

CURRENT TECHNIQUE IN RAINFALL-RUNOFF ANALYSIS

by

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To an unknown philosopher, probably a Persian, who lived more than 2,000 years ago, must be credited one of the first broad deductions relating to the hydrologic cycle. His observation as recorded in the Book of Ecclesiastes, Chapter 1, Verse 7, is as follows: "All the rivers run into the sea; yet the sea is never full: Unto the place from whence the rivers come, thither they return". We may know more today about the mechanics of the rainfall-runoff-evaporation cycle, but the accuracy of the basic observation made centuries ago remains unchanged.

Among the first in this country to determine quantitative relations between rainfall and runoff were Newell, Gannett, Babb, Rafter, and Vermeule, to whose studies in the early nineties we still refer. Well-known present day investigators include Mead, Meyer, Horner, Houk, Horton, Sherman, and a host of other enthusiasts too numerous to mention who are making remarkable progress in the development of new technique.

Each river basin in which there are continuous observations of stream flow and meteorologic phenomena constitutes a potential field laboratory for hydrologic research. The importance of this potential laboratory must not be overlooked in our present-day intensified studies of hydrologic phenomena through the medium of hydraulic laboratories and small experimental areas. Each has an important place in the broad field of scientific and applied hydrology. The more generalized results of the large basin-wide studies disclose tendencies, the exact mechanics of which may be examined through intensive studies in small areas. On the other hand, unless the results of the experiments on small areas can be applied to larger areas, their contribution in major present day hydrologic problems which are necessarily basin-wide in scope may be more theoretical than practicable.

By means of lysimeters and evaporation pans we may determine evaporation and transpiration from small areas. By means of plots the amount of direct surface runoff may be determined under different conditions of rainfall experiences and changing surficial cover. In the laboratory we may determine laws governing the flow of water in channels and through the ground and may even simulate channel storage in a major basin as has been done by Professor Thomas at Pittsburgh. Each device, however, only measures one phase of the hydrologic cycle and, while we may combine the results obtained and thus simulate actual stream flow under a certain set of conditions, the accuracy of any such artificial record must await verification by basin-wide observations; for, after all, the stream flow as it passes a river-measurement station reflects the practical operation of all the various phases of the hydrologic cycle as modified by inherent basin characteristics and ever-changing meteorologic conditions.

I can perhaps illustrate a point I have in mind by reference to observations made during the outstanding storm and flood of March 1938 in Southern California. During two 24-hour periods separated by less than a day, about 25 inches of rain fell on the steep slopes of the San Gabriel and the San Bernardino Mountains, tributary to the coastal plain on which the city of Los Angeles and adjacent communities are located. Observations of runoff from small plots, so located as to be typical of much of the contributing steep mountainside, indicated practically no direct surface runoff, maximum runoff values being about .17 inch with precipitation of about 24 inches. Yet less than four hours after the period of maximum rainfall intensity, much of the South Pacific coastal area was deluged by a flood which took a toll of 87 lives and did direct property damage conservatively estimated at \$78,000,000. It would appear that on the basis of plot observations such a flood could not have occurred. On the basis, however, of observations of the discharge from drainage areas, as such, the characteristics of the flood water that actually accumulated in river channels (whether as direct surface runoff or as outflow from infiltrated water to be later debouched onto the flood plain) are known. The plot observation gives a valuable insight into the mechanics of runoff in this particular area. Basin-wide observations give information essential in the vital flood problem involving the disposal of the flood waters, which in portions of the area amounted to as much as 10 inches in a period of 24 hours.

To those who are accustomed to the accuracy and refinement of laboratory practice, where, through precise observation, the magnitude of each constituent element and their water relationship are known, the information generally available for basin-wide study no doubt seems crude. It may be felt that conclusions based thereon must necessarily be uncertain. It is necessary to remember, however, in this connection that although any individual measurement or deduction therefrom may be considerably in error, averages based on a large mass of accumulated information under appropriate conditions are likely to be reliable and the indicated tendencies may reflect closely actual conditions. For example, in connection with the rainfall-runoff studies of the floods of March 1936 which occurred simultaneously over all the northeastern part of the United States from Virginia to Maine, the records of nearly 2,000 precipitation stations, snow surveys, and snow observations were compiled and analyzed. Hydrographs of mean daily discharge for the months of February, March, and April were plotted and studied for 420 river-measurement stations. All sources of information regarding temperature as it may have affected the melting of snow and of frost as it may have affected the runoff were examined, even including reports of all superintendents of cemeteries regarding frost penetration. Conclusions drawn from such a mass of information must closely represent actual conditions and may, it seems to the writer, be used with confidence. For example, the general uniformity of the results suggests that for most of the 200,000 square miles affected by the storm of March 1936 the direct runoff during the resulting flood was predominantly a function of the total amount of water on the area, in the form of rain and melting snow, and differences in inherent basin characteristics such as size, shape, cover, topography, channel conditions; and other features apparently had relatively little influence on the total direct runoff. These factors did, however, influence the degree to which the flood runoff was concentrated with respect to time. The studies further showed that only a relatively small amount of water was retained in the basin during this outstanding early spring storm. The amount so retained averaged three to four inches as compared to runoff of from eight to twelve inches. On the other hand, a similar study has recently been completed of the outstanding floods which occurred in the Sacramento and San Joaquin rivers in central and northern California during

December 1937 and, in southern California, of the flood of March 1938. In this study 1,600 precipitation records were compiled and analyzed, including the analyses by hours of nearly 100 recording rain gage records and several hundred continuous water-stage recorder records. The general conclusion is reached that in much of this semi-arid country the total runoff from rainfall somewhat similar in depth to the March 1938 storm was not so much a function of the total rainfall as it was a function of the ability of the area to absorb and retain water. Residuals or differences between rainfall and direct runoff ranging from 10 to 15 inches were common over wide areas and residuals as low as four inches were the exception, not the rule. Definite and well supported conclusions such as these over wide areas have immediate value to those who are studying the basic causes of floods and remedial measures for protection therefrom.

The topic assigned the writer covers "current technique." Fundamentally, the current technique consists largely of sifting and re-sifting a large mass of information. Lord Kelvin has remarked that "many of the greatest discoveries of science have been but the reward of accurate measurement and the long-continued labor in the minute sifting of numerical results." These processes are fundamental in rainfall-runoff analyses and to this extent they can perhaps be classed as a science.

One of the first major analyses carried on by the Geological Survey was sponsored by what was originally the Mississippi Valley Committee, and later the Water Resources Committee of the National Resources Committee. The study related largely to droughts. All of our more recent studies have been related largely to floods. It is strange, but nevertheless true, that during the last decade there have occurred some of the most outstanding widespread droughts and floods since the time of settlement by whites. Droughts and floods have occurred from 1930 to date in more than half the country, the severity of which has been exceeded rarely, if ever, in the history of the country, and were climaxed by the hurricane which swept through New England last September after immunity in that area for probably more than 100 years and which resulted in the loss of over 700 lives and 300 millions of dollars in property damage. From an administrative standpoint these unusual manifestations of nature have created outstanding problems of relief and control. They have also disrupted agricultural policies based on some hoped-

for degree of normalcy. From a technical standpoint these unusual occurrences have offered an excellent opportunity to study the characteristics of floods and droughts and their relations to meteorologic conditions and climatic provinces. In fact, the hydrologist is rarely much interested in normal conditions. When Wall Street or the weather makes the front page it is well for the public to stay indoors, but for the hydrologist unusual weather signifies unusual activity on his part.

The general problem of studies of relations between rainfall and runoff presented by the Mississippi Valley Committee was not specific and it was necessary to examine in a rather broad and exploratory manner certain phases of relations between rainfall and runoff and the factors that affect these relations. In 1930 the upper Mississippi Valley was experiencing an unprecedented drought of such magnitude that a prominent governmental official painted a word picture in which he saw the stark skeleton of what is now Kansas City rising in the midst of an uninhabited sand dune. The Committee hoped, among other things, that the studies would show to what extent over wide areas man's occupancy had caused measurable changes either in meteorologic conditions or in stream flow. With respect to this moot question it was clearly shown that during a period of less than 100 years changes of sufficient magnitude have occurred in meteorologic and hydrologic conditions to affect man's activities in certain parts of the United States. No definite indication could be found, however, that any of these changes over wide areas had resulted from man's occupancy. One interesting fact disclosed was that insofar as several major stream basins are concerned there was less annual runoff from the same amount of rain under conditions as they existed from 1930 to 1935 than formerly. This is somewhat at variance to the opinion frequently expressed that streams are "slicker" or more "flashy" than formerly. The studies seemed to disclose that the condition outlined may relate to temperature. In fact, it was indicated that much of the serious water shortage which existed in the central West during several years between 1930 and 1935 may have been directly related to a very decided upward trend in temperatures and its effect on evaporation. When we consider that of the total precipitation only that portion which escapes evaporation and transpiration is made available for man's use, in streams or as ground water, the importance of temperature changes is evident. Especially is this true throughout

this great Mississippi Valley and adjoining Red River Valley on the north where the average annual requirements of evaporation and transpiration so nearly equal the average annual precipitation that any changes which would tend to increase the losses would materially affect the amount of water available for stream flow and for the replenishment of soil moisture and ground water. Time does not permit, however, a general discussion of the many interesting facts disclosed regarding droughts, climatic cycles, soil moisture, ground water, and related features.

Analyses in connection with these problems involved a nationwide study of many long-time observations of precipitation and temperature for the purpose of determining changes and trends by major and minor areas and an analysis of the long-time records of stream flow collected by the Geological Survey and cooperating agencies, not only in terms of total runoff, but broken down into its component parts, i.e., the determination of the quantities that reached stream channels essentially as direct surface runoff and that part which consisted of outflow from ground water reservoir. The analysis included graphical study and other means for correlation of the direct surface runoff and flood-producing storms and also the investigation of changes in soil moisture as related to meteorologic conditions. The group making this study had the advice and consultation of a committee of engineers and hydrologists appointed by the Section of Hydrology of the American Geophysical Union.

Analyses in connection with the flood studies have involved the collection and compilation of all available information relating to rain, snow, ice, temperature, and frost during the storm-producing period and for pertinent antecedent periods; the determination of the amount of water available for runoff for each major and minor drainage basin affected by the storm; the analysis of each hydrograph of stream flow to determine the amount and distribution of the direct runoff resulting from the particular storm; the adjustment of the observed direct runoff for changes in channel storage in order more nearly to synchronize as to time the rainfall and the runoff. Not only has the total retention or difference between rainfall and runoff been determined, but also, where hourly records of precipitation have been available, the average rates of absorption, or infiltration indexes.

Some of the more or less general conclusions reached as a result

of flood studies in New England and California have been briefly outlined. In addition, a very detailed study has recently been completed of the hydrologic features associated with the great flood in the Ohio River during January 1937. Geologists in the Geological Survey have concluded that "Available geologic evidence, suggestive rather than compelling, seems to show that in part of the valley studied the flood exceeded in height any previous flood." Air-mass analyses by the Weather Bureau indicate that the total precipitation which occurred during the December storm was within about 15 per cent of what they consider the maximum possible for this particular area. Like the storm of March 1936, the Ohio River storm of January 1937 covered about 200,000 square miles. The storm of March 1936 was so centered, however, that the runoff therefrom was distributed over several major drainage basins and the flood waters found their outlet to the ocean through the St. Lawrence, Ohio, Connecticut, Hudson, Delaware, Susquehanna, Potomac, James and other North Atlantic Coast streams. The storm of January 1937 was centered largely over the Ohio River basin and the entire runoff therefrom amounted to about 90,000,000 acre feet, or, to those who like to think in terms of cubic feet, some 3,920,400,000,000 cubic feet of water, which had to flow out of the basin through the single river channel of the Ohio River at Cairo. Such accumulations of water in one channel resulting from a single storm period are extremely rare. The rainfall-runoff studies disclosed some interesting features. Although, as has been mentioned, the flood stages along the Ohio River proper, especially from Cincinnati to the mouth, were, by and large, the highest on record, the stages on none of the tributaries to the Ohio River broke previous records. This peculiar condition resulted from the occurrence during the full storm period of five or six individual storms which caused a series of isolated peaks on the tributaries, few of which broke previous records. All of the runoff from these isolated peaks gradually accumulated in the Ohio River channel and in its overflow section, with a result that during the flood the inflow to the Ohio River channel exceeded the outflow by 39,000,000 acre feet, or $1\frac{1}{2}$ times the capacity of Lake Mead formed by Boulder Dam, the largest artificial reservoir in the world. Shortly after the period of most intense precipitation, water was flowing into the Ohio River channel reservoir at the rate of nearly 5,000,000 acre feet a day or enough to have filled Lake Mead in six days; whereas it

would take about two years to fill Lake Mead if all the runoff of the Colorado River were impounded back of Boulder Dam. On January 28, 1937, 27,300,000 acre feet was being temporarily detained in the Ohio River channel at elevation above the flood stage as defined by the Weather Bureau. This figure gives some approximation at least of the vast amount of water that would have had to be stored or otherwise retarded to have kept the water in the channel of the Ohio River at or below the danger level.

On the average, of the 12.85 inches of rain which fell on the Ohio River Basin during the period December 26, 1936, to January 25, 1937, about 8.8 inches flowed past Cairo in the flood and four inches was retained in the basin as surface or ground storage. Here again the general uniformity of the residuals, or differences between rainfall and runoff, indicates that differences in basin characteristics, cover, or land use practices, had little effect on the residuals so that, conversely, it may be argued that such practical modifications as could be made in cover or in increasing absorption would have little effect upon the runoff during floods of the magnitude indicated, and more especially those that occur during the winter months, in the north central and northeastern parts of the United States, when frost may reduce infiltration capacities almost to zero. Analyses of the floods in the northeastern part of the United States during March 1936 seemed to indicate that rates of absorption increased downstream. Analyses just completed of the hurricane flood of September 1938 clearly confirm this observation for New England rivers. Average rates of absorption increased from about 0.06 inch per hour for drainage basins in headwater areas to about 0.20 inch per hour for downstream areas. These recent studies also seemed to confirm an earlier surmise that insofar as drainage basins in the northeastern part of the United States were concerned there is probably no definite rate of ground absorption below which there will be no runoff and above which there will be runoff.

All of the studies which have been made indicate the important part that natural storage in channels and overflow areas plays in the flood problem through the ironing out of the flood peaks. In many areas topographic and physiographic features fix a definite limit on the amount of artificial storage that can be provided. We also know, or should know, that depending on various conditions there are limitations in the ability of the ground to absorb and retain

water. True it is that the soil through its ability to absorb water constitutes a great underground reservoir—a reservoir, however, that has only a limited capacity and otherwise may be unreliable in that the rates of inflow and outflow are not subject to control by man. We also think of water in the form of snow or ice as constituting nature's large surface water-supply reservoir. Such a reservoir is, however, also fickle and unreliable in that its effectiveness and reliability depend on climatic whims and not on the control of man. Floods rarely occur when either of these reservoirs has capacity available and is in the process of storing water. On the other hand, any one who has analyzed meteorologic and hydrologic conditions during our widespread floods will realize that they have resulted from or been aggravated by either the release of water stored in the form of snow or ice, or the inability of the earth to absorb water, or a combination of these conditions, both of which relate largely to temperature.

In many areas the flood problem will not be entirely solved until our citizens recognize that nature designed and formed river channels, valleys, and overflow areas for the temporary storage and eventual passage of flood waters. As long as man continues to use and occupy these channels and flood plains for homes, farms, highways, communities, and cities, flood damage and loss of life will be inevitable. In such areas the quick, accurate, and dependable flood forecasting offers one of the principal precautions against flood damage and there is being built up in the River and Flood Division of the Weather Bureau a forecasting technique based largely on rainfall and runoff analyses.

Another type of rainfall-runoff analysis is now being actively carried on cooperatively by the Weather Bureau and the Corps of Engineers. Their study relates to the derivation of maximum floods that may be expected to occur in any river basin. These studies are essentially basin-wide in scope. The designation of the section in the Weather Bureau where these studies are conducted—namely, "hydrometeorological"—indicates the active participation in the studies by meteorologists as well as by hydrologists. Two principal steps are involved—first, the shifting or transposing of major storms that have occurred to drainage basins in such a position that the maximum concentration of flood water results and the determination of the probable runoff that would have occurred had the storm

so centered; and second, through air-mass analysis, the determination of the probable maximum storm rainfall that can occur in any area, from which some idea of the magnitude of the so-called "super-flood" may be approximated. I visualize that eventually, through rainfall-runoff analyses, there will be readily available for each river basin, as for example the Iowa River above Iowa City, information showing the flood magnitude and characteristic of: first, the maximum flood of record; second, the probable flood that would have occurred had the maximum storm of record in the Mississippi Valley been centered over the Iowa River Basin in such a position that maximum concentration of flood water would have resulted; and third, the magnitude of the flood that could occur under the most extreme storm conditions deemed possible, even though there may be no historic record of such a storm.

Analyses of flood characteristics being made by the writer and others seem to indicate that there may be a relation between flood characteristics and climatic provinces. Certain it is that the magnitude of flood runoff and the degree to which it concentrates in river channels vary within wide limits. To a considerable extent these variations may relate to the physiographic and edaphic features of the drainage basins as they have been developed by the geologic and climatic history of the particular province in which they are located. Floods in the arid or semi-arid west have different characteristics from those in the humid east or subhumid portions of the upper Mississippi River valley. Floods associated with melting snow have different characteristics than floods resulting wholly from rain. Flood-producing potentialities of vast intermountain valleys lying in the storm shadows of the massive mountain ranges of the west are less than those of the western slopes of these same mountains where moisture-laden air masses are wrung dry as they are deflected upward against their cold fronts. To the extent that different zones or provinces can be delineated, the flood problem becomes simplified.

The members of the faculties of our engineering schools would render an excellent service if they could instill into at least one student out of each graduating class an earnest desire to delve more deeply into unexplored hydrologic fields. We need to know much more about the mechanics of runoff: Through what paths does the water reach the defined stream channel, how much is direct surface runoff, and how much reaches the stream channel through the

ground; how, through channel-storage corrections, can we coordinate the basin-wide results with plot experiments; and, taking into account the marked effect of climate, physiography, and geology on flood characteristics, what permanent changes can reasonably be made in flood characteristics over wide areas? The answers to these and many other questions are needed today in the field of applied hydrology. The basic principles can be taught in schools, but each student must, to a considerable extent, develop his own technique. The schools, as such, can also be of great service if they will continue to impress upon the public the value of basic rainfall and stream flow data in the many, many problems of droughts and floods as they affect the present-day activities of our highly organized civilization.