL EROSION ADVANCED IN THIS THESIS, WITH SUGGESTIONS FOR FURTHER RESEARCH.

NEW CONTRIBUTIONS.

1. Chapter 5. A study of the control conditions required for calibration of the flour pellet method leads to a new and accurate calibration.

2. Chapter 6. New data is presented to show the effects of wind associated with high intensity convective rainfall. In general, higher intensities are associated with more vertical rain.

3. Chapter 8. New data is presented on drop size and distribution of thunderstorm rain at intensities not previously studied. This information is also used to establish new relationships between intensity and kinetic energy. Above 3 or 4 inches per hour there are significant changes in drop size distribution not previously reported, which materially affect the energy of high intensity rain.

4. Chapter 10. Significant improvements are made in the technique of using splash cups to measure the erosive power of rain.

5. Chapter 11. Using the results of simultaneous studies of rainfall characteristics and of measured erosion, correlations are established between erosion and parameters or indices of erosive power. A sequence of erosion conditions progresses from the particular case to the general by the addition of variables. Throughout the sequence it is found that erosion may best be estimated from the parameter (K.E. > 1), or the kinetic energy of that part of the rain falling at intensities greater than one inch per hour. The secondary effect of run-off is also evaluated, and an empirical but satisfactory method for estimating run-off from rainfall records is established.

6. Chapter 12. The new knowledge of rainfall characteristics and the mechanics of erosion is used to design a rainfall simulator suitable for field use in Africa. The design is taken to the stage of a working prototype which successfully meets the required conditions that it should be simple and portable while accurately reproducing the erosion effects of natural rainfall.

7. To demonstrate the practical value of the ability to calculate erosive power from rainfall records,
a) indications of annual and geographical variations in erosivity are presented,

b) from the results of field erosion experiments a first assessment is made of the effects of some soil and crop variables.

SUGGESTIONS FOR FURTHER RESEARCH.

1. The prototype rainfall simulator requires developing as a field instrument and detailed field testing. The physical requirements are a portable supporting framework, equipment for delimiting the test plot, and for collecting the run-off from the test plot. The experimental requirements are

1) The methods of measuring and recording the simulated rain, the run-off, and the soil loss.

2) The best technique for obtaining a standard condition of soil moisture.

3) Statistical tests of the reproducibility and accuracy of the results.

2. Having a simulator suitable in all respects for field use, the applications are almost unlimited. The proposed first step will be to quantitatively compare its results with those of the field experiments by actually using it on the field plots. The indications already shown of the effects of soil, slope, and crop will be tested, and then amplified in experiments of factorial design which will cover practical ranges of each variable and so allow the assessment of all the interactions. Initially this should be done on each of the soil types included in the present field experiments, and then extended to the other soils of Central Africa. Some care will be required in extrapolating the established rainfall characteristics to other climatic regions. The reported rainfall studies are relevant to the central watershed of Southern Rhodesia which has a consistent rainfall pattern, but before assuming that the rainfall simulator duplicates the erosive power of rain in other regions, more study of the rainfall characteristics will be required. The lengthy sampling of raindrop size distribution may be avoided by using the acoustic recorder to test the kinetic energy/intensity relationship. Only where this relationship differs from that already established will detailed studies be required.

Research using the simulator is also required in other agricultural fields. Measurements of infiltration rates are required in irrigation planning, hydrological research, veld management research, and the study of tillage practices.
BIBLIOGRAPHY.

CHAPTER I.


* Abbreviations of Journals and Periodicals are those specified by the Commonwealth Bureau of Soil Science Bibliography, 1958.


CHAPTER 2.


CHAPTER 3.

CHAPTER 4

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CHAPTER 5.


CHAPTER 6.

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CHAPTER 10.


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APPENDIX 1.

VARIATION OF MASS RATIO.

\[ M = \text{mass ratio} \quad d = \text{drop mass} \quad p = \text{pallet mass} \]

\[ M = \frac{d}{p} \]

\[ \Delta M = \frac{\Delta d}{\Delta d} \frac{d}{p} + \frac{\Delta p}{\Delta d} \frac{M}{p} \]

\[ \Delta M = \frac{\Delta d}{\Delta d} \frac{d}{p} + \frac{\Delta p}{\Delta d} \frac{M}{p} \]

\[ M = \frac{d}{p} = \frac{\Delta d}{\Delta d} + \frac{\Delta p}{\Delta d} \frac{M}{p} \]

\[ \text{var}(M) = \left( \frac{\Delta M}{M} \right)^2 \text{var}(d) + \left( \frac{\Delta M}{M} \right)^2 \text{var}(p) + 2 \left( \frac{\Delta M}{M} \right) \left( \frac{\text{covar}(d,p)}{\Delta d \Delta p} \right) \]

\[ \text{From (1) \quad } \frac{\Delta d}{\Delta d} = 1 \quad \text{and} \quad \frac{\Delta p}{\Delta d} = \frac{-M}{p^2} \]

Substituting in (2)

\[ \text{var}(M) = \frac{d^2}{p^2} \left[ \frac{V_d^2}{p^2} + \frac{V_p^2}{p^2} - 2 \frac{V_{dp}}{p} \right] = s^2 \]

Now \((M - \mu)^2 = t^2\)

Substitute for \(s^2\) from (3)

\[ p^2 (\mu - \frac{s}{\delta})^2 = t^2 (V_d^2 - 2 \mu V_{dp} + \mu^2 V_p^2) \]

\[ p^2 \left( \frac{\mu^2 - 2 \mu \frac{s}{\delta} + \left( \frac{s}{\delta} \right)^2}{p^2} \right) = t^2 (V_d^2 - 2 \mu V_{dp} + \mu^2 V_p^2) \]

\[ \mu^2 (s^2 - t^2 V_p^2) - 2 \mu (s^2 - t^2 V_p^2) + (s^2 - t^2 V_d^2) = 0 \]

Solving this quadratic for \(\mu\), the roots are:

\[
\frac{2(3s^2 - t^2 V_p^2) + \sqrt{4(3s^2 - t^2 V_p^2)^2 - 4(2s^2 - t^2 V_p^2)(3s^2 - t^2 V_d^2)}}{2(2s^2 - t^2 V_p^2)}
\]

Put \(g = \frac{t^2 V_p}{p^2}\) i.e., \(1 - g = \frac{s^2 - t^2 V_p^2}{p^2}\)

The roots now become:

\[
\frac{s^2}{p^2} \left( \frac{V_d}{p^2} - \frac{V_{dp}}{p^2} \right) \pm \frac{t}{(1-g) \sqrt{s^2 + t^2 V_p^2}} \sqrt{s^2 V_d - 2s^2 V_{dp}^2 + s^2 V_p^2 - t^2 V_{dp}^2 - t^2 V_p^2} \]

or \[ \frac{M}{(1-g) \sqrt{s^2 + t^2 V_p^2}} \pm \frac{t}{(1-g) \sqrt{s^2 + t^2 V_p^2}} \sqrt{s^2 V_d - 2s^2 V_{dp}^2 + s^2 V_p^2 - t^2 V_{dp}^2 - t^2 V_p^2} \]

or \[ (1-g) \frac{-s}{p} \frac{V_{dp}}{p^2} \frac{1}{p^2} \frac{1}{(1-g) \sqrt{s^2 + t^2 V_p^2}} \sqrt{s^2 V_d - 2s^2 V_{dp}^2 + s^2 V_p^2 - t^2 V_{dp}^2 - t^2 V_p^2} \]

or \[ \frac{M}{(1-g) \sqrt{s^2 + t^2 V_p^2}} \pm \frac{t}{(1-g) \sqrt{s^2 + t^2 V_p^2}} \sqrt{s^2 V_d - 2s^2 V_{dp}^2 + s^2 V_p^2 - t^2 V_{dp}^2 - t^2 V_p^2} \]

or \[ (1-g) \frac{-s}{p} \frac{V_{dp}}{p^2} \frac{1}{p^2} \frac{1}{(1-g) \sqrt{s^2 + t^2 V_p^2}} \sqrt{s^2 V_d - 2s^2 V_{dp}^2 + s^2 V_p^2 - t^2 V_{dp}^2 - t^2 V_p^2} \]

which is Pinney's equation.
Since \( g = \frac{t^2 Y_p}{p^2} \), where \( g \) is of the order of \( 10^{-3} \) or less, this equation may be simplified to

\[
M = \tau T
\]

where

\[
s^2 = \frac{1}{p^2} \left[ d + n^2 Y_p - 2W d p \right]
\]

In the present calibration \( g \) decreases from \( 2.5 \times 10^{-3} \) for the smallest drop to \( 4.03 \times 10^{-5} \) for the largest drop and the simplified equation has been used throughout.
## APPENDIX 2.

### Chapter 8

**MOMENTUM AND INTENSITY AVERAGED WITHIN STORES IN THE LOW RANGE OF INTENSITY.**

<table>
<thead>
<tr>
<th>I (ins/hr)</th>
<th>X</th>
<th>( Y )</th>
<th>( \log 10(I) )</th>
<th>( \log MV_A )</th>
<th>( \text{Average Momentum} )</th>
<th>( \text{Average Intensity} )</th>
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<td>2114</td>
<td>3.3253</td>
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</table>

### 1) Logarithmic regression

\[
\begin{align*}
\sum x^2 &= 1.007663 \\
\sum y^2 &= 1.18359 \\
\sum xy^2 &= 1.16703 \\
Y &= 1.15835 X + 1.484845 \\
MV_A &= 30,538 I^{1.15835} (I = 10 \text{ to make logs positive}) \\
MV_A &= 30,538 \times 10^{1.158 \times I} \\
MV_A &= 439.74 I^{1.158} \text{ dynes x } 10^{-2} / \text{cm}^2
\end{align*}
\]

### 2) Linear regression

\[
\begin{align*}
\sum x^2 &= 19.2171 \\
\sum mv^2 &= 5,903.094 \\
\sum mvi &= 10,512.52 \\
MV_A &= 547.04 I - 89.97
\end{align*}
\]

### 3) Analysis of variance.

Residual S.S. from eqn. 8-2 \[153.673\] *Not significantly different.*

Residual S.S. from eqn. 8-1 \[179.857\] *Different.*
### Appendix 3.

(Chapter 8)

**MOMENTUM PER SECOND AND INTENSITY AT HIGH LEVELS OF INTENSITY.**

<table>
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<tr>
<th>X</th>
<th>Y</th>
</tr>
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<td>2050</td>
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<td>40</td>
<td>2180</td>
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<tr>
<td>48</td>
<td>2670</td>
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<td>50</td>
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<td>2830</td>
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<td>57</td>
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<td>3105</td>
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<td>66</td>
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<tr>
<td>71</td>
<td>3600</td>
</tr>
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<td>73</td>
<td>3990</td>
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<td>2800</td>
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<td>54</td>
<td>2795</td>
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<td>57</td>
<td>2940</td>
</tr>
<tr>
<td>62</td>
<td>3345</td>
</tr>
<tr>
<td>65</td>
<td>3315</td>
</tr>
</tbody>
</table>

\[
\begin{align*}
\sum x^2 &= 4024 \\
\sum y^2 &= 10258942 \\
\sum xy &= 200732 \\
\end{align*}
\]

\[
\begin{align*}
r &= 0.989 \\
b &= 49.882 \\
a &= 145.75 \\
\end{align*}
\]

\[
Y = 49.882X + 145.75 \quad (X = 10.1) \\
M/Y = 496.82 \quad 1 + 145.75 \text{ dynes} \times 10^{-2}/\text{cm}^2 \\
\]
APPENDIX 4.

(Chapter 8)

ANALYSIS OF COVARIANCE. MOMENTUM DATA.

1) Low range of intensity (0 - 4 ins./hr.)

\[ \begin{align*} 
\sum i^2 &= 19.22 \quad \sum m^2 = 5,903,004 \quad \sum mi = 10,512.5 \quad n = 22 \\
M &= 547.04 \quad I = 89.97 
\end{align*} \]  

\[ (8-2) \]

2) High range of intensity (3 - 9 ins./hr.)

\[ \begin{align*} 
\sum i^2 &= 40.24 \quad \sum m^2 = 10,258,942 \quad \sum mi = 20,073.2 \quad n = 28 \\
M &= 496.82 \quad I + 145.75 
\end{align*} \]  

\[ (8-3) \]

3) Pooled data, whole range

\[ \begin{align*} 
\sum i^2 &= 202.93 \quad \sum m^2 = 57,681,693 \quad \sum mi = 107,768 \\
M &= 531.1 \quad I = 43.12 
\end{align*} \]  

\[ (8-4) \]

<table>
<thead>
<tr>
<th></th>
<th>df</th>
<th>( \sum i^2 )</th>
<th>( \sum m^2 )</th>
<th>( \sum mi )</th>
<th>Reg. Conf. df</th>
<th>S.S.</th>
<th>M.S.</th>
</tr>
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<td>Low Range</td>
<td>21</td>
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<td>10,512</td>
<td>5,903,004</td>
<td>20</td>
<td>153.674</td>
<td>7.684</td>
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<td>High Range</td>
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<td>20,073</td>
<td>10,258,942</td>
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<td>245.887</td>
<td>9.457</td>
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<tr>
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<td></td>
<td></td>
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<tr>
<td>Reg. Coef.</td>
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<td>30,585</td>
<td>16,161,946</td>
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<td></td>
<td></td>
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<td>57,681,693</td>
<td>48</td>
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<td>50.862</td>
<td>25.431</td>
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</table>

Test 1. Difference in slope

\[ F = \frac{20.091 - 3.46}{8.686} = 2.46 \]

\[ F_{1,46} @ 5\% \text{ is } 4.05 \]

So not significant

Test 2. Difference in elevation

\[ F = \frac{20.771 - 2.27}{9.142} = 2.27 \]

Not significant

The equations for high and low range are not significantly different from each other.

Test 3. Efficiency of 2 separate equations or a single combined equation.

\[ F = \frac{38.411 - 2.71}{3.374} = 2.71 \]

\[ F_{1,46} @ 5\% \text{ is } 3.19 \]

The improved efficiency of the two equations is not quite significant at 5\%. 
**APPENDIX 5.**

*(Chapter 8)*

**KINETIC ENERGY AND INTENSITY AVERAGED WITHIN STORMS IN THE LOW RANGE OF INTENSITY.**

<table>
<thead>
<tr>
<th>I</th>
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<th>Average Kinetic Energy</th>
<th>log K.E. A</th>
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<td>2.9455</td>
<td></td>
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</tbody>
</table>

1) Logarithmic regression

\[ \log x = 1.007463 \]
\[ \log y = 1.30945 \]
\[ \log y = 1.30945 X + 0.85139 \]

2) Linear regression

\[ \log x = 19.217 \]
\[ \log y = 1.022,003 \]
\[ \log y = 4.262.29 \]

3) Analysis of variance.

Residual S.S. from logarithmic regression 89,927 Not Significant
Residual S.S. from linear regression 76,641 Significant
APPENDIX 6.

(Chapter 8)

KINETIC ENERGY (A FORM) AND INTENSITY
IN HIGH RANGE OF INTENSITIES.

<table>
<thead>
<tr>
<th>X</th>
<th>Intensity (ins/hr x 10)</th>
<th>Y</th>
<th>Kinetic Energy (ergs/cm²/sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>36</td>
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</tr>
<tr>
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<td>44</td>
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<tr>
<td>47</td>
<td>880</td>
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<td>57</td>
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<tr>
<td>62</td>
<td>1325</td>
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<td></td>
</tr>
<tr>
<td>65</td>
<td>1265</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\[ \sum x^2 = 4.024 \quad r = 0.952 \]
\[ \sum y^2 = 1.621,155 \quad b = 18.91 \]
\[ \sum xy = 7,632.5 \quad a = 79.71 \]

\[ y = 18.91 x + 79.71 \]

\[ KE_A = 189.1 I + 79.71 \text{ ergs/cm}^2/\text{sec}. \]
APPENDIX 7
(Chapter 8)

ANALYSIS OF COVARIANCE. KINETIC ENERGY DATA.

1) Low range of intensity (0 - 4 ins/hr.)

\[ \chi_1^2 = 19.22 \quad \chi_2^2 = 1,022,003 \quad \chi_3 = 4,262.29 \]

\[ K_{E_A} = 221.79 \frac{I}{1 - 66.79} \]

2) High range of intensity (3 - 9 ins/hr.)

\[ \chi_1^2 = 40.24 \quad \chi_2^2 = 1,621,155 \quad \chi_3 = 7,662.5 \]

\[ K_{E_A} = 190.92 \frac{I}{1 + 79.71} \]

3) Pooled data, whole range.

\[ \chi_1^2 = 206.93 \quad \chi_2^2 = 9,263,271 \quad \chi_3 = 42,744 \]

\[ K_{E_A} = 210.7 \frac{I}{1 - 35.56} \]

(8-6)

<table>
<thead>
<tr>
<th>df</th>
<th>( \chi_1^2 )</th>
<th>( \chi_3 )</th>
<th>( \chi_2^2 )</th>
<th>Reg. Coef.</th>
<th>df</th>
<th>S.S.</th>
<th>M.S.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Low range</td>
<td>21</td>
<td>19.22</td>
<td>4,262</td>
<td>1,022,003</td>
<td>20</td>
<td>76.942</td>
</tr>
<tr>
<td>2</td>
<td>High range</td>
<td>27</td>
<td>40.24</td>
<td>7,662</td>
<td>1,621,155</td>
<td>26</td>
<td>154.435</td>
</tr>
<tr>
<td>3</td>
<td>Within</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>46</td>
<td>231.377</td>
</tr>
<tr>
<td>4</td>
<td>Reg. Coef.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1</td>
<td>12.536</td>
</tr>
<tr>
<td>5</td>
<td>Common</td>
<td>48</td>
<td>59.46</td>
<td>11,944</td>
<td>2,643,158</td>
<td>47</td>
<td>243.913</td>
</tr>
<tr>
<td>6</td>
<td>Adjusted Means</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1</td>
<td>7.583</td>
</tr>
<tr>
<td>7</td>
<td>Total</td>
<td>49</td>
<td>202.93</td>
<td>42,764</td>
<td>9,263,271</td>
<td>210.7</td>
<td>251.496</td>
</tr>
<tr>
<td>8</td>
<td>Residual ((7-3))</td>
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<td></td>
<td></td>
<td></td>
<td>2</td>
<td>20.119</td>
</tr>
</tbody>
</table>

Test 1) Difference in slope

\[ F = \frac{12.536}{5.030} = 2.50 \text{ N.S.} \quad t_{1.46} @ 5\% 4.05 \]

Test 2) Difference in elevation

\[ F = \frac{7.583}{5.190} = 1.46 \text{ N.S.} \quad t_{1.47} @ 5\% 4.04 \]

The equations for high and low range are not significantly different.

Test 3) Efficiency of 2 separate equations or a single combined equation.

\[ F = \frac{10.059}{5.240} = 1.92 \text{ N.S.} \quad t_{2.48} @ 5\% 3.19 \]

The improved efficiency of two equations is not significant.
## APPENDIX B.

(Chapter 11)

### SPLASH EROSION DATA.

<table>
<thead>
<tr>
<th>Y</th>
<th>$X_1$ (K.E. &gt; 1)</th>
<th>$X_2$ (K.E. &gt; 1) with wind correction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Splash (gm.)</td>
<td>ergs x 10$^3$/cm$^2$</td>
<td>ergs x 10$^3$/cm$^2$</td>
</tr>
<tr>
<td>0.3</td>
<td>28</td>
<td>31</td>
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<td>0.3</td>
<td>20</td>
<td>27</td>
</tr>
<tr>
<td>0.9</td>
<td>36</td>
<td>40</td>
</tr>
<tr>
<td>1.0</td>
<td>51</td>
<td>69</td>
</tr>
<tr>
<td>1.2</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>1.2</td>
<td>28</td>
<td>34</td>
</tr>
<tr>
<td>1.6</td>
<td>16</td>
<td>16</td>
</tr>
<tr>
<td>1.6</td>
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<td>200</td>
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<tr>
<td>2.2</td>
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<td>205</td>
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<tr>
<td>2.5</td>
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<td>71</td>
</tr>
<tr>
<td>2.8</td>
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<td>97</td>
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<tr>
<td>3.0</td>
<td>99</td>
<td>106</td>
</tr>
<tr>
<td>3.1</td>
<td>113</td>
<td>151</td>
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<tr>
<td>4.0</td>
<td>125</td>
<td>126</td>
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<td>4.6</td>
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<td>269</td>
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<td>800</td>
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<td>16.6</td>
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<td>3.6</td>
<td>82</td>
<td>85</td>
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<tr>
<td>3.8</td>
<td>159</td>
<td>185</td>
</tr>
<tr>
<td>5.2</td>
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<tr>
<td>9.9</td>
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<td>423</td>
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<td>5.4</td>
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<td>227</td>
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<tr>
<td>7.4</td>
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<tr>
<td>18.7</td>
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<td>894</td>
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<td>7.0</td>
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<td>14.8</td>
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<td>824</td>
</tr>
<tr>
<td>17.5</td>
<td>913</td>
<td>952</td>
</tr>
</tbody>
</table>

\[ \Sigma y^2 = 833.41 \quad \Sigma x_1^2 = 1,948,969 \quad \Sigma x_2^2 = 2,286,880 \]

\[ \Sigma x_{1y} = 38,598.9 \quad \Sigma x_{2y} = 42,629.7 \]

\[ Y = 0.0198 X_1 + 0.645 \text{ ergs} \quad (r = 0.998) \]

\[ Y = 0.0186 X_2 + 0.432 \text{ ergs} \quad (r = 0.977) \]

Test of intercept

\[ t_1 = \frac{6.45}{2.05} = 3.17 \quad \text{which is significant} \]

\[ (t_{29} = 2.05 @ 5\%, 2.76 @ 1\%) \]

\[ t_2 = \frac{4.12}{2.146} = 1.90 \quad \text{not significant.} \]

Difference between regression coefficients is not significant.
### Appendix C.

(Chapter 11)

**Soil Loss from Soil Trays**

<table>
<thead>
<tr>
<th>Y</th>
<th>$X_1$</th>
<th>$X_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil Loss (gms)</td>
<td>(K.R. &gt; 1)</td>
<td>(K.R. &gt; 1) with wind correction</td>
</tr>
<tr>
<td></td>
<td>$\text{ergs} \times 10^3 / \text{cm}^2$</td>
<td>$\text{ergs} \times 10^3 / \text{cm}^2$</td>
</tr>
<tr>
<td>218</td>
<td>65</td>
<td>71</td>
</tr>
<tr>
<td>227</td>
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<td>304</td>
<td>113</td>
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</tr>
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<td>34</td>
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<td>147</td>
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<td>894</td>
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<td>371</td>
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<tr>
<td>502</td>
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<td>824</td>
</tr>
<tr>
<td>670</td>
<td>963</td>
<td>952</td>
</tr>
</tbody>
</table>

\[ \Sigma y^2 = 847,853 \quad \Sigma x_1^2 = 1,912,791 \quad \Sigma x_2^2 = 2,167,668 \]
\[ \Sigma x_1y = 1,169,738 \quad \Sigma x_2y = 1,207,550 \]

\[ Y = 0.612 x_1 + 22.96 \quad (r = 0.919) \]
\[ Y = 0.557 x_2 + 21.24 \quad (r = 0.891) \]

Test of intercept

for $X_1$ \[ t = \frac{22.96}{13.03} = 1.76 \text{ not significant } (t_{.05} = 2.05 \text{ at } 5\%) \]

for $X_2$ \[ t = \frac{21.24}{14.96} = 1.42 \text{ not significant } \]

Difference between regression coefficients not significant.
APPENDIX 10.
(Chapter 11)

CORRELATION OF RUN-OFF FROM FIELD PLOT
WITH SOIL MOISTURE INDEX (1965/61)

<table>
<thead>
<tr>
<th>Y (inches x 100)</th>
<th>X (inches x 100)</th>
<th>Estimated Run-off (inches x 100)</th>
</tr>
</thead>
<tbody>
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<td>16</td>
<td>6</td>
</tr>
<tr>
<td>2</td>
<td>35</td>
<td>17</td>
</tr>
<tr>
<td>5</td>
<td>21</td>
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<td>161</td>
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<tr>
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<td>3</td>
<td>-</td>
</tr>
<tr>
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<tr>
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<td>13</td>
<td>4</td>
</tr>
<tr>
<td>11</td>
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<td>338</td>
<td>201</td>
</tr>
<tr>
<td>13</td>
<td>54</td>
<td>28</td>
</tr>
</tbody>
</table>

\[ \sum x^2 = 86,991 \quad \sum y^2 = 211,670 \quad \sum xy = 128,672 \]

\[ Y = 0.606X - 3.90 \] (inches x 100) \( r = 0.948 \)
or \[ Y = 0.61 X - 0.04 \] (inches)
### Appendix II

(Chapter 11)

#### Estimation of Run-off from Soil Moisture Index

(1961/62)

<table>
<thead>
<tr>
<th>( Y )</th>
<th>( X_1 )</th>
<th>( X_2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Actual Run-off (inches x 100)</td>
<td>&quot;Surplus&quot;</td>
<td>Predicted Run-off</td>
</tr>
<tr>
<td>5</td>
<td>41</td>
<td>21</td>
</tr>
<tr>
<td>12</td>
<td>47</td>
<td>35</td>
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<tr>
<td>5</td>
<td>9</td>
<td>1</td>
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<td>10</td>
<td>6</td>
<td>-</td>
</tr>
<tr>
<td>40</td>
<td>72</td>
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</tr>
<tr>
<td>21</td>
<td>24</td>
<td>11</td>
</tr>
<tr>
<td>40</td>
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</tr>
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<td>5</td>
<td>-</td>
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<tr>
<td>18</td>
<td>31</td>
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<td>37</td>
</tr>
<tr>
<td>84</td>
<td>122</td>
<td>70</td>
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</table>

\[ \sum y^2 = 11,206 \quad \sum x_1^2 = 23,024 \quad \sum x_1 y = 15,062 \]

\[
Y = 0.654 \ x_1 - 0.5 \text{ (inches x 100) (r = 0.938)}
\]

or \( Y = 0.65 \ x_1 - 0.005 \text{ (inches)} \)

**Pooled data 1960/61 and 1961/62**

\[ \sum y^2 = 99,176 \quad \sum x^2 = 241,017 \quad \sum xy = 146,225 \]

\[
Y = 0.607 \ x - 1.7 \text{ (inches x 100) (r = 0.948)}
\]

or \( Y = 0.61 \ x - 0.02 \text{ (inches)} \)
APPENDIX 12.

(Chapter 11)

CORRELATION OF SOIL LOSS FROM FIELD PLOT.

\[ Y = bX + a \]

(soil loss in lb) 

\[ Y_1 = Y + f \] 

(quantity of run-off)

\[ Y_2 = Y + f \] 

(rate of run-off)

<table>
<thead>
<tr>
<th>( X )</th>
<th>( Y )</th>
<th>( Y_1 )</th>
<th>( Y_2 )</th>
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<tr>
<td>48.2</td>
<td>366</td>
<td>43.2</td>
<td>42.2</td>
</tr>
</tbody>
</table>

\[ \Sigma Y^2 = 18,754.08 \quad \Sigma X^2 = 2,423,323 \quad \Sigma Y_1^2 = 351,805.1 \]

\[ \Sigma Y_2^2 = 201,195.4 \quad \Sigma X Y = 187,868.1 \quad \Sigma X Y_1 = 187,468.1 \]

\[ \Sigma Y_2 = 15,030.55 \]

\[ Y = 0.0830 X - 2.6 \quad (r = 0.943) \]

\[ Y_1 = 0.0775 X - 1.0 \quad (r = 0.973) \]

\[ Y_2 = 0.0774 X - 0.1 \quad (r = 0.982) \]