HYDROLOGIC CHARACTERISTICS of CATCHMENTS

Walter C. Boughton

LAG TIME for NATURAL CATCHMENTS

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FOREWORD

Lincoln College, the College of Agriculture of the University of Canterbury, sponsors an active research and teaching programme in hydrology, soil conservation and water resources development. The purpose of these Papers is to communicate research results and new developments in these fields as rapidly as possible, and particularly to report the results of projects undertaken in conjunction by the Department of Agricultural Engineering and the New Zealand Agricultural Engineering Institute. From time to time the opportunity will be taken to publish material originating elsewhere in New Zealand with which the College is associated and which could not otherwise be made available.

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PREFACE

Volume 3 of the Lincoln Papers in Water Resources contains two papers.

The first of the papers - Hydrologic Characteristics of Catchments - was presented in November 1967 to a Symposium arranged by the New Zealand Hydrological Society and held at Wellington, New Zealand.

The second paper - Lag Time for Natural Catchments - was read in January 1968 to a meeting of Section H (E) of the 40th ANZAAS Congress held at Christchurch, New Zealand.

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ABSTRACTS OF PAPERS

HYDROLOGICAL CHARACTERISTICS OF CATCHMENTS

Mr. W.C. Boughton,
Senior Lecturer,
Agricultural Engineering Department,
Lincoln College.

The systematic description and classification of catchment characteristics has never been adequately treated in any hydrological text. This paper summarises available measures for the quantitative description of catchments and points to aspects of catchment mensuration where deficiencies occur.

Measures and definitions of catchment characteristics which have appeared in hydrological literature are described in 5 groups, these being topographical characteristics, vegetation, soils, climatic characteristics, and human effects. The characteristics of a catchment such as the unit hydrograph which are contained in the streamflow record are noted, and areal and temporal variations in characteristics are briefly discussed.

THE DEVELOPMENT OF A RELATIONSHIP FOR THE VARIABLE LAG OF UNGAUGED CATCHMENTS

Mr. A.J. Askew,
School of Civil Engineering,
University of New South Wales.

Pluviograph and runoff records for an experimental catchment were studied in detail. A procedure was developed for the computation of the lag to direct run-off and the weighted mean discharge for any number of floods. This procedure was written into the form of a computer programme and the records of five catchments were analysed with the use of a digital computer. The relationships between lag and discharge were developed for each catchment and the effect of other factors was studied. Finally the form of the relationships and the parameters defining them were related to the characteristics of the catchment areas.

HYDROLOGIC CHARACTERISTICS OF CATCHMENTS

Walter C. Boughton,
Senior Lecturer,
Agricultural Engineering Department,
LINCOLN COLLEGE.

INTRODUCTION

The physical processes that occur between rainfall on a catchment and runoff at the outlet are very complex and it is virtually impossible to give a full description of this part of the hydrologic cycle. As a result of this complexity, most hydrologic analyses have made use of only a few of those characteristics of catchments which influence the process or have used empirical factors which integrate the behaviour of many of the characteristics.

To avoid the complexities of measurement and definition, many topography-soils-vegetation complexes are described in qualitative terms such as "average grassed land, few trees, moderate slopes." Subjective assessments such as these can be of little use in comparing one catchment with another unless they are made by a single observer who maintains a constant standard of judgment. It is desirable that these qualitative terms be replaced by quantitative descriptions based on reproducable field measurements.

Horton (ref. 20) in 1932 proposed that the factors descriptive of a catchment as related to its hydrology could be classified broadly as:

1. morphologic
2. soil factors
3. geologic
4. vegetational
5. climatic

Horton confined his detailed description of characteristics to a few morphologic factors in which he appeared to be primarily interested. He described and gave methods for evaluation of a form factor, compactness, mean elevation, general slope and mean slope, orders of streams, drainage density and stream density, and the direction and length of overland flow. In a later paper (ref. 22) he suggested 57 variables which could be used in the description and classification of landscapes. The statistical analysis of landform is now well established in geomorphology.

However, the systematic description and classification of catchment characteristics other than those of topography has never been adequately treated in any hydrology text, and even topographic characteristics have largely been overlooked since Horton's introduction. There are many reasons why a formal description of catchment characteristics is desirable at the present time.

Many characteristics are so ill-defined that different methods in use for evaluation can give widely different answers for the same characteristics. For example, the value of average channel slope depends upon the definition used, and the stream order of a basin depends upon the scale of map used in the derivation.

Because of poor training, many workers in hydrology are unaware of the definitions and measures which have been standardised to some extent for the description of catchments. Too often, resort is made to qualitative descriptions such as fair, good, poor, etc., with little meaning or definition when quantitative measures of the characteristic could be made.

Hydrology is a broad-scope science and covers a wide range of disciplines but hydrologists are rarely trained in such breadth of knowledge. Generally, the engineer is reluctant to step into the biological world for description and measurement of the vegetative cover of catchments, and the hydraulic properties of channels and drainage nets is equally unappealing to the agricultural scientist and forester.

The need for better definition of characteristics is becoming more urgent because of the very rapid increase in collection of hydrologic data which has occurred in the last few years and which is now accelerating steadily.

The research data assembly project initiated at Colorado State University in 1963 (ref. 30) is an example of many such data collection projects now in progress throughout the world. The specific aim of this project is to collect, process, and store rainfall, streamflow, and catchment data for several hundred recorded floods on small watersheds in the United States of America. The specific characteristics which are being recorded in this project are 20 characteristics which are constant from flood to flood, and 7 characteristics which vary from flood to flood. The constant characteristics are comprised of the catchment area, a measure of channel storage, drainage density, seven measures of catchment shape, four measures of stream slope, and six measures of overland slope. The varying characteristics are season, infiltration capacity, interception capacity, initial loss, loss rate, and two measures of antecedent wetness.

More recently, considerable interest has been drawn to the statistical surveys of vegetative cover, soils, and other measures of catchments (called hydrologic condition surveys in U.S. literature) by the Tennessee Valley Authority (ref. 55). Attempts to ensure that sufficient data were collected in these surveys for future studies resulted in a total of 53 variables being defined. The characteristics studied were classed under the general headings of physical, cover, litter-humus, soils and management.

These two examples are not isolated. Many countries are engaged in the establishment of representative and experimental catchments as part of the International Hydrological Decade program and during the period of the I.H.D., many catchments will be surveyed and described in much greater detail than ever attempted before. This paper attempts to review the problems of measuring the characteristics of catchments, and of selecting characteristics for measurement in any hydrologic study.

GENERAL CLASSES OF CHARACTERISTICS.

It will be self-evident that the characteristics of a catchment which will be important in any analysis will depend upon the purpose and objective of the analysis. This paper is directed towards those characteristics which have, or may have, an effect on floods or catchment yield, and is not intended to encompass other aspects of hydrology such as sediment movement, groundwater recharge, etc. However, many of the characteristics listed will have application in aspects of hydrology other than floods and yield.

Topographic characteristics of catchments are better defined than most other types, principly because of the ease, high accuracy, and low cost with which they can be evaluated. Many topographic characteristics can be measured or evaluated from maps in the comfort of an office and have the advantage of being clear to define and measure. Measurements can be replicated with ease and this permits precise definitions to be made.

These advantages do not occur with the measurement of soils and vegetation. The infinite variation over a catchment makes any measurement of soils or vegetation into a problem of sampling with consequent loss of definition. However, there are many standard procedures for survey and evaluation already in use by botanists, foresters, agricultural scientists and others, and these provide a framework for the hydrologist to use in the measurement of catchments.

The following list is a summary of those measures and definitions of hydrologic interest which have appeared at some time in the literature. A definition of each is given in Appendix A together with a reference to where further details of the parameter may be obtained. To keep some similarity with previous workers, the measures are grouped under the following headings:-

A. Topographic characteristics

B. Vegetative characteristics

C. Soils characteristics

D. Climatic characteristics

E. Human effects

A. TOPOGRAPHIC CHARACTERISTICS

A.1. Lineal Characteristics

Stream order

Bifurcation ratio

Stream length

Mean stream segment length

Mean stream length

Stream length ratio

Length to centre of catchment

Average length of overland flow

Interbasin length of overland flow

Average width of catchment

Maximum basin length

A.2. Areal Characteristics

Catchment area

Mean catchment area of stream segments

Area ratio

Area - distance curve

Area - stream length curve

Time-area contributing diagram

A.3. Drainage Characteristics

Drainage density

Belgrand's ratio

Stream frequency or stream density

A.4. Shape Characteristics

Form factor

Compactness coefficient

Circularity ratio

Elongation ratio

Area- shape curve

A.5. Slope Characteristics

Mean Stream segment slope

Slope ratio of stream segments

Mean stream slope

Equivalent main stream slope

Mean slope of catchment surface

Slope frequency distribution

General slope

Slope - orientation combination

Valleyside slope

Slope ratio

Ruggedness number

Texture ratio

A.6. Elevation Characteristics

Relief

Maximum relief

Maximum basin relief

Relief ratio

Mean elevation

Rise

Hypsometric curve

A.7. Orientation Characteristics

Orientation

Exposure

A.8. Channel Characteristics

(see text)

A.9. Surface Characteristics

Percentage of surface impervious

Percentage of surface as open water

B. VEGETATION CHARACTERISTICS

B.1. Trees

Diameter at breast height (d.b.h.)

Diameter breast height outside bark (d.b.h.o.b.)

Diameter breast height under bark (d.b.h.u.b.)

Basal area

Stand basal area

Tree density

Tree height

Mean stand height

Bole area

Crown diameter

Crown closure

Foliage weight

B.2. Grass and Shrubs (and mosses and lichen)

Frequency of occurrence, degree of frequency and percentage frequency

Abundance

Population density

Percentage composition

Leaf spread

Basal area

Cover

Composition by area

Green weight

Dry weight

Percent weight

B.3. Litter and Humus

Litter depth

Litter weight

Water holding capacity

Percent of area covered by litter

Humus depth

B.4. General

Leaf area index

Biomass

C. SOIL CHARACTERISTICS

C.1. Morphological Classification

Solum differentiation

Accumulations of salts

Soil properties

C.2. Depth Characteristics

Solum depth

Depths of horizons

Depth to accumulation of salts

C.3. Texture and Structure

Texture

Coefficient of uniformity

Structure

C.4. Porosity and Permeability

Total pore space

Porosity ratio

Voids ratio

Non-capillary porosity

Hydraulic conductivity and coefficient of permeability

C.5. Moisture-Holding Characteristics

Wilting point

Field capacity

Saturation

Root constant

Soil moisture storage

C.6. Chemical Characteristics

Abundance of Si, AE, Fe, Ca, Mg, K, Na, and P, and their oxides.

Ion exchange capacity

pH

Colour

C.7. Mechanical Characteristics

Plastic limit

Liquid limit

Plasticity index

Proctor maximum density

Cohesion

Shearing resistance

C.8. Surface Characteristics

Exposed rock

Random roughness

Wettability

Erosion

C.9. Organic Soils

Percent of organic matter

Thickness of organic deposit

Nature and degree of decomposition of organic matter

Nature of underlying mineral layers.

D. CLIMATIC CHARACTERISTICS

D.1. Rainfall and Snow

Rainfall depth - annual, seasonal, monthly, storm total, daily, and hourly.

Average depth - annual, seasonal, monthly

Median rainfall

Percentiles of rainfall

Normal rainfall

Precipitation per rainy day

Average rainfall over an area

Point depth - duration relationships

Depth-area-duration relationships

Excessive precipitation

Intensity-duration-frequency relationships

Probable maximum precipitation

Standard project storm

Snow depth

Water equivalent

Capillary retentivity

D.2. Radiation and Temperature

Albedo

Incoming radiation

Mean temperature - daily, monthly

Mean maximum temperatures

Mean minimum temperatures

Normal temperature

Wet bulb depression

Frost depth

D.3. Humidity and Evaporation

Humidity

Relative humidity

Pan evaporation - daily, monthly, annual

Evapotranspiration - potential, actual

D.4. Wind

Wind speed

Sind direction

E. HUMAN EFFECTS

E.1. Urban Development

E.2. Vegetational changes

E.3. Surface Storage Effects

E.4. Cultivation

E.5. Fire

DISCUSSION OF CHARACTERISTICS

It is overstating the obvious to note that the above list is not exhaustive. It is doubtful that a finite list of characteristics could be set out unless every type of physical measurement ever made was included, as the boundary between items of interest to hydrologists and those not of interest is not clearly defineable.

The above list is intended to be a basic set of measurable physical characteristics of catchments from which specialists in particular fields of hydrology might develop better measures and definitions. The objective has been to report those measures which have been used in the past and to point out those areas where clearly defined characteristics are not available.

The separation of the characteristics into 5 basic classes, viz. topographic, vegetation, soils, climate, and human effects, was decided arbitrarily. The influencing factors here were the groupings used by previous writers such as Horton (ref. 20) and the T.V.A. (ref. 55). Discussion of the sets of characteristics is made under these headings in the following sections for sake of continuity.

TOPOGRAPHIC CHARACTERISTICS

Topography is a well-covered subject in geomorphological literature, and this literature offers a profusion of catchment characteristics which might or might not be of use to hydrology. The present problem seems to be one of establishing the degrees of correlation between similar measures and definitions, in order to avoid making two measurements where one would suffice.

The division of the characteristics into lineal, areal, drainage, shape, slope, elevation, orientation, and channel characteristics, is due to Thistlethwaite (ref. 56).

The major deficiency at the present time in definition of topography is in channel characteristics. Formulae for calculation of the velocity of flow in channels give slope and hydraulic radius (the ratio of area of flow to wetted perimeter) together with a measure of roughness, usually Mannings N, as measures of the channel. River meanders have also been dealt with in geomorphological literature.

Recent studies by Bard (ref. 2) and Neil and Galay (ref. 41) suggest that the development of channel criteria is still progressing rapidly and it seems pertinent to omit a detailed treatment of this section at the present time.

A measure not specifically mentioned in the list of characteristics is location. Latitude and longitude might be considered as measures of topography if one takes a broad view of the matter and could be included in this section.

VEGETATION CHARACTERISTICS

A common subdivision of plant communities is the vertical separation into trees, shrubs, grasses, mosses and lichen, and litter and humus. The separation is arbitrary and, for the present purposes, a separation into three divisions i.e. trees, then shrubs, grasses, mosses and lichen, and lastly, litter and humus, is adequate for description of measurable characteristics.

The characteristics of trees is mostly covered in forestry literature and the summary given in this paper is taken mainly from Carron (ref. 12). One of the best-known texts for measurement of vegetation other than trees is that of Dorothy Brown (ref. 8) and the measures and definitions for shrubs, grasses, mosses and lichen, are derived mainly from this reference.

The few measures available for describing litter in a quantitative way are clear enough and the extensive review of litter data by Bray and Gorham (ref. 5) illustrates the amount of information available on this subject. However, humus is still treated mainly in a qualitative way (e.g. see ref. 57).

There are a few characteristics such as leaf area index and biomass which are not specifically reserved for any one of the three divisions given above. These two appear to have some significance for hydrology and are included for this reason.

SOIL CHARACTERISTICS

Soil is treated by so many disciplines in so many ways that it is difficult to collect together all those characteristics of a soil which can be measured. However, the list given here at least encompasses the majority of the more common measures. The problem is illustrated by the need to include a subject such as erosion as a single heading under "Surface Characteristics".

From a quantitative hydrologic point of view, the morphological classifications of soil are probably the least useful of all, as there can be a great deal of variation in infiltration capacity and moisture storage capacity within a single soil type. This comment may prove to be in error as data of the detailed characteristics of each soil type accumulates but, as yet, the practicing hydrologist and even the research hydrologist makes little use of these classifications.

The efforts made towards numerical classification of soils by Sarkar etal (ref. 47) and others should prove of major interest in the near future.

Organic soils are usually defined as those which contain sufficient organic matter so that the soil properties are dominated more by the organic matter than by the mineral matter. In addition to those measures of organic soils given under item C.9. in the list, factors such as colour and pH can be significant and these are included under headings elsewhere in the list.

CLIMATIC CHARACTERISTICS

The importance of rainfall as a climatic characteristic is indicated in the literature by the wide range of different measures of rainfall depth and intensity used in hydrologic analysis. Totals on an annual, or seasonal, or monthly basis are considered by means medians and percentiles, among others. Differences between rainfalls in the open and under tree foliage is used as a measure of interception, and so on.

The appropriate measures have been summarised as simply as possible, the object being to include such factors as rainfall depth without specific definition of all variations and combinations of the measure that could be used.

It is difficult to separate the long-term climatic pattern which shapes a catchment and determines its soil and vegetative patterns from the short-term meteorological events which become the input to the catchment system for any hydrologic study. In writing this paper, it was considered necessary to include climate in any list of characteristics of catchments. It would be simpler though unrealistic to omit it.

HUMAN EFFECTS

At best, this section can only point to the deficiencies which exist in the definition and measurement of human effects on the hydrologic cycle. As a starting point, a division into 5 sections is suggested, these being urban development, vegetational changes, surface storage effects, cultivation, and fire.

A description of the transition stages which occur when a catchment develops from a rural condition to a condition of urban development is given in the Handbook of Applied Hydrology (ref.16).

However, the description is qualitative rather than quantitative and provides no useful measure of the development other than percentage impervious area. Most attention has been given in the literature to the hydraulics of stormwater design rather than to hydrologic measures.

Vegetational changes occur when forest cover is removed from an area or a cleared area reforested, when one type of cover replaces another or when vegetation is completely removed, either deliberately or by erosion or fire.

Man's most obvious effects occur with the increase of surface storage on a catchment either by construction of major reservoirs or small dams, or by soil conservation measures and works. The storage effects of surface geometry blend into the storage effects of cultivation as a change in the pore size distribution of the soil, and the effects of cultivation continue as effects on the infiltration pattern. Burwell, Allmaras and Cloneker (ref.9) have approached this problem with a definition of random roughness of the soil surface.

Fire is both a natural effect and a human effect. Wild fires undoubtedly occurred before man commenced the deliberate firing of vegetation for hunting or agricultural purposes. More recently man has introduced controlled burning to reduce fuel quantities in area of high fire hazard. The measures used in fire control for estimation of fuel quantity in litter and undergrowth could be useful as hydrologic measures of interception capacity and moisture-holding capacity, but it was not possible to undertake the additional review needed to include those measures here.

AREAL VARIATION IN CHARACTERISTICS

Characteristics, particularly those of soil and vegetation, often have considerable variation within a catchment and the distribution can be of more importance than the average value. The standard statistical measures of variance and skewness seem to be applicable to the treatment of catchment characteristics but little use of such an approach has been made.

CHANGE OF CHARACTERISTICS

From many points of view, many of the catchment characteristics can be regarded as constant and unchanging. From the viewpoint of geology and geomorphology, even the topographic features are subject to change.

It is best that catchments be regarded as dynamic rather than static systems and each characteristic be considered as subject to change.

The rate of change may be insignificantly slow as in the change of topography, or spread over a number of years as in the fluctuations of climate about long-term averages, or subject to seasonal fluctuations as is vegetation, or subject to such rapid changes as in rainfall intensity that the response of measuring instruments becomes a matter of concern.

A need exists for some systematic means of describing expected changes in a catchment such as increases in urban development or spread of soil conservation measures. It is as well to ensure that future changes in catchment condition, even accidental changes such as the removal of surface cover by fire, are assessed in the analysis of future flood flows or yield.

STREAMFLOW CHARACTERISTICS

The streamflow record itself contains features which are characteristics of the catchment. The most commonly used of these features are minimum period of rise, the unit hydrograph, and the recession curves of surface runoff, interflow, and groundwater flow. The unit hydrograph represents the combined effects of all topographic characteristics on hydrograph shape while the recession curves give a direct representation of channel storage effects and storage delay times of the catchment.

There are not many streamflow characteristics in common use. However, each of these characteristics has the advantage of being an integration of the effects of many other characteristics such as those of topography, vegetation and soils. Much work has already been done to relate streamflow characteristics to other characteristics of the catchment but much yet remains to be done.

SUMMARY

The purpose of this paper has been to summarise available measures for the quantitative description of catchments and to point to current deficiencies. Past neglect of this aspect of hydrology has made the subject difficult to treat in complete detail and the author is aware of the incompleteness of this work. It is hoped that the paper will serve as an introduction for those better equipped to deal with specialised aspects of the subject.

APPENDIX A.

DEFINITIONS OF THE CHARACTERISTICS

Stream Order (ref. 22). Starting at the head of a catchment, the small unbranching streams first encountered are designated Stream Order 1. A stream of Order 2 is formed by the confluence of two Order 1 streams; a stream of Order 3 by the confluence of two Order 2 streams; and so on.

The order number assigned to any stream segment and the maximum order of any stream segment in the catchment depends upon the scale of map used and on the amount of channel detail shown on the map.

Bifurcation Ratio (ref. 52), is the ratio of the number of stream segments of a given order N_u to the number of segments of the next highest order N_{u+1}.

Stream Length is the length of the main stream channel of a catchment, the measurement being along the actual stream path and including all sinuosities.

Mean Stream Segment Length (Ref. 16). The mean length of stream segments of a given order is the sum of all stream lengths of the given order divided by the number of segments of that order.

Mean Stream Length. The mean stream length of the catchment is sum of the mean stream segment lengths for all orders of streams in the catchment.

Stream Length Ratio (ref. 56), is the ratio of the mean length of segments of order U to the mean length of segments of the next lowest order.

Length to the Centre of the Catchment (ref. 33) is the distance along the stream channel from the catchment outlet to the centroid of area of the catchment. If the centroid does not fall on the main channel, the distance should be measured along the main channel to a point opposite the centre of the area.

Average Length of Overland Flow (ref. 56) is the average length of flow path projected to the horizontal of non-channel flow from a point on the drainage divide to a point on the adjacent stream channel.

Interbasin Length of Overland Flow (ref. 16). A particular case of the length of overland flow is that used to describe the length of a triangular element of ground surface lying between two adjacent tributary basins and the larger stream that they join.

Average Width of Catchment (ref. 30) is the catchment area divided by the length of the main stream from the outlet to the catchment boundary.

Maximum Basin Length is the maximum straight-line distance from the outlet to the catchment boundary.

Catchment Area. The Catchment area of a given point on a stream channel is the area projected upon a horizontal plane that contributes surface runoff to the measuring point.

Mean Area of Stream Segments (ref. 16). The mean area of stream segments of order U is total of all areas, projected upon a horizontal plane, which contribute surface runoff to channel segments of the given order and including tributaries of lower order.

Area Ratio (ref. 22) is the ratio of the mean area of stream segments of order U to the mean area of stream segments of the next lowest order.

Area-Distance Curve (ref. 56) is a plot of area of the catchment at a given distance from the outlet against that distance. This curve is the integral of the area-shape curve.

Area-Stream Length Curve (ref. 38) is a plot of mean length of stream segments of order U against mean area of stream segments of order U. (usually log-log plot).

Time-Area Contributing Diagram (ref. 29) is a plot of area between isochrones of equal travel time to the outlet against the time of travel.

Drainage Density (ref. 20) is the sum of all stream lengths of all orders in the catchment divided by the catchment area.

Belgrand's Ratio (ref. 20) is the ratio of the area of the catchment to the total number of stream segments of all orders within the catchment.

Stream Frequency or Stream Density (ref. 20) is the reciprocal of Belgrand's Ratio and is the total number of stream segments of all orders divided by the catchment area.

Form Factor (ref. 20) is the ratio of the average width of catchment to the length of the main stream.

Compactness Coefficient (ref. 20) is the ratio of the perimeter of the catchment to the circumference of a circle having the same area as the catchment.

Circularity Ratio (ref. 56) is the ratio of the area of the catchment to the area of a circle having the same perimeter as the catchment.

Elongation Ratio (ref. 49) is the ratio of the diameter of a circle of same area as the catchment to the maximum basin length.

Area-Shape Curve (ref. 56) is a plot of catchment width against distance from the catchment outlet.

Mean Stream Segment Slopes (ref. 16). The mean slope of stream segments of order U is the average drop in elevation of all segments of that order divided by the average horizontal distance of those segments measured along the channel paths.

Slope Ratio (ref. 16) is the ratio of the mean slope of stream segments of order U to the mean slope of stream segments of the next highest order.

Mean Stream Slope is commonly defined as the difference in elevation from head of the catchment (perimeter of the catchment at the end of the main stream channel) to the catchment outlet, divided by the horizontal distance from head to outlet measured along the stream path.

Equivalent Main Stream Slope (ref. 54) is the slope of a uniformly sloping channel having the same length as the main stream and an equal time of travel, assuming cross-sectional area and roughness coefficients to be the same.

Mean Slope of Catchment Surface (ref. 56). The mean slope of catchment surface is a self-defining title. It is distinct from and should not be confused with general slope.

Slope Frequency Distribution (ref. 16) is the frequency distribution of slope of the catchment surface.

General Slope (ref. 20). The general slope of a catchment is the average slope of a surface generated by a line, one end of which is fixed at a given point on the stream above which the slope is to be determined, while the other sweeps along the watershed-line.

Slope-Orientation Combination (ref. 24) is a measure of the amount of solar radiation a slope may receive because of its situation.

Valleyside Slopes (ref. 16) is the slope from the watershed line to the adjacent stream channel. A maximum valleyside slope is sometimes used.

Slope Ratio (ref. 16) is the ratio of the mean slope of the catchment surface to the mean stream slope.

Ruggedness Number (ref. 16) is the product of relief and drainage density, both in the same units, where relief is the height of the head of the catchment above the outlet.

Texture Ratio (ref. 16) is the number of crenulations in the contour with the most crenulations divided by the perimeter length of the catchment.

Relief (ref. 56) is the difference in elevation between any two points.

Maximum Relief (ref. 56) is the difference in elevation between the highest and lowest points.

Maximum Basin Relief (ref. 56) is the difference in elevation between the catchment outlet and the highest point on the watershed line.

Relief Ratio (ref. 49) is the ratio of the maximum basin relief to the maximum basin length measured on the horizontal plane along the longest dimension of the catchment parallel to the principal drainage line.

Mean Elevation (ref. 20) is the mean elevation of all points on the catchment surface. A median elevation is sometimes defined.

Rise (ref. 33) is the difference in elevation between the catchment outlet and the highest point within a 5 mile radius.

Hypsometric Curve (ref. 20) is a plot of elevation against area of the catchment above that elevation. A dimensionless form of the graph is also used.

Orientation (ref. 33) of a particular slope is the compass bearing of a line drawn normal to the contours and looking in the direction of maximum fall.

Exposure (ref. 33) of a station is the sum, in degrees, of those sectors of a 20-mile radius circle about the observing station not containing a barrier 1000 feet or more above the station elevation.

Diameter at Breast Height (ref. 12). Breast height is generally given an absolute value of 1.3 metres or 4'3". The diameter of a tree at breast height may be measured outside of the bark (d.b.h.o.b. - diameter breast height outside bark) or under the bark (d.u.b. - diameter under bark) or left unspecified (d.b.h. - diameter at breast height)

Basal Area (ref. 12) is the cross-sectional area of a tree at breast height.

Stand Basal Area (ref. 12) is the sum of the sectional area at breast height of each tree in the stand.

Tree Density is the number of trees per acre.

Tree Height is a self-explanatory term, and is included as a characteristic because so many other features of trees are related to height.

Mean Stand Height is the average height of all trees in a stand.

Bole Area (ref. 12) is the lateral surface of the tree trunk under bark.

Crown Diameter (ref. 12) is the diameter of a horizontal circle which encloses the tree foliage.

Crown Closure (ref. 12) is the ratio of the vertical projections of tree crowns to the equivalent ground area of the stand.

Foliage Weight is the total weight of all leaves and small twigs less than $\frac{1}{4}$ inch in diameter.

Frequency of Occurrence (ref. 8) is a measure of the presence or absence of a species in a number of small samples. "Degree of frequency" and "percentage frequency" are variants in expressing the frequency of occurrence.

Abundance (ref. 8) is a measure of the actual numbers of a species which occur in samples.

Population Density (ref. 8) is the number of a species per unit area of ground.

Percentage Composition by Number (ref. 8) is the number of individuals of a species expressed as a percentage of all individuals of all species present.

Leaf Spread (ref. 8) or "maximum spread of the foliage" is the vertical projection of the above ground parts of the plant on to the ground.

Basal Area (ref. 8) of plants other than trees is the cross-sectional area of the base of the plant at ground level.

Cover (ref. 8) is the percentage of the total ground surface covered by vegetation. A distinction may be made between measures based on leaf spread and those based on basal area.

Composition by area (ref. 8) is the area covered by each species expressed as percentages of the total area covered by vegetation.

Green Weight (ref. 8) is the weight of above-ground parts of the plant measured without any drying.

Dry Weight (ref. 8) is the weight of above-ground parts of the plant when air-dried or oven-dried to constant weight.

Percentage Weight (ref. 8) is the air-dried weight of a species expressed as a percentage of the weight of all species present.

Litter Depth (ref. 5) is the depth of loose leaves, twigs, bark, fruits, and other organic debris on top of the humus layers or mineral soils.

Litter Weight (ref. 5) is the weight of litter per unit area of ground cover. The term may be used to express the annual increment of litter produced.

Water Holding Capacity of Litter (ref. 4) is the difference in water content of the litter between field capacity and air-dry.

Percentage of Area Covered by Litter is the proportion of ground surface covered by litter expressed as a percentage.

Humus Depth (ref. 16) is the depth of the organic layer which is beneath the litter layer and consists of decomposed organic matter, unrecognisable as to origin, which may or may not be incorporated with the mineral soil.

Leaf Area Index (ref. 16) is the ratio of total leaf area to the area of ground covered.

Biomass is the total weight of all vegetation usually expressed as per unit area of ground covered.

SOIL CLASSIFICATIONS

Current systems of classifying soil profiles are mainly based on the morphology of the solum (ref. 1) although methods of numerical classification of soils are already well developed. (ref. 47).

Soils are commonly classified into orders, suborders, great soil groups, families, series, and types. There are differences among various systems of classification as to the characteristics which are used to distinguish and separate soils at each level of classification. It is not possible to fully describe here any one system of classification but the following illustrates the scope of soil characteristics used in classification.

Solum Differentiation. The primary division of soil orders is usually based on the development of the soil profile, e.g. zonal, azonal, or intra-zonal, depending on whether the soil has a well-developed profile, is without profile development, or is intermediate between these two extremes.

Accumulations of Salts. The presence or absence of chlorides and of calcium salts, particularly lime or gypsum, and the depth to accumulations of these salts are the distinguishing features.

Soil Properties. Detailed classification of a profile will be dependant upon such other factors as the drainage conditions, texture and structure of the horizons, colour and pH, humus content, nutrient content, and parent material.

Solum Depth is the depth of soil above the parent material.

Horizons. The depth of each differentiated layer or horizon within the soil profile is a characteristic of the profile.

Depth to Accumulations of Salts. The depths to accumulations of calcium salts, particularly $CaCO_3$, frequently characterise soils in arid and semi-arid regions.

Texture of a soil is the proportion of different size particle groups in the soil on a percentage basis.

Coefficient of Uniformity is the ratio of the sieve size through which 60% of the material passes to the sieve size through which 10% passes.

Structure of a soil is the aggregation of primary soil particles into compound particles, or clusters of primary particles, which are separated from adjoining aggregates by surfaces of weakness.

Porosity is the total pore space in a soil.

Porosity Ratio is the ratio of the volume of voids to the total volume of soil including voids.

Voids Ratio is the volume of voids to the volume of solids in a soil.

Non-capillary Porosity is the volume of soil pores not filled with water or soil at field capacity moisture content.

Hydraulic Conductivity is the ratio of the volume of water flowing across unit area of cross-section of soil in unit time to the hydraulic gradient. (sometimes called the coefficient of permeability)

Permanent Wilting Point is the moisture content at which plants permanently wilt and do not recover when left overnight in a moist environment.

Field Capacity is the moisture content retained against the drainage pull of gravity after saturation of the soil. The usual measure is 2 days after the saturation.

Saturation is the condition of zero air voids in a soil when all pore spaces are filled with water.

Moisture Holding Capacity (or available moisture) is the difference in moisture contents between field capacity and wilting point.

Root Constant is the product of available moisture of the soil and the root depth of the vegetation.

Soil Moisture Storage is the total moisture storage capacity of the solum.

Chemical Composition of Soils. Many elements in the composition of soil have significance depending upon the type of soil analysis undertaken. The major interest is in the elements Si, Ae, Fe, Ca, Bg, K, Na, and P, together with their oxides and the ratios of the amount of one to the amount of another.

Ion Exchange Capacity. Cation-exchange is the taking up or giving off of positively charged ions by a soil. The total cation-exchange capacity of a soil is expressed by the milliequivalents (m.e.) of ions 100 grams of soil will absorb.

pH. pH of a soil is the negative logarithm of the hydrogen ion concentration.

Plastic Limit is the moisture content at which a thread of the soil can be rolled without breaking until it is only $\frac{1}{8}$ inch in diameter.

Liquid Limit is the moisture content at which the soil is sufficiently fluid to flow a specified amount when lightly jarred 25 times in a standard apparatus.

Plasticity Index is the numerical difference in moisture contents between the plastic and liquid limits of a soil.

Proctor Maximum Density is the maximum dry density which can be obtained when soil is compacted using standard equipment and procedures.

Cohesion and Shear Strength are properties of soil samples derived from laboratory tests which give a measure of the resistance of the soil to shearing forces.

Exposed Rock (ref. 55) is the percentage of the ground surface showing exposed rock.

Random Roughness (ref. 9) of a soil surface is computed as the variance of 400 soil surface height measurements expressed in inches made on a 2 inch grid over a 40 inch by 40 inch sample area.

Soil Wettability (ref. 28) is the elapsed time between placement of a drop of water on the soil surface and its disappearance into the soil. Letey et al (ref. 32) measured wettability in terms of the liquid-solid contact angle.

Percentage of Organic Matter is usually taken from the loss in weight of the soil after ignition at high temperatures. There are other methods and measures for estimating organic matter content.

Rainfall Characteristics are well-defined in most hydrology texts which describe meteorology and these definitions are omitted here for reasons of space.

Degree of Urbanization (ref. 25) is the fraction of the total catchment area devoted to urban uses.

Degree of Channelization (ref. 25) is the fraction of the total stream channel length which has been improved.

A major deficiency in this paper is the omission (deliberately by the author) of any treatment of geological characteristics. Geology and soils are interrelated.

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THE VARIATION OF LAG TIME FOR NATURAL CATCHMENTS

A.J. Askew, B.Sc., M.Sc.(Eng.)

Research Student, University of New South Wales,

Australia.

INTRODUCTION

Much of the recent work on the synthesis of streamflow hydrographs has centred around the use of flood routing and catchment storage models. One such model, proposed by Dr. E.M. Laurenson of the University of N.S.W., consists of a series of concentrated storages which route the rainfall-excess hydrograph downstream from each sub-area to the next. Laurenson (1964) has shown that the storage delay time of points corresponding to the centroid of the time-area diagram is equal to the lag, where this is defined as the time interval between the centres of mass of the rainfall-excess hyetograph and the resulting portion of the surface-runoff hydrograph. Therefore the magnitude of the routing coefficients is directly dependant upon the lag time for the catchment. However, in attempting to assess this lag time for South Creek Laurenson found it varied so greatly from flood to flood that he was obliged to define it as a variable dependant on discharge rather than as a constant. The equation he developed was,

$$t_m = 64(q_m)^{-0.27}. \qquad (r - -0.90)$$

where t_m = lag in hours and

q_m = mean surface-runoff discharge in cusecs.

Thus an element of non-linearity was introduced into the model which when tested for South Creek produced most encouraging results.

Laurenson's model would be ideally suited for the synthesis of hydrographs for ungauged catchments if it were not for the two indeterminate factors; (a) the value of constant or variable loss-rate to be used and (b) the form of the lag-discharge relationship for the catchment. The work described below was undertaken in an attempt to solve the latter problem, encouraged by such findings as those published by Rockwood (1958), viz:

Storage time $\quad$ (Discharge)$^{-0.2}$ for the Columbia River.

ANALYTICAL TECHNIQUES

A second experimental catchment, Eastern Creek, was selected, and its records were carefully analysed in full, following the manner described by Laurenson (1962). The resulting relationship obtained was,

$$t_m = 17.4(q_m)^{-0.205}, \qquad (r = -0.65)$$

which would have been most encouraging if it were not for the low value of the coefficient of correlation. It was decided that alterations had to be made to the definitions of lag and mean discharge so that they became more logical and could be calculated more objectively. Lag (t''_m) was therefore defined as the time interval between the centres of mass of rainfall-excess and direct-runoff (total flow minus ground-water flow) so as to eliminate the problem of interflow seperation. Also, weighted-mean-discharge (q_{wm}) was defined as the mean rate of discharge over the time of occurrence of direct-runoff weighted according to the proportion of the direct-runoff which was discharged at that rate. (See Figure 1). The regression of lag (t''_m) on lag (q_{wm}) produced the equation,

$$t''_m = 39.0(q_{wm})^{-0.259} \quad (r = -0.90).$$

Having now established a meaningful analytical procedure which was largely of an objective nature it was possible to write a computer programme to carry out the numerical calculations. The programme, Lag-Discharge (LAGDCH), was written in PL1 language for use on the I.B.M. 360/50 digital computer installed at the University of N.S.W. A simplified flow diagram for LAGDCH is shown in Figure 3.

For each catchment about forty floods were chosen from the records so as to cover as wide a range in magnitude as was possible. These floods occurred as a number of events each composed of either an isolated peak or a series of peaks, which were plotted as shown in Figure 2, the individual direct-runoff hydrographs being seperated from the ground-water flow. The hyetographs for the storm associated with the event were plotted on the same time base as the hydrographs, as is shown for pluviometers I, II and III. The burst of rainfall attributable to each flood were then seperated, e.g. a-b with A. The average depth of precipitation which was representative of the area surrounding each pluviometer was calculated using isohyetal maps and a Thiessen Polygon such as that illustrated for Burst A.

LAGDCH

The operation of the programme LAGDCH commences with the reading in of the parameters associated with the catchment as a whole. This is followed by the processing of the data one event at a time, the resultant values of t''_m, q_{wm} etc. being stored in memory.

The hydrographs, both total and direct runoff, are read in as one-dimensional arrays, successive values being the discharges at successive time intervals starting at time zero. The hyetographs are represented in a similar manner except that the successive values give the number of points of rain which fell during the previous time interval. HVOL is the volume of direct-runoff in the hydrograph and CMY is the time of its centre of mass. The hyetograph ordinates are adjusted so that in every case their total for the burst is equal to the average depth of precipitation mentioned above.

An iterative loop is entered which in a few steps calculates the value of the constant loss rate (PHI) which will give a volume of rainfall excess (VPEA) equal to HVOL within a prescribed accuracy. The centre of mass of the resulting rainfall-excess for each pluviometer is weighted in proportion to the volume it contributed to VPEA and an average centre of mass (CMP) is thus calculated. The lag is therefore CMY minus CMP.

The above calculations are repeated for each burst/flood in an event and then for each event, the results being given in both the printed and punched-card form. Finally LAGDCH performs a simple regression analysis of $\log(t''_m)$ on long (q_{wm}) and prints out the result.

RESULTS - I

This analytical procedure was carried out for the five best instrumented experimental catchments operated by the University, including both South Creek and Eastern Creek. The resulting expressions for lag as a function of weighted mean discharge are listed below. The necessity of only using data which was readily available and which was known to be of acceptable accuracy restricted the streams that could be studied to these five:

South Creek (22,000 acres), $t''_m = 72.1(q_{wm})^{-0.241}$
(212320) $r = -0.93$

Hacking River (10,000 acres), $t''_m = 25.0(q_{wm})^{-0.193}$
(214340) $r = -0.88$

Eastern Creek (6,000 acres), $t''_m = 39.4(q_{wm})^{-0.263}$
(212340 $r = -0.88$

Cawleys Creek (1,300 acres), $t''_m = 11.3(q_{wm})^{-0.190}$
(214334) $r = -0.70$

Research Creek (96 acres), $t''_m = 3.61(q_{wm})^{-0.328}$
(214330) $r = -0.88$

Listed above with the catchments are their index numbers according to the Australian Water Resources Council designation.

Although the scatter of points about the regression lines was not great, attempts were made to explain it in terms of the hyetographs' parameters. The effects of three parameters were investigated, namely, the relative time of occurrence of the peak rainfall intensity within each burst, the length of time during which rainfall-excess was generated and the variation in areal distribution of the storm. None of these parameters appeared to have any significant influence upon lag and so a study was made of the possible alternative forms for the t''_m v q_{wm} relationship. This also proved fruitless since even the most promising form, $(t''_m + \text{Constant}) = m(q_{wm})^{-n}$, gave meaningless or unstable optimum values for the 'Constant'. It therefore appeared that the variation in lag for the catchments could best be described by the equations as listed above.

RESULTS - II

Cawleys Creek catchment has certain topographic features which could help explain the poor correlation, and in addition some difficulty was found in applying timing corrections to certain of its records. Apart from this the five results provide strong evidence for the non-linear behaviour of catchments as it is exhibited in their time response. The relative magnitude of this non-linear effect can be judged by the variation in value of the exponent 'n', in

$$t''_m = m(q_{wm})^{-n}.$$

'n' is the regression coefficient in the log/log analysis and as such its variation between four of the five was found to be insignificant at the 0.10 significance level. The exception was the value of -0.328 for Research Creek. Simple hydraulic considerations such as those detailed by Pitman and Midgley (1966) suggested an exponent of the same order but failed to explain the variation in value. The only parameter upon which n appeared to depend was the form factor for the catchment, n $(A/L^2)^+$, where A is the catchment area and L is the length of the main stream. However, this dependence was not at all strong and although it helped explain the high value for Research Creek it was decided not to propose a formula for n which had no obvious physical explanation and which was based on a poor correlation between only five values.

Therefore a constant value for n was chosen such that the standard error of estimate of t''_m for all floods and catchments was a minimum when computed using the five re-calculated regression equations. This optimum value of the exponent was found to be -0.23 and the corresponding values of m were re-calculated as:

67.4, 31.1, 32.7, 13.6 and 2.74.

Strong correlation was found between the logarithms of these latter values and those of A, L, $A/(S_s)^{0.29}$, $L/(S_s)^{0.41}$. S_s is proportional to the statistical overland slope and is equal to $\frac{nh}{Lg}$ where,

n = number of intersections of grid lines and contours,

h = contour interval, and

Lg = total length of grid lines within the catchment.

The introduction of S_s in the above correlations appreciably reduced the standard error of estimate of log (m) and hence of t''_m. 'A' can be far more accurately and objectively measured than 'L' since the latter depends on the scale and accuracy of the map used. It would therefore appear to be preferable to develop the formula in terms of 'A' rather than 'L'. However, the final expression incorporating 'L' gave a slightly smaller standard error than did that using 'A',

i.e. $$t''_m = 5.64(A)^{0.541}(S_s)^{-0.16}(q_{wm})^{-0.23}$$

St. error of log (t''_m) = 0.0813.

$$t''_m = 2.51(L)^{0.80}(S_s)^{-0.33}(q_{wm})^{-0.23}$$

St. error of log (t''_m) = 0.0759.

With the exception of the (q_{wm}) term these two relationships are very similar to those often used for the estimation of a constant value for the lag of an ungauged catchment. The relative magnitudes of the powers to which A, L and S_s are raised are fully in accordance with what one would expect from theoretical considerations.

Some work still remains to be done on the question of the exact relationship for t''_m which should be proposed, but it is clear that it will take the form of one of the above two and that the values of the constants will remain almost unaltered.

CONCLUSIONS

The primary objective of this study was to provide a means of predicting the variable lag-discharge relationship for an ungauged catchment. This could then be used, together with some estimator of the loss rate, in a model such as that proposed by Laurenson, thus synthesising run-off hydrographs from given rainfall. Such an application of the results has not yet been attempted, however, certain conclusions can be drawn from the results presented above.

The consistent correlation between t''_m and $(q_{wm})^{-n}$ demonstrates the non-linear response of catchments. It also shows that the effect of this non-linearity varies little in magnitude from one catchment to another.

Although only five catchments were studied it was possible to develop a relationship that can be used to estimate with reasonable accuracy the lag of a catchment for a given flood. The form of this relationship is consistent with theoretical considerations and is very similar to equivalent formulae used in estimating values of constant lag.

For many purposes a catchment is regarded as operating as a linear system, but in fact it never does so. Consequently the more that can be learnt of the form of the true response of a catchment the more accurate will be the predictions of hydrologic events.

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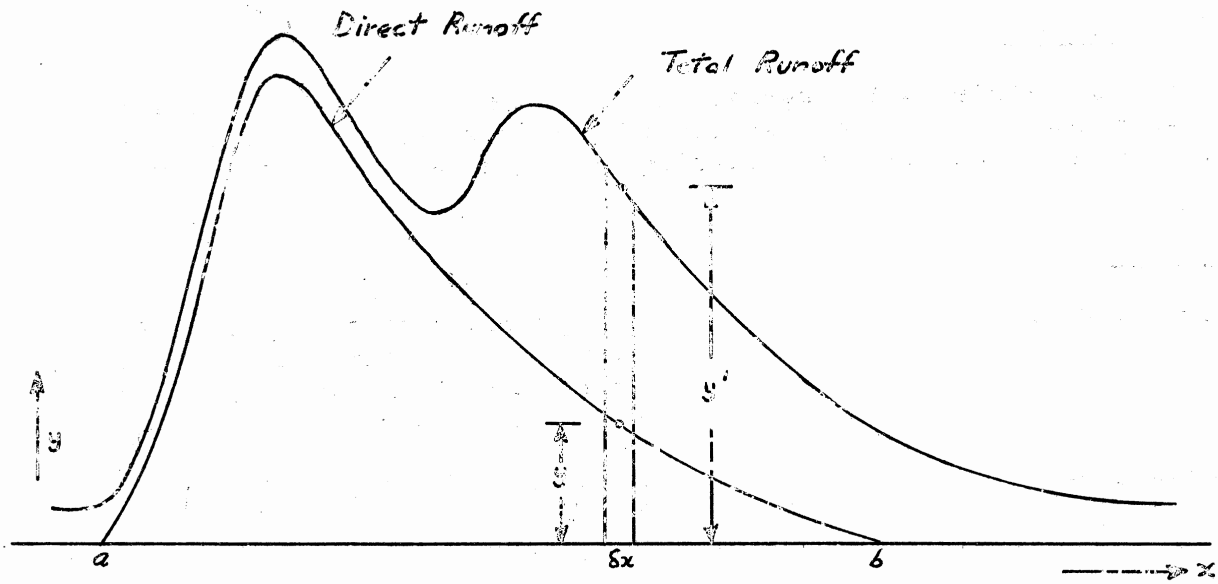

Rate of discharge in the stream $= y$

Volume of direct runoff discharged at this rate $= y\,\delta x$

Total volume of direct runoff discharged $= \int_a^b y\,dx$

Weighted rate of discharge $= y' \cdot \left(\frac{y\,\delta x}{\int_a^b y\,dx}\right.$

Weighted mean discharge (q_{wm}) $= \int y' \cdot \frac{y\,dx}{\int_a^b y\,dx}$

$q_{wm} = \frac{\int_a^b y' y\,dx}{\int_a^b y\,dx}$ or using discrete ordinates: $q_{wm} = \frac{\sum_a^b y' y}{\sum_a^b y}$

<u>Figure 1 - Definition of Weighted Mean Discharge</u>

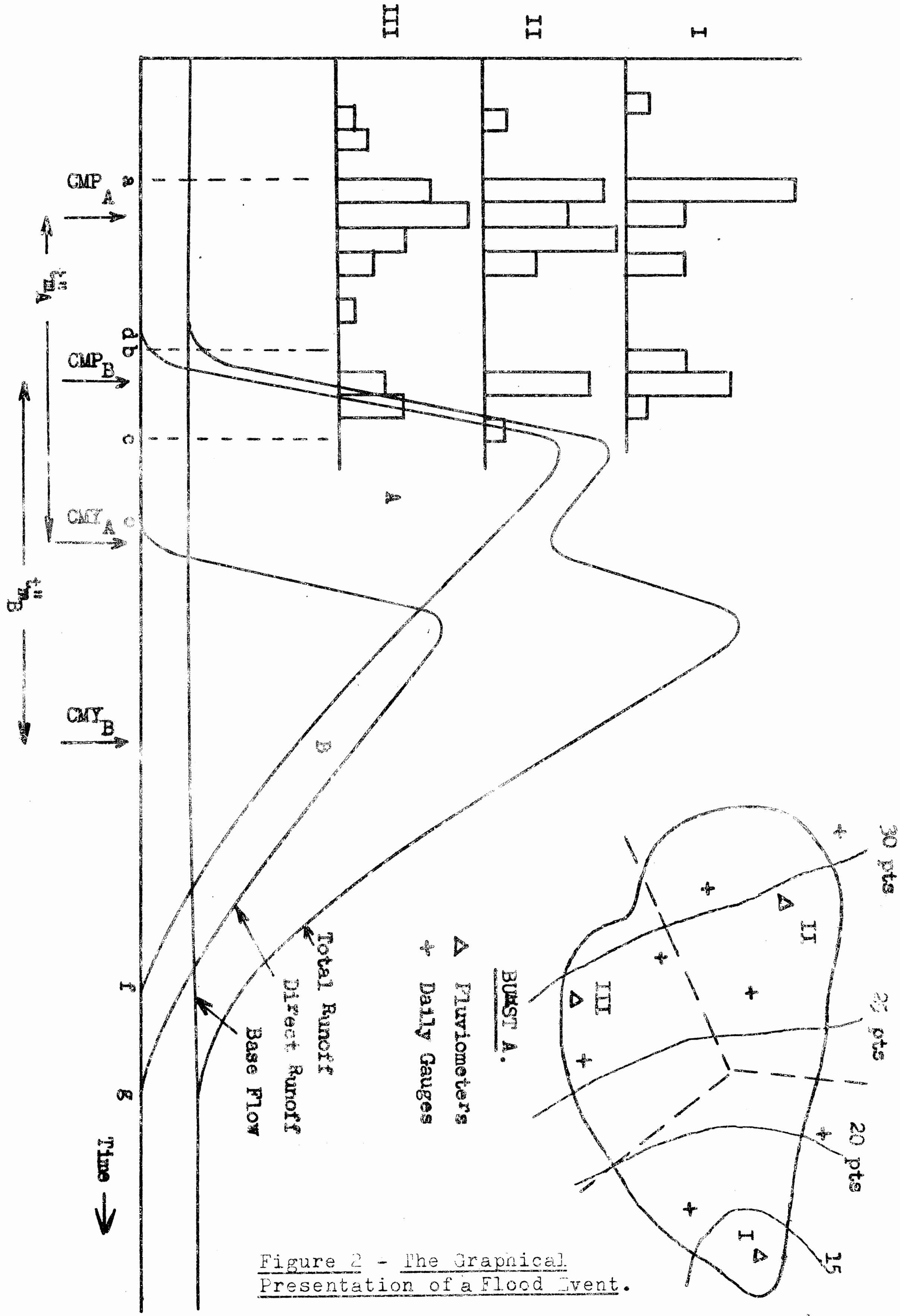

Figure 2 - The Graphical Presentation of a Flood Event.

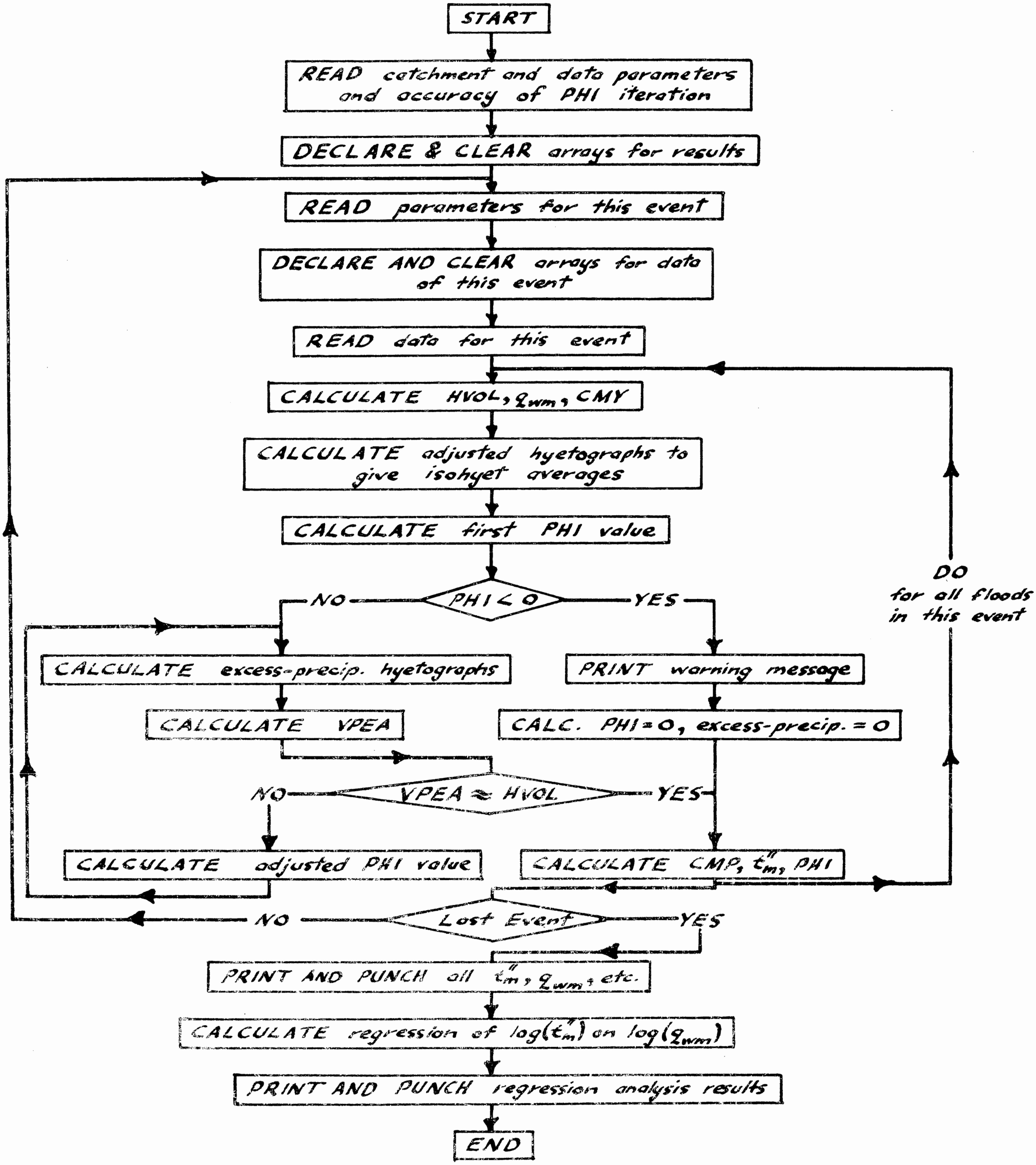

Figure 3 A Simplified Flow Diagram for LAGDCH

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