DESIGN CRITERIA
FOR LABORATORY CATCHMENT EXPERIMENTS,
WITH PARTICULAR REFERENCE
TO RAINFALL SIMULATION

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SUMMARY

The study of the hydrological cycle of an artificial catchment area under laboratory conditions has, for many years, remained a possible, but exciting, future development. If the term “laboratory catchment” is defined as a physical system of limited areal extent on to which an “input” of rainfall, either real or simulated, is applied to produce an “output” in the form of surface and/or subsurface run-off, it is seen that the concept is not as recent as one might at first imagine. The pioneer work on soil erosion problems in the United States during the 1930’s was largely based upon the study under controlled conditions of small plots, each of which was effectively a simplified model of the hydrological cycle. In studies of the hydraulics of overland flow during the 1940’s, an even simpler conceptual model was investigated.

What appears to have been the first attempt to construct a scale model of a natural catchment was made during the 1950’s. Another decade has seen a return to the use of the plane, two-dimensional impervious surface, not as a small hydraulic prototype, but as a “system” for generating data against which non-linear rainfall/run-off theories can be tested.

The above studies have by no means exhausted the potential uses of laboratory catchments. In the following paper, existing work is reviewed, and a new approach to the problem of determining the influence of catchment characteristics on the shape of flood hydrographs using artificial catchment areas in the laboratory is suggested.

A major difficulty in any laboratory catchment experiment is the design of the associated equipment for the production of storms of artificial rainfall. The selection of design criteria for the rainfall simulator to be used in the proposed experiments is discussed in detail, and a working solution outlined.

RÉSUMÉ

Étudier le cycle hydrologique d’un bassin hydrographique artificiel est resté depuis beaucoup d’années un développement à venir, possible et excitant. Si le terme « bassin hydrographique de laboratoire » est déterminé comme un système physique d’une étendue bornée sur laquelle « une entrée » de précipitation, soit naturelle soit simulée, a été appliqué pour produire « une issue » en forme d’un écoulement de la surface et/ou de la sous-surface, cela se voit que cette idée n’est pas si récente a ce qu’il paraissait auparavant. Le travail pionnier sur des problèmes de l’érosion de terrain aux États-Unis pendant les 1930 était fondé pour la plupart sur l’étude sous des conditions contrôlées de petites pièces de terre chacune étant effectivement un modèle simplifié du cycle hydrologique. Aux études hydrauliques d’écoulement par la voie de terre pendant les 1940, un modèle même plus simple était recherché.

Ce qui paraît avoir été le premier essai de construire un modèle en proportion d’un bassin hydrographique a été fait pendant les 1950. Une autre décennie a vu un retour de l’usage de la surface plane, imperméable et en deux dimensions, pas comme un petit prototype hydraulique mais comme un « système » pour produire des données contre lesquelles des théories non-linéaire de l’écoulement de précipitation peut être éprouvées.

Ces études ci-dessus n’ont par aucun moyen épuisé les usages possibles de bassins hydrographiques. Sur la dissertation suivante le travail existant a été revu et une approche nouvelle au problème de déterminer l’influence de traits caractéristiques d’un bassin hydrographique sur la forme des hydrogrammes d’inondation utilisant des bassins hydrographiques simulés au laboratoire a été donnée.

Une grande difficulté dans aucune expérience concernant un bassin hydrographique de laboratoire est le dessin de l’équipement associé pour produire des orages de précipitation simulée. Le choix du critérium du dessin pour le mécanisme à simuler de précipitation qui peut être utilisé aux expériences proposées a été discuté en détail et une solution pratique a été esquissée.

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INTRODUCTION

In a critique of current methods in hydrological research, Amorocho and Hart (1964) commented upon the growth of two distinct approaches to the basic problem of establishing the relationship between rainfall and run-off.

The first approach, which those authors referred to as "physical hydrology", involves the investigation of the behaviour and interdependence of component phenomena within the hydrological cycle. Individual studies may cover the working of only one component under a restricted range of conditions, but their long-term objective is a complete synthesis of the cycle. Although the application of results to the solution of technological problems is recognised, such investigations are not made with the primary objective of providing data for this purpose. Interest is centred on the scientific understanding of the mechanism of the particular component process under study.

The second approach, however, is concerned with providing solutions to engineering problems within limited periods of time. Historical sequences of measurements of only those variables within the hydrological cycle which appear significant to the overall behaviour of the catchment are used. Relationships are developed between these variables to provide a solution which it is hoped is applicable within the range of working conditions represented by the data. In this approach, to which Amorocho and Hart gave the name "system investigation", interest is centred upon the methods of solution rather than the behaviour of the physical processes involved.

Despite the differences between the two approaches, system investigation cannot proceed without reference to the results of physical studies. Knowledge of the working of the component processes is necessary for the selection of pertinent variables for system investigation. The interpretation of results from such work also depends upon a clear understanding of the physical processes involved.

Studies which can be included under the general heading of physical hydrology usually involve the presentation of a hypothesis which, if a successful test can be applied, may be converted into a theory. Hence these studies have proceeded largely through the collection of field data. Such investigations are notoriously difficult to design and execute when natural rainfall, with its high variability in space and time of intensity and duration, is included as a major variable. In addition, detailed and accurate field observation of the consequences of rainfall in the hydrological cycle appear so difficult and wasteful in time and effort that this approach has rarely been undertaken in practice. Economically the impetus to seek alternative methods of investigations seems to have been stronger in soil-erosion rather than hydrological studies. The pioneer investigators of soil-erosion problems in the United States of America chose to develop mechanical methods for producing artificial rainfall.

"Rainfall simulators" or "artificial rainfall applicators" allow an investigator to create artificially conditions in which hydrological processes are set in motion. He is provided with a degree of control over these conditions which is conspicuously lacking in the more traditional methods of field testing. Moreover, provided that the physical system under study can be reproduced satisfactorily in the laboratory, results can be obtained more rapidly and costs reduced to a minimum.

Rainfall simulators have now become a standard item of research equipment for work on many other aspects of soil behaviour which could be classified under physical hydrology. The extension of their use to more general hydrological problems falling within the scope of system investigation has proceeded more slowly. The possibility of studying the hydrological cycle of a laboratory-size artificial catchment area has remained no more than an exciting future development. The theoretical and practical problems presented by such experiments are manifold, and yet sufficient progress has been made during the last ten years for Amorocho and Hart (1965) to propose a classification for this type of study.
A "laboratory catchment" may be defined as a physical system of limited areal extent on to which an "input" of rainfall, controlled in space and time, in intensity and possibly in drop-size distribution, is applied to produce an "output" in the form of surface and/or subsurface run-off. Given a similar definition, laboratory catchments were considered by Amorocho and Hart to fall into the following categories:

1) Model catchments;
2) Laboratory prototype systems;
   1) Hydromechanic prototypes;
   2) Prediction analysis prototypes.

This classification forms a convenient basis for reviewing the progress that has been made in the use of laboratory catchments at the present time.

2. LABORATORY CATCHMENT STUDIES

a) Model Catchments

When the physical features of a natural (prototype) catchment are reproduced to an appropriate scale in a laboratory model from which predictions of prototype behaviour are obtained by the application of similarity criteria, the catchment is termed a "model catchment". In developing a prediction equation for the model, a set of variables must be selected relating to the condition of the catchment which are thought to be significant in transforming rainfall into a discharge at the outfall of the area. For example, the relationship between the rate of rainfall (i) and the rate of runoff (Q) may be considered to be affected by, inter alia, the space co-ordinates of the catchment area (x, y, z), the infiltration capacity of the soil (f), time (t), the roughness of the surface and resistance of the vegetation (r), the density, viscosity and surface tension of water (ρ, μ, σ) and the acceleration due to gravity (g). A functional relationship of significant dimensionless terms might be of the form:

$$\frac{Q}{ix^2} = fn\left\{\frac{it}{x^2}, \frac{x}{gt^2}, \frac{y}{zt}, \frac{z}{xt}, \frac{p}{\rho \mu \sigma r^2}, \frac{p}{\rho x^2}, \frac{R}{gt^2}\right\}$$

The first four terms on the right-hand side of equation (1) (the second of which has the structure of the Froude number) may be completely satisfied in a model. If the Froude number criterion is satisfied, then the sixth and seventh terms (Reynolds and Weber numbers) cannot be satisfied simultaneously. In addition, in an impervious model variables such as infiltration capacity and surface roughness are vastly distorted. The prediction equation must therefore contain an additional distortion (or scale) factor which is a function of the last four terms on the right-hand side of equation (1). The problem of assigning a value to this factor may be approached by adjusting the roughness distortion to compensate for the other three terms and attempting to make the factor unity, in which case the model must be verified by adjusting its surface roughness until acceptable correspondence is obtained between prototype and model values of Q and i.

An early model catchment study was reported by Mamisao (1952). The object of his study was the evaluation of the effect of cultural practices on run-off from an agricultural catchment. Although Mamisao was unable to complete the verification of his model, some interesting results were obtained. The general form of the model hydrographs closely resembled their prototype counterparts, although times-to-peak were underestimated and the total volumes of run-off overestimated by the model.

The results of another model catchment study have recently been reported by Chery (1966). The differences between his work and that of Mamisao lay in the choice of the principal scaling ratios and the modelling material, as shown in table (1).
TABLE 1
A comparison between the details of two model catchment experiments

<table>
<thead>
<tr>
<th>Author</th>
<th>Date of publication</th>
<th>Length ratio</th>
<th>Time ratio</th>
<th>Modelling material</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mamisao</td>
<td>1952</td>
<td>1:450</td>
<td>1:240</td>
<td>mortar</td>
</tr>
<tr>
<td>Chery</td>
<td>1966</td>
<td>1:175</td>
<td>1:175</td>
<td>fibreglass</td>
</tr>
</tbody>
</table>

The results from a series of preliminary tests presented by Chery provide an interesting contrast to those obtained by Mamisao. Chery found that when a scaled rainstorm was released on to a dry model, the water gathered into small globules scattered over its surface, and no run-off occurred. Two alternative operating procedures were tried in an attempt to eliminate this effect. The application of sufficient water to the model surface to compensate for the initial storage before reproducing the scaled storm provided a multi-peak model hydrograph totally different in form to the reduced prototype hydrograph. When the scaled rainfall intensities were magnified by a factor of three and applied to a dry model, the displacement in time of the run-off relative to the rainfall was found to agree closely with that obtained by applying the appropriate scaling ratios to the prototype data. However, run-off from model again occurred in a succession of peaks not produced by the prototype.

It is interesting to note that all the tests made by Mamisao were performed with storms whose intensities were magnified as a matter of convenience in controlling the variations in time of the artificial rainfall. Furthermore, by using a topographic model having a vertical distortion, Mamisao was able to avoid the surface retention effect so apparent in Chery’s results. The reasoning which led Mamisao to introduce a vertical scale distortion is not clear from his writing, and it is possible that the choice was again made for experimental convenience.

Neither investigator appears to have published any conclusions on the use of scale models in evaluating catchment behaviour; neither reported his studies beyond initial verification tests. The theoretical basis of the method has been examined by Amorocho and Hart (loc. cit., 1965) who pointed out that (a) there is no assurance that the surface texture of a model may be adjusted over a sufficiently wide range of values to yield the correct correspondence between prototype and model behaviour, and (b) once correspondence between two variables (say inflow and outflow) has been established, the system can be relied upon only to predict the two variables, but—except accidentally—cannot reproduce prototype behaviour in any other respect. The empirical treatment of the scaling laws which is necessary to provide a prediction equation, and the apparent need to apply separate scaling factors to the rainfall and the topographic model still cast considerable doubt upon the validity of the whole method.

b) Laboratory Prototype Systems

In contrast to model catchments, “laboratory prototype systems” are employed for the investigation of specific flow phenomena. Historically, the first laboratory catchment studies were made with hydromechanic prototypes. The study plots used during the 1930’s to investigate soil-erosion problems could be said to fall under this heading. However, the term is more generally associated with the two-dimensional, impervious and semi-impervious surfaces used in connection with studies of the fluid mechanics of overland flow. The classical work of Izzard (1946) and more recent studies by Woo and
Brater (1962) and Yu and McNown (1964) provide ready examples of this type of work.

The prediction analysis prototype is a product of the system investigation approach. Whereas the hydromechanic prototype is used to study a detailed flow mechanism, the prediction analysis prototype is used as a tool for the development of methods of analysis. The relationship between rainfall inputs and outputs of run-off is considered as a macroscopic natural process which is capable of description by mathematical expressions involving the use of the measured input and output data only. The prediction analysis prototype is used to generate data with which the theories and methods of analysis may be tested. Both linear (Nash, undated) and non-linear conceptual models (Amorocho and Oriob, 1961; Amorocho, 1963) have been studied in this manner.

c) A Further Classification: Microcatchments

The three-fold classification proposed by Amorocho and Hart is adequate in covering all varieties of laboratory catchment known to the authors. However, the advantages in the control of inputs, which the use of a rainfall simulator permits, coupled with the possibilities of creating artificial catchments in the laboratory that are capable of unlimited variations in form, roughness, permeability and other subsurface properties, etc., provide a further dimension to laboratory catchment studies not included in their classification.

Methods of analysis may in themselves contribute nothing to our understanding of the time-distribution of the hydrological processes involved in transforming rainfall into run-off. If the assumption that rainfall patterns over a drainage basin are uniformly consistent or geometrically similar is accepted, the shape of the run-off hydrograph from the area may be regarded as reflecting only the effects of certain characteristics of the catchment. Similarly, the shapes of hydrographs are determined solely by catchment characteristics if the catchments are large enough for the effects of any local variations in rainfall intensity to be damped. This logic has formed the basis of many methods for producing hydrographs for ungauged catchments, in which one or more parameters of the hydrographs from other basins in similar climatic areas have been correlated with one or more measurable catchment characteristics.

The success of these methods is beyond the scope of the present discussion, but the fact remains that certain characteristics of a catchment have been found to exert a profound influence on their behaviour in times of flood, as illustrated, for example, by Dobbie and Wolf (1953). In their paper, the topographic features of the immature Lyn River catchment in Devon were discussed in relation to the catastrophic flood of August, 1952. This catchment was described as having gently rounded moors curving at ever increasing slopes down to streams which have curved deep valleys for themselves. The sides of the valleys are steep and never very far apart, so leaving little room for flood storage. The longitudinal slopes are steep. In an appendix to a later paper, Wolf (1957) showed by the application of simple hydraulic concepts that the amount of flood storage would be underestimated, and the peak rate of flow overestimated unless the pronounced convexity of the catchment was taken into account. The Lynmouth catastrophe would have been even worse without the great breadth of the Exmoor plateaux.

To study the time distribution of the various component phases of the hydrological cycle on natural catchments in relation to their surface topography, geometry and other hydraulic factors in detail seems to require a virtually unattainable effort involving accurate measurements in many places almost continuously over many years. The more economical alternative approach would be to investigate these same effects on laboratory catchments. In effect, this treatment would amount to a process of synthesis in which the system is described by a series of components whose functions are known, and whose presence in the system is assumed initially by the investigator. With the distribution in time and space of artificial rainfall controlled, the physical features of the
laboratory catchment could be varied as required, and the different responses in outflow measured directly.

The operation of such laboratory catchments would not involve the application of similarity criteria. Whereas the prediction analysis prototypes used by Amorocho and his fellow investigators are simple, non-linear systems with controlled input parameters, the laboratory catchment experiments suggested above would also involve the study of controlled catchment parameters. The laboratory catchments used in the latter type of study would be miniature catchments whose features could be varied to take any geometrical and topographical forms, especially those typical of natural drainage basins. To distinguish between this and the other varieties of laboratory catchment described above, the present writers propose to refer these to miniature catchments as “microcatchments”.

The microcatchment experiments would begin with the study of very simple examples in which the total volume of artificial rainfall applied to the catchment appears as direct run-off. In mathematical terms, the microcatchment would act as a “closed system”. The extension of studies to “open systems” could be undertaken once the basic case, which might correspond all in essential details to an urban or impervious natural catchment, has been largely understood.

A raised reinforced concrete tank measuring 36 ft. (11.0 m) by 23 ft. (7.0 m) by 5 ft. (1.5 m) deep has been constructed in the Hydraulics laboratory of the Department of Civil Engineering, Imperial College of Science and Technology (University of London) to permit this kind of experimentation. A grid of nozzles has been erected above the tank to supply the artificial rainfall. A pattern of 16 pipes cast into the sides of the tank and 96 drains in the floor will permit the control of groundwater flows once a permeable medium has been introduced, and the control of channel flow for special studies of “sub-catchments”.

3. THE SIMULATION OF RAINFALL FOR LABORATORY CATCHMENT STUDIES

A problem which must be faced immediately upon beginning any laboratory catchment experiment is the choice of a suitable method of generating artificial storms. In compiling a specification for a rainfall simulator, whatever the purpose of the investigation for which the apparatus is intended, an obvious requirement must be that its mode of operation must not influence the working of the hydrological process under study. In other words, the properties of the spray which are significant to the investigation must be known before the choice of a suitable method of simulating rainfall is made.

A feature common to many of the designs of rainfall simulator devised during the 1930’s for work on soil erosion problems was the use of commercially available sprinkler-irrigation equipment to generate the spray. The comparison between the artificial rainfall and natural rainfall was based solely on the ability of the apparatus to apply specific depths of application at all points over a test area within a given duration, i.e., depths of application were checked for uniformity in space only. At that time, little information had been obtained regarding either the distribution of drop sizes or the velocity of fall of drops in natural rainfall. Although the importance of these parameters in the erosion process was appreciated by some investigators, the formulation of the additional criteria was prevented by the lack of reliable quantitative measurements of the prototype. This deficiency of knowledge was not remedied until the U.S. Soil Conservation Service published the results of prolonged and detailed laboratory and field studies (see Laws, 1941; Laws and Parsons, 1943).

When the operating pressure of a system of nozzles increases, the discharge from the nozzles, and therefore the intensity of the spray at a given level below the system, is increased. The same increases in pressure cause a greater degree of atomisation of the
spray, resulting in larger quantities of smaller drops and a narrower spectrum of drop sizes. In contrast, when the intensity of natural rainfall increases, there is a general tendency for a wider spectrum of drop sizes to occur having a decreasing proportion of small-diameter drops and increasing numbers of large-diameter drops. Most writers on rainfall simulation (for example: Mutchler and Hermsmeier, 1965) agree that nozzles and sprinkler-irrigation equipment present the only practicable method of producing a drop-size distribution comparable with that found on the average in natural rainfall. Unfortunately, as the same authors have noted, there are many nozzles capable of providing drop-size distributions similar to those in natural rainfall, but with discharges giving application rates much higher than the natural rainfall intensity associated with those size distributions.

In an effort to overcome this difficulty, various attempts have been made to devise methods by which conventional equipment can be modified to make the drop-size distribution and the intensity of the simulated rainfall correspond. These modifications have consisted of either control systems which close down the nozzles at regular intervals during a test, or driving mechanisms which move the nozzle system so that larger areas are covered, or both. The "rainulator" (see Meyer and McCune, 1958; Meyer, 1960), a rainfall simulator designed specifically for soil-erosion research, provides an outstanding example of a device in which both features were found to be necessary.

Where either or both modifications have been made to an apparatus, its performance differs from that of a stationary continuously spraying device in one important respect. The total depths of water applied to any given points within the study area may be roughly equal when considered over the full duration of a test, but at any time during the test the rate at which water is being applied to those same points may be widely different. A rotating irrigation sprinkler provides an illustration of this type of performance. The application depths are uniform in space, but application rates are not uniform in time.

For the purposes of sprinkler irrigation, where the objective is the satisfaction of an existing soil moisture deficit, the uniformity in time of application rates has little bearing on the success of the procedure. In general, hydrological systems varying in size from field plots measured in fractions of an acre to catchments of many thousands of square miles are known to be "highly damped", so that high-frequency perturbations in the time distribution of rainfall are unlikely to produce similar variations in the time distribution of the run-off from the system. The higher the frequency of an intermittent application, the less the effect is likely to be. However, when the system under study consists of a relatively smooth, impervious surface, as is predominantly the case with a laboratory catchment in its simplest form, the existence of a similar damping mechanism cannot be assumed with the same degree of assurance. Until further information on this aspect of laboratory catchment behaviour becomes available, continuous applications of water should be specified, thereby ensuring both uniformity in time of application rates and uniformity in space of application depths.

After the inclusion of these criteria in the specification of apparatus for a laboratory catchment experiment, the problem of the generation and the significance of drop-size distributions must be considered. A clear distinction must be drawn between the role of drop sizes and their velocities of fall in determining the behaviour of soils, particularly with regard to erosion, and that of the same parameters in disturbing the flow across the surface of a laboratory catchment.

Unlike the effect of intermittent applications of water on the behaviour of a system, the influence of rainfall on sheet flow over impervious and semi-impervious surfaces has received some attention in recent years, and the available literature does allow some tentative conclusions to be drawn upon this topic. Yu and McNown (1964) presented data on the variation of resistance coefficients with Reynolds number for a concrete surface during steady runs both with and without artificial rainfall. Despite considerable
scatter these data show that, in the transition zone, the resistance coefficients obtained with rainfall are higher than those without rainfall. In the fully turbulent region, the coefficients were essentially the same either with or without rainfall.

These results confirmed the opinion previously expressed by Woo and Brater (1962) that the impact of raindrops hastens the change in the regime of sheet flow from laminar to turbulent. The effect of the impact of drops can therefore be included in any analysis by suitable adjustment in the value of the resistance coefficient for the particular surface under study. If attention is centred upon the relationship between rainfall and run-off, as in a laboratory catchment experiment, the drop-size distribution of the simulated rainfall and the velocities of the drops on impact may be taken into account in this manner. As a first approximation, therefore, the consideration of drop-size distributions need not enter into a specification.

Once the constraint that a rainfall simulator should produce a specific size distribution of drops has been removed, the designer may turn his attention to other methods of generating artificial storms which do not involve the use of nozzle networks. Both of the principal alternatives were devised by scientists whose objectives were to study independently the influence of drop-sizes, of the velocities of fall of drops at impact and of the intensity of rainfall on the behaviour of soils. Both designs of apparatus incorporate a large number of closely spaced drop formers each of which discharges a stream of individual drops.

The first of these designs, which is often referred to as the “dripolator” or “stalactometer” was devised during the U.S. Soil Conservation Service experiments in 1937. The drop-forming stage of the apparatus consisted of a sheet of cloth supported by a screen of chicken wire. The cloth was depressed into each opening in the wire mesh, and lengths of woollen yarn were attached to the underside of each pocket. Water sprayed on to the cloth was collected in the depressions, and released as individual drops from the lengths of yarn. The impact velocities of the drops were changed by altering the height of this “drip screen” above the test area. The size of drops produced was controlled by the size of the wire mesh and the grade of the yarn, and the intensity of application was regulated by the rate of supply of water to the drip screen. Woo and Brater (1962) used an apparatus of this type in their studies with a hydromechanic prototype.

This two-stage method is relatively cumbersome compared with the second design in which the drop-formers have consisted of short lengths of fine-bore capillary tubing or hypodermic needles. The major disadvantage of both this type of apparatus and the dripolator type has been that the individual drop formers have been considered to provide a uniform application of water to elemental areas defined by their spacing. The larger the discharge from a drop former, the wider the spacing necessary to provide a given intensity of application. The absence of guidance from the originators of both types of apparatus on the choice of spacings to produce predetermined levels of uniformity of application has been conspicuous. Intervals of from \( \frac{1}{2} \) to \( 2\frac{1}{2} \) inches (1\( \frac{1}{4} \) to 6\( \frac{1}{4} \) cm) have been used, although 1 inch (2\( \frac{1}{2} \) cm) appears to have been the most popular figure. Unless the rainfall simulator or the test area is rotated or oscillated in some way (thereby providing discontinuous applications), such devices may provide a large number of “point sources” rather than a homogeneous spray of drops. Recent work by Mutchler (1965) on the drift of water drops falling in still air has enable some estimate to be made of the spacing of drop-formers necessary to produce a given uniformity of distribution. It is interesting to speculate on the differences in the design of apparatus which would have resulted had this work been carried out some 15 to 20 years earlier.

Fine-bore capillary tubing is susceptible to blockage by fine grit carried in suspension, and their quality tends to deteriorate with time. Small variations in the diameter of individual drop formers may cause significant differences in their discharge under identical head conditions. To date, this method of simulating rainfall has been confined to relatively small test areas, although Chery (1966) devised an apparatus for
model catchment experiments to cover an area approximately 22 ft (6.7 m) long and 10 ft (3 m) wide. Chow and Harbaugh (1965) have recently proposed the use of nearly 60,000 drop-formers in one apparatus for a similar type of study.

The advantage of having an apparatus with individual drop formers tends to lie in the convenience with which the apparatus may be adapted to provide complex storm patterns. Compared with a network of nozzles, in which the smallest elemental area or "cell" over which the application pattern may be varied is limited by the spacing of the nozzles, both the dipolator type and the capillary-tubing type of apparatus permit greater refinement in the definition of the patterns by providing greater flexibility in the choice of the size of a cell. The smaller the cell, the more closely moving storms or "distributed parameter" inputs may be simulated. However, the larger the number of cells, the greater the control problem, and when working within a limited budget the cost of the additional equipment must be balanced against the value of producing the more finely defined artificial storms.

The simulation of storms of more complex than "pulse" or "step function" patterns is impossible if changes in the intensity of the input can only be made discontinuously. Many of the rainfall simulators that have been used in soil-science research were designed to provide discrete intensities of rainfall. These intensities were altered either by changing the nozzles on a spray system of by adjusting the working pressure of the apparatus. For model catchment experiments, in which the reproduction of prototype storm events is fundamental, the provision of continuously varying intensities of artificial rainfall is an essential design criterion. This criterion should perhaps be extended to cover all types of laboratory catchment study, even though, to date, work with prediction analysis prototypes has been concerned with the responses to idealised inputs and that with hydromechanic prototypes with steady behaviour.

Investigators who have concerned themselves with the simulation of more complex storm patterns have varied in their selection of the range of rainfall intensities to be provided for their experiments. As outlined in section 2(a) above, the results of model catchment experiments published to date tend to indicate that correspondence between model and prototype may only be obtained when a scaling factor is applied to the intensities of rainfall recorded on the prototype. Where the magnitude of this factor is unknown, the choice of the range of intensities of artificial rainfall to be provided must be made at the discretion of the investigator. For laboratory catchment experiments which do not involve problems of dynamic similarity, the choice is predominantly influenced by the need for a versatile apparatus capable of providing a wide range of experimental conditions. In general, a range of 10:1 or 20:1, with an upper limit of 10 in/h (or say 250 mm/h), is probably sufficient for most purposes.

Taking into account all points in the above discussion, the specification for a rainfall simulator for use in laboratory catchment experiments can be summarised as follows:

a) The artificial rainfall should be applied continuously to the test area, i.e., depths of application should be uniform in space, and under steady conditions rates of application should be uniform in time;

b) Depths and rates of application should be reproducible under given experimental control conditions;

c) Rates of application should be continuously variable over a range of at least 10:1;

d) The maximum rate of application provided should be at least 10 in/h, and

e) Provision should be made for the production of moving storms (or distributed-parameter inputs), subject to the conditions that such storms should be reproducible.
4. Studies at Imperial College, London; A suggested solution

The above specification formed the basis of a recent investigation by M.J. Hall, into methods of producing artificial storms for laboratory catchment experiments at Imperial College, London. Of the methods of simulating rainfall described in section 3, a system of nozzles was thought to offer the most economical solution for the area of 828 ft.² (77 m²) available for the proposed microcatchment studies. The possible limitations of a nozzle system in producing the type of input listed under point (c) above have already been discussed. However, by placing the nozzles on lines supplied from a manifold running along one side of the test area, and controlling each line independently, a system is obtained which is sufficiently flexible to produce a large variety of storm patterns. Although storm movements are restricted to the direction parallel to the manifold, the orientation of the catchment with respect to the rainfall simulator may be altered to suit the needs of any experiment. A more sophisticated system, in which control is applied to individual nozzles rather than lines of nozzles may be seen as a possible future development.

Continuous applications of water meeting the requirements outlined in point (a) of the above specification can only be obtained when the nozzle system remains in the same position relative to the laboratory catchment. A stationary nozzle system is also beneficial in providing a high standard of reproductivity (point (b)). However, the provision of continuously varying intensities of artificial rainfall (point (c)) may only be obtained from a fixed system of nozzles if the rates of application are altered by changing their working pressure. Some investigators have discounted such a proposal on the grounds that the patterns of application change in configuration with variations in head. The investigation at Imperial College has shown that a nozzle network can be designed to minimise the effect of these changes on the overall uniformity of the application pattern from the network.

When a nozzle system is orientated to spray directly downwards, the uniformity of the application pattern is dependent upon the spacing of the nozzles and the shape in both cross section and plan of the pattern from a representative nozzle. A series of steady-state tests can be made at intervals over a chosen range of working pressures to optimise the selection of the nozzle spacing to produce a predetermined level of uniformity throughout the range. A design of swirl-type nozzles has been devised, which when erected in a network at 18 in (45.7 cm) centres, is capable of providing application patterns with uniformity coefficients, based on the absolute deviations of individual depths from their mean, greater than 85 per cent over a range of application rates from 6 to 12 in/h. Further tests have indicated qualitatively the possibility of reducing the lower limit of this working range to meet the specification outlined in section 3.

This work will be described in greater detail in a future publication.

REFERENCES


**DISCUSSION**

*Intervention of Dr. Joseph B.P.M. Ouma*

**Question:** Dr. Hall and Prof. Wolf, geomorphologists lay a lot of stress on cohesion among particles and the erodibility of soils on slopes. How have you overcome this problem of simulating cohesions... or have you never considered it at all?

**Answer**

Dr. Ouma’s question takes the discussion beyond the point reached at present in the design of the microcatchment. The present plan provides for successive experiments on impermeable catchments of various topographies to be followed by similar experiments on catchments of various infiltration capacities, ground-water storages and permeabilities, but all of inerodible material. There is no theoretical reason for excluding studies of catchment erosion, sediment transport or deposition, but the practical difficulties will no doubt be very great. Decisions on the details of such experiments may well not be made for several years.

*Intervention of Prof. KRAIJENHOFF VAN DE LEUR*

**Question:** If nozzles are applied, would the overlap of the spray patterns cause a systematic irregularity in the total pattern?

**Answer**

Professor Kraijenhoff Van De Leur is perfectly correct in identifying the nozzle spacing as one of the two determinants of the precipitation pattern, the other being the variations in application depths within the cone of influence of a single nozzle. Dr. Hall’s analysis of the patterns of various forms of nozzle formed a substantial part of his research. Having once determined the single nozzle which, over a certain part of the microcatchment, gave the highest degree of uniformity in space and with variation
in intensity (i.e. water pressure), he then studied the application rate under a number of nozzles arranged in various patterns until he obtained the smallest “systematic irregularity” overall. Of course, Professor Kraijenhoff’s question has deeper implications, in relation both to the meaning of uniformity and to the variability of natural rainfall.

**Intervention of Dr. E.M. Laurendon**

**Question:** A problem that frequently besets investigations of the kind described by the authors is the growth of algae and other impurities in the water being used. Such growths might change the discharge characteristics of the nozzles or drop-forming equipment. Have the authors experienced any such difficulties in their tests?

**Answer**

In reply to Professor Laurendon, the deposits on the rainfall generator may be expected to disturb the discharge in inverse proportion to the dimension of the rain-producing element. E.g. a deposit in a capillary tube will cause a much greater reduction in discharge than a deposit of equal thickness in a nozzle of 3-mm diameter. At Imperial College, the laboratory water is drawn from the municipal supply and contains a considerable proportion of salts which, after each run of the rainfall simulator, are deposited on the internal surfaces; but they seem to be washed away by the initial flush of the next run and the slight effect of the thin film appears to be temporary. However, it is clearly desirable to keep the water and the nozzles so clean as to maintain unchanged physical conditions which will satisfy the criterion of repeatability. One method at present under study is the use of additives in the circulating water supply in the laboratory. Prof. P.O. Wolf added a general comment on the utility of physical models, in terms of providing mechanical data on the effects of (1) constant rainfall input of various intensities, (2) rainfall inputs varying in time, (3) rainfall inputs varying in space, and (4) rainfall inputs varying both in time and in space; on microcatchments of topographies which may be called typical, e.g. two-dimensional flat and curved surfaces, valleys consisting of flat or conical surfaces or of convex or concave curved surfaces; with varying relationships between precipitation rates and infiltration capacity etc.; and with such control of ground-water flow that there might be, in different parts of the microcatchment, flows into and out of ground-water. The only part of the hydrological cycle which it was not intended to reproduce was transpiration!

Other schools of modern hydrology, notably those of Professors Yevjevich, Chow, Amoroccho and Eagleson were engaged in the study of microcatchments on different scales and of various degrees of variability, and collaboration among all schools might lead to elucidation of scale effects; but in any case such catchment work would serve all researches, whether interested in hydromechanical or in mathematical systems.

Finally Prof. Wolf stated that he had left Imperial College for the new City University, London, and that Dr. Hall was now in charge of the microcatchment.