PLOTS FOR EVALUATING THE CATCHMENT CHARACTERISTICS AFFECTING SOIL LOSS

1 — Design of Experiments

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ABSTRACT

The use of sampling theory as a statistical basis for design and analysis of soil-loss plot experiments is proposed. Bias of plot data due to interference of natural flow conditions is described and some methods of investigating this are discussed. The use of variance analysis for testing the significance of differences between soil-loss data from different areas is suggested, and methods for locating plot sites within an area are examined.

INTRODUCTION

The difficulty of directly measuring sediment movement in New Zealand rivers is almost as great a problem as the amount of sediment moved. Most sediment movement occurs at very high river flows, and changes rapidly in catchments such as the Waimakariri in Canterbury, which is subject to flash flooding. The problem is complicated by constantly changing river beds which degrade in the rising stages of floods and later aggrade in the falling stages.

The measurement problem is multiplied many times when the sources of sediment are to be traced into tributary catchments. Small sample plots spread throughout a catchment provide a useful supplement to direct measurement, and some studies of soil loss from small plots in alpine regions have already been made. A comprehensive review of soil-loss plot experiments has recently been made by Hayward (1967).

Plots appear to have potential for two different types of soil-loss studies: as an estimator of the total surface erosion from catchments, and as an indicator of the relative rates of soil loss from sources of different characteristics. A statistical basis for these two types of experiment is discussed in this paper.

Many plot studies have been poorly designed, little attention having been given to the validity of the data collected, and frequent attempts made to extrapolate the results beyond the limitations of

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the original experiments. The major criticisms made of plot experiments have been concerned with the validity of the data (i.e. bias) and the statistical significance of the results. Plot studies require very careful experimental design and operational control if they are to provide valid and significant results.

A point frequently overlooked in plot studies is that the investigation carried out is fundamentally a sampling project. If plots of 1/1,000 acre each in area were used to estimate the behaviour of a 100-acre catchment, we can suppose that the total catchment consists of a population of 100,000 units and, by sampling the properties or behaviour of a small number of these units, we infer the behaviour of the total population (i.e. the whole catchment). As in all sampling experiments, attention must be given both to bias and to uncertainty.

BIAS OF PLOT DATA

Two assumptions that are fundamental in most theories of overland flow are that both velocity and depth of flow increase as the distance travelled by the flow increases. From established hydraulic knowledge, this demands that erosive power increases correspondingly with distance travelled.

The installation of boards surrounding plot-sample areas disturbs the build-up of overland flow. It must be inferred from this that plots will bias a sample because the nature of the plot construction tends to reduce velocity and depth of flow and correspondingly to underestimate soil movement. There may, however, be other factors which are as yet unknown and which could compensate for, or even reverse, this bias. No detailed studies have yet been made of the nature and magnitude of the bias created by plots, yet it seems essential that a study of bias inherent in the experiment should be made as part of any project which involves plot.

A project now in progress at Lincoln College involves a study of possible bias in conjunction with the use of plots for estimation of surface-soil loss. The objective is to estimate volumes of surface-soil movement by methods which do not interfere with the natural pattern of surface-water flow, and to compare these estimates with measurements of soil loss from closely adjacent plots.

The non-interfering methods for estimating soil movement will be combinations of the following:

(i) Permanent plugs will be set into the ground so that a straight-edge can be laid across them and a record taken of the microprofile of the ground. A series of such plugs will be used to cover an area about the same size as a plot. It is assumed at this stage that the plugs can be set deeply enough for them to remain rigid despite expansion and contraction of the surface-soil layers or mass downhill movement of the soil. Repeated measurements of the microprofile will be taken, in particular immediately after each heavy storm that occurs.

(ii) A permanent pedestal will be set up immediately downhill of the test area so that the soil surface can be repeatedly photographed from the same position over the period of the study. A study will be made to see if the varying exposure of semi-buried stones or the movement of surface stones can be used to estimate loss or movement of surface soil. Painted lines will also be used to assess the behaviour of surface soil.

(iii) Small-diameter holes will be drilled vertically into the soil and small chains will be buried in a vertical position in these holes. At intervals during the study, small trenches will be excavated to expose the vertical profile of the chain as a check for mass downhill soil movement.

UNCERTAINTY

There are two major types of experiment for which plots are used:

(a) homogeneous areas where plots are used as a sample of a single population and extrapolations are made from the sample to estimate the behaviour of the whole homogeneous area;

(b) areas representing different populations (e.g. different soil-cover complexes in a heterogeneous catchment) where plots are used as samples to establish the significance of differences between the populations.

Homogeneous Areas

Within any small catchment area or sub-area (these may be regarded as homogeneous because of visual uniformity in obvious characteristics such as vegetation, cover, or soil type) there will inevitably be variations in surface-soil loss due to unavoidable variations in such things as aspect, position on slope, and rainfall.

Assuming that estimates of soil loss obtained from plots are unbiased, the results obtained from the plots may be regarded as a small sample from a large population (i.e. the whole catchment) and the samples may be averaged to estimate the average loss per sample, and subsequently to derive an estimate of soil loss from the whole catchment.

The number of samples taken will always be only a small portion of the total population being examined; there will be a degree of uncertainty attached to an estimate of average loss or total catchment loss. The confidence which can be placed in the estimate is a function of the variance of the sample, and this is rarely calculated in practice.

If there are n plots in a homogeneous sub-area or catchment, and the amounts of soil loss measured in a specified period are $x_1\ x_2\ \ldots\ x_n$, then:

$$\text{Mean value of soil loss per plot, } \bar{x} = \frac{\Sigma_{i=1}^{n} x_i}{n}$$

$$\text{Variance of sample} = \frac{\Sigma(x-\bar{x})^2}{(n-1)}$$

$$\text{Standard error of the mean} = \sqrt{\frac{\text{variance}}{n}}$$

The standard error of the mean gives an indication of the degree of uncertainty associated with the estimate of average loss per plot or total loss from the sub-area or catchment. It is possible to calculate the range of values (confidence limits) within which it is 95% certain that the true average will lie — or limits for 99% certainty or 90% certainty, and so on.

A more important result that can be obtained from the variance is an estimate of how many plots would be necessary to determine the value of the total soil loss from the catchment within any specified permissible tolerance.

If the tolerable error in estimating the mean soil loss per plot is specified as ε tons/acre (or whatever units of loss are used in the experiment), then the required sample size may be computed from the formula:

$$n = \frac{t^2 \ .\ \text{variance}}{\varepsilon^2},$$

where n = number of samples required,

t = value of student's t corresponding to required significance of results (use $t = 2$ for 95% confidence).

Differences between Areas

The variance of soil loss from plots in a single homogeneous area can establish the significance of any extrapolation of plot data for estimating total soil loss from the whole area as described above. However, the problem more commonly encountered in practice is that of establishing whether there are significant differences among the soil losses from a number of homogeneous sub-areas.

The object of any such study must be to establish that there is more variation between different sub-areas than there is variation within sub-areas. The statistical technique of analysis of variance gives a straightforward method for determining whether the differences between samples are significant or due to chance occurrence.

To test the significance of the differences between sub-areas, a null hypothesis that all samples come from a common population and that differences between sub-areas are due to chance occurrence is adopted. The assumption can be tested by considering the ratio of the variance between sub-areas to the variance within sub-areas. The greater the variance ratio, the less likely it is that the null hypothesis is valid.

The significance of the differences between sub-areas is given by Snedecor's Variance Ratio Tables. These give the probability that the differences arose by chance. The method of application is straightforward and is covered in standard statistical texts, e.g. Weatherburn (1949) or Moroney (1954, Ch. 19).

The experiment being conducted by J. Hayward of Lincoln College at Porters Pass, on the divide between the Rakaia and Waimakariri catchments, illustrates the use of variance analysis in the design of a soil-loss plot experiment.

The catchment used for the experiment has an area of 55 acres and rises from an elevation of 3,200 ft at Porters Pass to about 5,000 ft at the top, in a distance of three-quarters of a mile. From a surface reconnaissance of the area aided by aerial photographs, five relatively homogeneous sub-areas have been defined on the basis of vegetation cover and, to a lesser extent, soil type. Four plots are located within each sub-area.

The 20 plots have been installed to examine the variability of soil loss within this catchment and the validity of results which are obtained from small plots. If significant differences of soil loss from the different sub-areas can be established, a further step will be taken to calculate the number of plots needed to determine the mean rate of soil loss from each sub-area for different levels of confidence. These are determined by the method set out for homogeneous areas in the preceding section.

The total number of plots selected (20) was determined by an estimate of the work which could be handled by one man in servicing the plots, bearing in mind that an estimated fewer than four plots per sub-area would not provide worthwhile data for analysis. The information on variance of soil-loss data provided by this experiment should give a rational basis for determining numbers of plots when later experiments are to be made.

SELECTION OF PLOT LOCATIONS

If each so-called homogeneous area or sub-area were perfectly homogeneous, the location of plots within the area would not matter. By definition, the rate of soil loss at any time would be the same over the whole of the area or sub-area and only a single sample would be needed to determine the mean soil loss or the total soil loss.

Because of the variability within each area, more than one sample is required. The question arises as to where the plots are to be located within the area for most efficient exploration of the variability. The three options available are to select locations on site deliberately, to select locations entirely at random, or to select according to some systematic pattern.

The deliberate on-site selection of location introduces a maximum of personal bias and consequently a maximum of uncertainty in the results. If a serious attempt is to be made to estimate the variance within the area, the selection of locations entirely at random is to be preferred. There will be a maximum of confidence in the standard error of the results obtained in this way. The random locations can be found by selecting grid co-ordinates of the locations on a map of the area from random number tables.

An alternative is to locate the samples in each homogeneous area according to a systematic pattern. For example, plots could be located in such a way that the Thiessen weights of the areas of Thiessen polygons, drawn around the plot locations, are equal. The advantage of systematic sampling is that it is most efficient in exploring the variability within each area. The disadvantage is, however, that there is no completely reliable method for estimating the amount of uncertainty (i.e. the standard error) with systematic sampling.

Considering the present lack of knowledge of variance within so-called homogeneous areas, it seems desirable that the random location of plots be adopted in soil-loss experiments. The plot locations for the Porters Pass experiment were established using random numbers for grid co-ordinates on a map of the area, and these were subsequently transferred to the actual sites by a tacheometer survey.

SUMMARY

Most of the disagreements between protagonists and antagonists of plot studies are concerned with the bias of data caused by the plot construction, and the statistical analysis of the uncertainty associated with the results. The experiment at Porters Pass has been designed to examine both of these aspects and to clarify the value of plot studies as a hydrological method of experiment for future work.

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