ably withstanding pressures considerably in excess of the critical pressure indicated by the formula quoted by Mr. Barber. For example, consider the pipe culvert installed to replace the Coal Creek Viaduct on the Denver and Salt Lake Railway which was described in *Engineering News-Record*, 125: 632–633, for November 7, 1940. This culvert is 180 in. in diameter and the moment of inertia of the pipe wall is 0.08 in^4 per in., giving an equivalent diameter/thickness ratio of about 183, which is well within the realm of thin tubes. According to the critical pressure formula

$$p = \frac{3.3 \times 29{,}000{,}000 \times .08}{90^3} = 10.5 \text{ psi}$$

The dead weight pressure of the 42-ft. high embankment above the top of the culvert is in the neighborhood of 35 psi, and it is probable that the vertical pressure on the pipe is not much different from this weight. Also, since the soil at the sides of the pipe was compacted during construction is is reasonable to conclude that the maximum unit passive pressures at the horizontal axis of the pipe are equal to or greater than the vertical pressure. It seems reasonably certain, therefore, that this culvert is successfully carrying maximum unit pressures three to four times greater than the critical buckling pressure.

In view of the foregoing considerations, Mr. Barber's suggestion as to the applicability of the critical buckling pressure formula to flexible pipe culverts does not appear to be tenable.

ON THE HYDROLOGY OF CULVERTS

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SYNOPSIS

Since the hydrologic problems in planning highway drainage are similar to those encountered in many phases of soil and water conservation, highway engineers may be interested in the experience of conservationists. When the large scale program of soil and water conservation began in 1933, an attempt was made to use Ramser's curves, developed by the rational method with coefficients and times of concentration, based largely on measurements made in 1918 on six small watersheds in Tennessee. These curves were gradually supplanted by direct application of the rational method to individual cases. The need for additional information led to the establishment by the Soil Conservation Service of runoff studies at some 22 locations. It was expected that these studies and the experimental watersheds of the Service would furnish coefficients of runoff and times of concentration for a wide variety of conditions.

Analysis of rainfall intensities and rates of runoff obtained from these studies over several years not only did not produce the expected values, but gave support to those who doubted the validity of the rational method and of the rainfall runoff relationship. It was found that watershed characteristics and conditions of soils and of vegetal cover at the time of the storm are as important, if not more so, than rainfall amounts and intensities.

Clearer understanding of the problem and information on soils, physiography and land use made possible delineation of areas in which results from the runoff studies are applicable. Through probability analysis of the runoff records, design curves were developed for several areas of application. Samples of such curves show variation of peak rates of runoff with soils, vegetal cover, as well as rainfall intensities and other climatic factors in various geographic locations. The shapes of the several curves express the relation of peak rates of runoff to size of drainage area in various physiographic provinces. Some of the curves have already been published. Reports containing others are in various stages of completion. All are subject to revision in the light of longer records and records

from watersheds of various sizes in each area of application. Many additional records are required to verify the results and to develop similar information for the remainder of the United States.

If this new approach is accepted, additional records from small watersheds can be obtained with a minimum of effort and expense. With published information, most of it recent, on the hydraulics of culverts and on discharge coefficients of notches and inlet structures, records of peak rates of runoff can be obtained by a limited number of stage readings on properly installed staff gages. Box culverts and even streams spanned by small bridges can be rated with the "velocity-head rod" which, while very much simpler, is more suitable for the purpose than the current meter method.

Highway engineers and conservationists can make a perfect team in solving this common problem. The former, who maintain thousands of miles of highways, can install the gages and secure the records. The conservationists can contribute a vast amount of information needed in the proper selection of watersheds and in delineating the areas of application and make available the unique experience gained in almost a decade of measuring runoff from small natural watersheds.

A list of 31 references, dealing with various phases of this subject, completes this paper.

The basic hydrologic problems in planning highway drainage are similar to those encountered in many phases of soil and water conservation. There are practically no differences in the principles involved. Highway and railroad engineers have been exposed to these problems much longer than the soil and water conservationists. Through many years of experience and of hard knocks, the former have developed certain rules of thumb and a host of empirical formulae.

In 1934, T. A. Munson (*1*)[1] listed 36 formulae and four sets of curves used at that time in determining runoff and sizes of highway and railroad drainage structures. Many of these formulae, such as the Burkli-Ziegler and the Talbot have been applied quite widely and for many years. Through local experience, coefficients were developed which, in some cases, made these formulae "safe" for specific local conditions. That these formulae do not always work is evidenced by frequent reports of washed-out culverts and small bridges.

For instance: In Texas in November 1940 (*2*)

"... 23 major state and federal highways have been closed because of washouts and damaged bridges. Commissioners of Anderson County at Palestine estimate nearly 100 bridges and culverts were washed out ..."

[1] Italicized numbers in parentheses refer to the list of references at the end of the paper.

In September 1938 (*3*)

"... Connecticut lost 30 bridges on the state highway system compared with only 12 in 1936. Only four of these were of major size and only one a relatively new structure. ... In Massachusetts, 20 state highway bridges are out, of which four are relatively large; ... In contrast to the state highway bridge losses, preliminary reports to the state highway department indicate that 375 other bridges, mostly small, were washed out, most of them completely demolished. ... In New Hampshire the bridge and highway loss, while relatively large in number of structures, will not bulk large in dollars."

and in August 1940 (*4*)

"... The Virginia State Highway Department lost 332 bridges during the flood, suffering an estimated damage of $800,000."

I could continue quoting similar published reports. Anyone who has anything to do with highway maintenance could add much that has not been published. It is, however, not my purpose to spotlight these washouts. Practically speaking, some of them are unavoidable. One might even go further and say that, except in special cases, culverts, small bridges, or any other small drainage structures should be considered improperly designed if they prove large enough to carry flows which can be expected only once in 50 years or less frequently. My purpose in quoting these reports is to point out that it is culverts and other small drainage structures that figure most prominently in flood damages, and to call attention to the large unnecessary expenditures entailed in overdesigning them. For an entire district or a state, the aggregate cost of these numerous small structures probably exceeds that of the larger bridges. It is not surprising, therefore, that many highway engineers have of late been looking for better methods of estimating peak flows from small drainage areas. The work of the Committee on Surface Drainage of Highways shows that the problem is under active consideration.

Soil and water conservation work did not begin on a large scale until 1933 when millions of dollars and thousands of men suddenly had to be utilized in the construction of terraces, intercepting ditches, culverts, dams and similar structures on small drainage areas. It was imperative that something in the way of simple formulae or curves be made available quickly for estimating peak rates of runoff from such areas. The early phase of this program was greatly facilitated by what are known as "Ramser's Curves" (*5*). These curves for 10- and 50-year expectancies were computed by the rational method with values of "*C*" and of "times of concentration" based largely on the results of measurements made in 1918 on six small watersheds (1.25 to 112 acres) near Jackson, Tennessee (*6*). Rainfall intensities for various durations and the two expectancies (10- and 50-year) were taken from Table 15 of Adolph Meyer's "Elements of Hydrology" (*7*). With the publication in 1935 of Yarnell's "Rainfall Intensity-Frequency Data," (*8*) the application of Ramser's curves was extended beyond Meyer's five groups. It was not long, however, before actual experience showed that these curves could not be applied over such a wide range of conditions as are encountered in the United States. The use of the curves was gradually abandoned in favor of direct application of the rational method. It was felt, however, that more information was needed on values of "*C*". It also became apparent that improper selection of the "time of concentration" in the rational formula affects the estimated rate of runoff even more than errors in selecting the coefficients of runoff. In outlining the "modified" rational method, Bernard (*9*) has this to say about the time of concentration:

"The rational method is based upon the theory that, for a given frequency, maximum runoff rate at the channel location being studied, results from a rainfall of duration equal to the time of concentration of the particular watershed. In this, the simplicity of the *CiA* equation is misleading, for the critical value of the rainfall intensity *i*, through the medium of concentration time, entails a consideration of such factors as watershed size, shape and slope; channel length, shape, slope, and condition; as well as variation in rainfall rate, duration, and frequency; all of which can and should be considered in determining its value."

He then outlines a solution which is hardly practicable for the design of ordinary conservation or highway drainage structure. The realization of these difficulties led the Soil Conservation Service to establish runoff studies in widely separated locations (*10*). It was expected that the records from these studies and from the experimental watersheds near Coshocton, Ohio (*11*), Waco, Texas (*12*), and Hastings, Nebraska (*13*), Figure 3, would make possible determination of coefficients of runoff and of times of concentration for a wide variety of conditions, thereby insuring proper and wider use of this method.

Most of the runoff and experimental watershed studies have now been in operation for about 8 years. Records of amounts and intensities of rainfall and complete runoff hydrographs are now available for hundreds of storms on small natural watersheds with a wide range in topography, soils, vegetal cover and tillage practices.

The analyses of a large number of these records not only failed to produce the desired "coefficients of runoff" and "times of concentration," but, on the contrary, offered a good deal of support to those who doubted the validity of the rational method in estimating peak rates of runoff from small natural watersheds.

The rational method is expressed by the well known formula $Q = Ci_tA$ or $q = Ci_t$ where "q" is peak rate of runoff in c.f.s. per acre and "i" the rainfall intensity for time of concentration "t." Emil Kuichling developed this method for estimating rates of runoff from urban areas and derived the formula from measurements of rainfall and of the flow in the sewers of Rochester, N. Y., during 1877 and 1888 (*14*).

The formula $q = Ci_t$ looks a whole lot simpler than it is. As it stands and as it has been generally used in estimating peak rates of runoff, it implies the following assumptions:

1. The rate of runoff resulting from any rainfall intensity is a maximum when this rainfall intensity lasts as long or longer than the time of concentration; that is, the time required for water to flow from all parts of the watershed to the outlet.
2. The maximum runoff resulting from a rainfall intensity with a duration equal to or greater than the time of concentration is a simple fraction of such rainfall intensity. That is, it assumes a straight line relation between "q" and "i_t" and that $q = 0$ when $i_t = 0$.
3. The expectancy of peak rates of runoff is the same as that of the rainfall intensity for the time of concentration.
4. The relationship between peak rates of runoff and size of drainage area is the same as the relationship between duration and intensity of rainfall.
5. The coefficient of runoff is the same for storms of various expectancies (10-yr., 25-yr., 50-yr., etc.).
6. The coefficient of runoff is the same for all storms on a given watershed.

It should be pointed out that the effect of the duration of the rain has long been recognized in storm sewer design. It was one of Kuichling's cardinal points. Several formulae expressing the relation of "C" to the duration of the rain have been proposed (*15*). The values suggested by Horner (*16*) range from 0.2 for a duration of 10 min. to 0.4 for a duration of 30 min.

These assumptions might conceivably hold for paved areas with gutters and sewers of fixed dimensions and hydraulic characteristics such as roughness, slopes and hydraulic radii. With good judgment the application of the method might be extended to urban areas not fully paved but with fixed channels.

Leaders in the field have of late been calling attention to the inadequacy of this method, even in the design of storm sewers. In the synopsis of "Surface Runoff Determination from Rainfall Without Using Coefficients," Horner and Jens (*17*) make the following statement:

"In hydraulic engineering practice, the relation between rainfall and runoff has generally been represented as a ratio or coefficient. It has been recognized that the form of this relationship should be 'rainfall minus losses equals runoff.' Heretofore the inadequacy of hydrologic data has discouraged attempts to evaluate losses as they occur during a storm period. In this paper the writers call attention to the recent improvement in hydrologic data with respect to precipitation and stream flow, and to the information with respect to infiltration that has developed from the research program of the U. S. Department of Agriculture; and they outline a method of applying this information to the evaluation of surface runoff from precipitation data without the use of a coefficient. The method is presented as being generally applicable to all drainage basins, and is described in detail as it would be used in urban storm drainage."

In the light of the information obtained from the runoff studies it is difficult to see how these assumptions can apply to small natural watersheds where characteristics and conditions of the drainage area as well as of the channels are affected greatly, not only by amounts and intensities of rainfall, but by other climatic factors and by land use, tillage and cropping practices.

What takes place on a natural watershed during a storm and how changes in watershed conditions affect runoff has been discussed in considerable detail elsewhere (*18*) and will not be repeated here. It may, however, be well to show how some of these assumptions stand up in the light of actual records. In Figure 1 are plotted peak rates of runoff "q" in inches per hour against "i_t"-rainfall intensity for the time of concentration. The plotted points represent storms over a period of several years which most nearly meet the requirements of the rational method. Rainfall intensities, rates of runoff and times of concentration were carefully determined from hydrographs and mass curves of rainfall obtained with sensitive, properly synchronized installations capable of recording time to the nearest minute, depth of rainfall to the nearest 0.025 in. or less and runoff to a small fraction of a cubic foot per second.

If $q = Ci$ expresses the relationship between rainfall and runoff, then the points in the several diagrams must fall on straight lines with slopes = "C." Furthermore, the lines must go through the origin. Of the 16 diagrams, the one for the 52-acre watershed at Fennimore comes closest to meeting one of the requirements. Three of the eight points fall nearly on a straight line; and all three have the same time of concentration-8 min. It should be noted that this line does not go through the origin. Its equation $q = 0.637i_t - 2.325$

is qualitatively more nearly expressive of what actually takes place. It shows that when $q = 0$, "i_t" is not zero. But even this more logical expression of the rainfall runoff relationship does not hold quantitatively. Two of the eight points show fairly high rates of runoff for "i_t" smaller than 3.65 in. per hr.—the value for which this equation indicates zero runoff. A close examination of the original records shows that two of these three points represent storms, in which the amount of rainfall preceding the period of rise (time of concentration) was less than in the remaining six storms. It is, therefore, quite likely that the relationship expressed by the line drawn through the three points has no more physical significance than would straight lines fitted to the points in the several diagrams by least squares or by other statistical methods.

But even if a relationship between "q" and "i_t" could be established, there would still remain the most important shortcoming of the rational method and of all other methods involving the rainfall runoff relationship; namely, the assumption that the expectancy (frequency) of runoff is the same as the expectancy of the rainfall producing the runoff. The records from the runoff studies (*18*) show that rainfall intensities and even both intensities and amounts of rainfall are not the only factors determining rates of runoff from a given watershed. Conditions of soil and of vegetative cover are fully as important if not more so. It is obvious, therefore, that the expectancy of runoff cannot be the same as the expectancy of the rainfall intensity. This conclusion could not have been reached without the records from the runoff studies, which have as yet not been made generally available. It is, therefore, not surprising to read Professor Mavis' recent article (*19*) in which he suggests the use of culverts in obtaining hydrographs for the purpose of determining "C" and "i" in the rational formula.

There is another point in Professor Mavis' article which I wish to discuss. Before doing so it is necessary to point out the important positive aspect of the results from the runoff studies. The data for the 16 watersheds shown in Figure 1, which are only a sample of similar results from over 100 watersheds, showed that the solution of the problem lies not in securing values of "C" and of times of concentration. The careful measurements and observations and results from other hydrologic studies shed light on the basic factors involved and point to a different approach. Those who had an opportunity to study this new information in detail are beginning to question the virtue of the rainfall-runoff relationship. It now appears more logical to try to arrive at estimates of peak rates of runoff directly from runoff records. This approach involves probability studies of runoff records from carefully selected watersheds with soils, vegetal cover and physiographic characteristics representative of large areas in which rainfall (amounts and intensities) and other climatic factors are similar. Such areas may be called areas of application. As long as such records remain meager and short, they must be carefully scrutinized to determine how well they represent longer periods. However, as the length of record increases the results of probability analysis becomes increasingly more reliable. In developing design values by this method it is also necessary to have, for each "area of application," records from watersheds of varying sizes so that variation in peak rates with size of drainage area can be determined. Even records from 100 watersheds are utterly inadequate for the many different conditions in a country as large and as varied as the United States. However, where records for a period of several years are available from watersheds of several sizes in the same "area of application," it is possible to derive at least tentative values for the conditions and the range in size of drainage areas most commonly dealt with in the design of culverts, small bridges and of other highway and conservation structures. Values derived in this manner must of necessity remain tentative until a longer record becomes available. Samples of the results obtained by this method are shown in Figure 2. The general areas in which the curves apply are indicated in Figure 3. Curves 3 and 4 are both for the Claypan Prairies which have rather definite physiographic and soil characteristics. The greater rates shown by Curve 4 reflect the higher rainfall intensities in Kansas and Oklahoma. Curves 1 and 2 show the effect of soil characteristics within a physiographic area with little or no variation in rainfall and in other climatic conditions. The large differences in rates of runoff from cultivated and grassed areas are shown by Curves 7 and 8.

The shapes of the several curves are determined by the relationship between peak rates of runoff and size of drainage area. All of these curves are intended to illustrate the type of information that can be obtained. Only those for the Claypan Prairies for a 25-yr expectancy have so far been published (*20*). Reports for the other areas, which will contain the remaining curves in final form together with additional ones for different soils, vegetal cover and land use, and possibly for other expectancies, are in various stages of

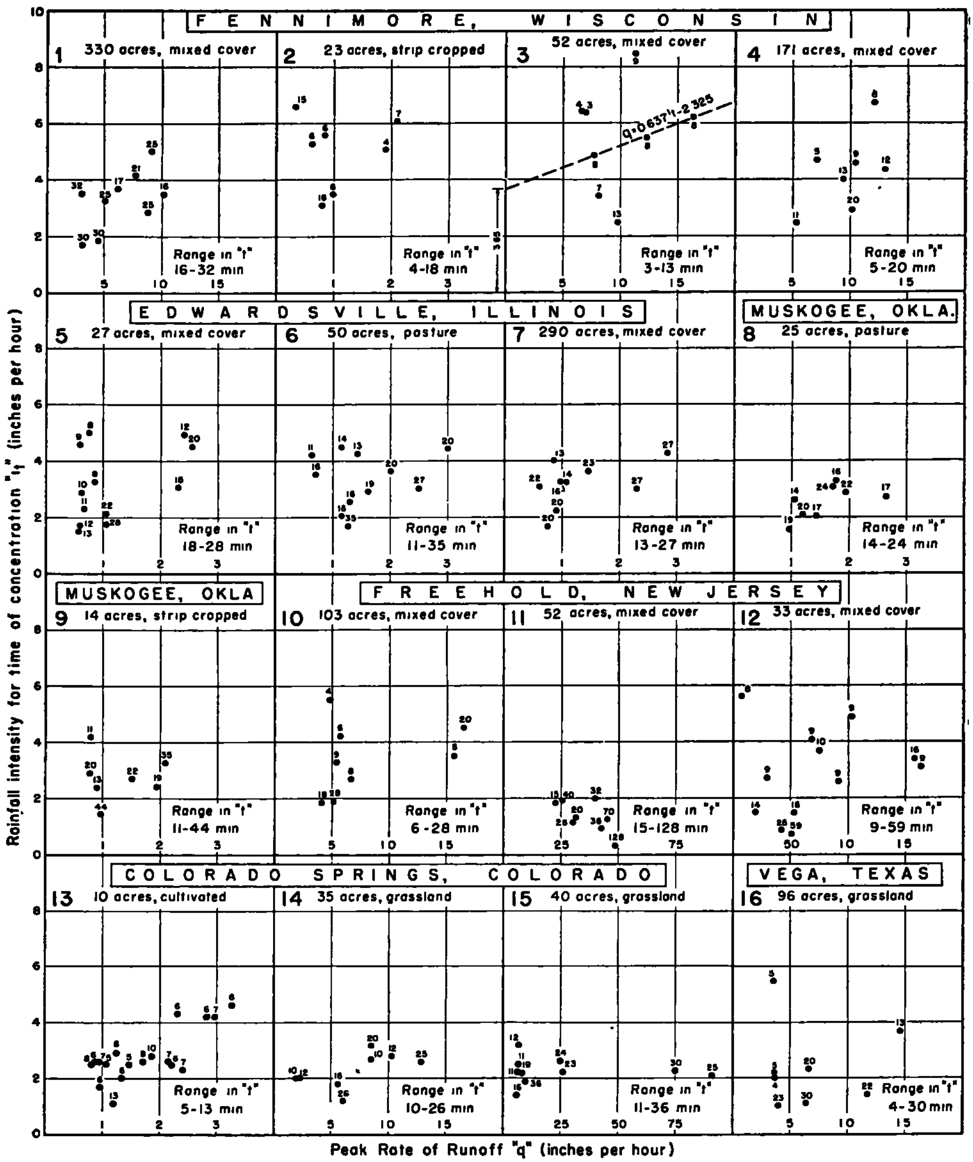

Figure 1. Relation of Peak Rates of Runoff to Rainfall Intensities for Watersheds of Various Sizes and Types at Widely Separated Locations. (Numbers at plotted points show time of concentration in minutes.)

completion. It may be well to repeat here that even the published curves are subject to revision in the light of longer records and particularly of additional information on the relation of peak rates to size of drainage area. peak rate in 9 years on the 290-acre mixed cover watershed. This storm offered an opportunity to check the published curves for the Claypan Prairies. The expectancy of the peak rate for this storm has not yet been

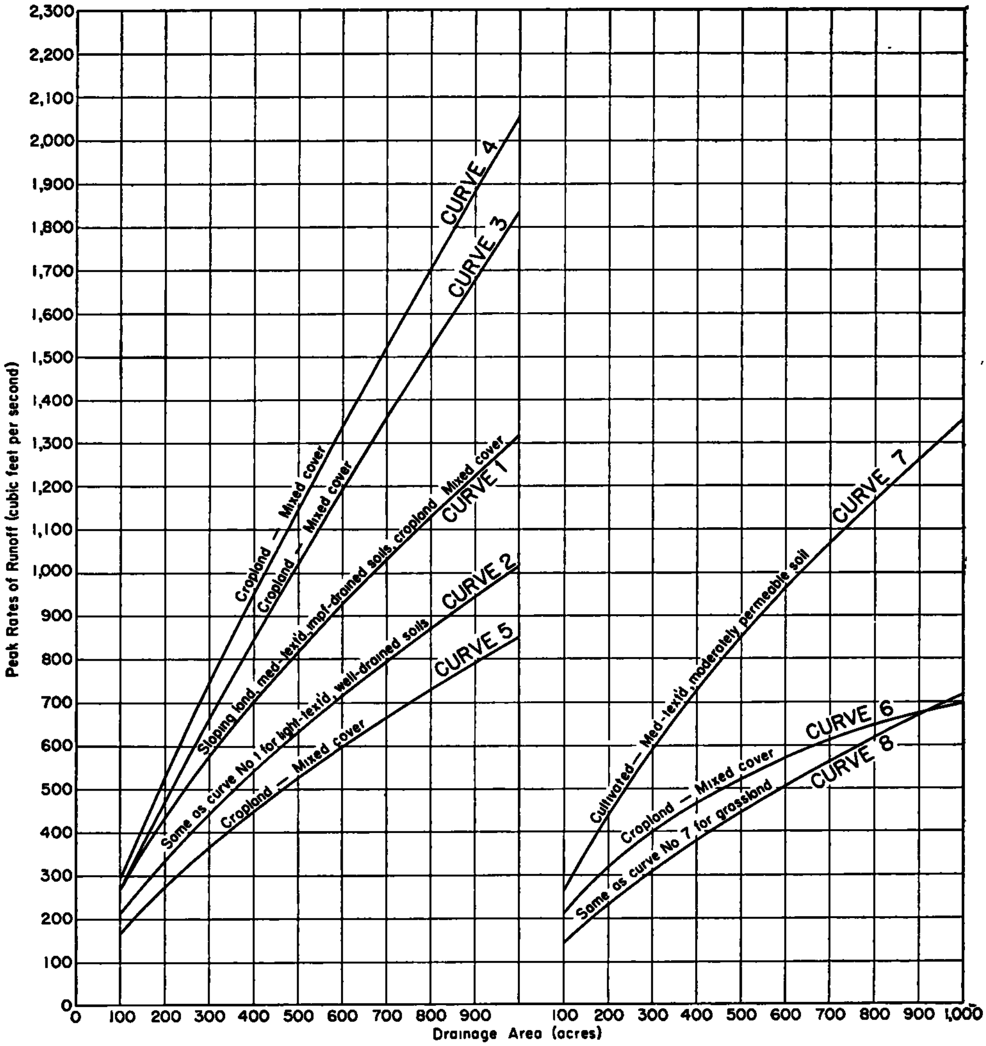

Figure 2. Samples of 10-year Peak Rates of Runoff Derived from Runoff Studies and Experimental Watershed Data. (Curve numbers refer to numbered areas in figure 3.)

Records from watersheds at many additional locations within the "areas of application" are needed also to verify the geographical boundaries of these areas.

A storm on August 14–15, 1946, at Edwardsville, Illinois, resulted in the highest definitely determined; it appears, however, to be somewhat above a 25-yr value. This rate was found to be only 8 percent higher than the 25-yr value derived from a 6-yr record (1938–1943).

One of the most important conclusions from

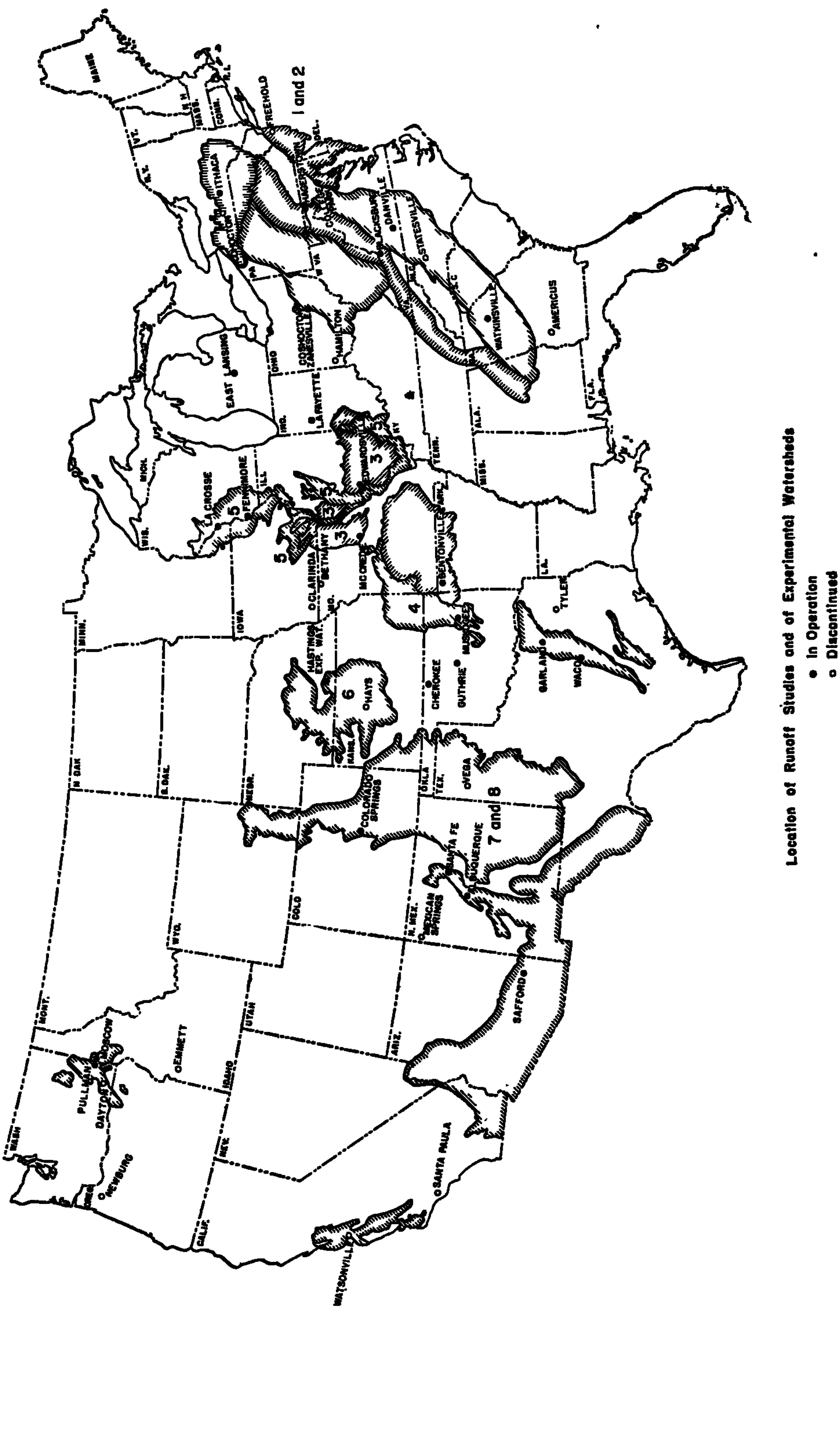

Figure 3. General Areas Represented by Some of the Runoff Studies and Experimental Watersheds of the Soil Conservation Service. (Numbers designate general areas in which correspondingly numbered curves of Figure 2 apply.)

the analysis of the data is that suitable records from a great number of watersheds of various sizes in all parts of the United States can now be obtained with a minimum of effort and expense; that is, if the suggested approach to the problem is accepted. It is here that I wish to refer once more to Professor Mavis article (*19*) and to strongly indorse his plea to utilize highway culverts in obtaining records of peak rates of runoff. I would like to add that not only pipe culverts, but box culverts, drop structures and headwalls will often be suitable for the purpose. In view of the results from the runoff studies, it should not, in the great majority of cases, be necessary to resort to elaborate and expensive installations involving recording instruments and trained observers. The desired information can be obtained with shielded staff gages, properly installed, at pipe and box culverts draining areas of various sizes and representative of the various physiographic, soil and land use complexes. The drainage structures selected for this purpose should preferably be large in relation to the drainage area—there are plenty of them—so that the records will not be seriously affected by submergence or pondage.

Mavis' excellent recent bulletin on "Hydraulics of Culverts" (*21*), an earlier publication of the University of Iowa (*22*) and recent results of the St. Anthony Falls (*23*) and of the Spartanburg Hydraulic Laboratories (*24*) of the Soil Conservation Service make it possible readily to develop rating tables for a wide variety of highway drainage structures.

The runoff measuring station on one of the water sheds near Freehold, New Jersey, presented an opportunity to check the Basic Stage Discharge Relationship shown in Figure 23 of "Hydraulics of Culverts" by Mavis (*21*). A short distance above the runoff measuring station on this watershed there is a 24-in. bell mouth, vitrified clay culvert through which passes practically all the surface runoff from the watershed. To determine the effect of this culvert on rates of runoff, records of head on the invert were kept for a number of storms. Since very little flow entered the channel between the culvert and the runoff measuring station, the discharge recorded at the station was practically that of the culvert. The maximum heads on the culvert were plotted against the peak discharges at the runoff measuring station for several storms. A comparison with the discharge curve of a

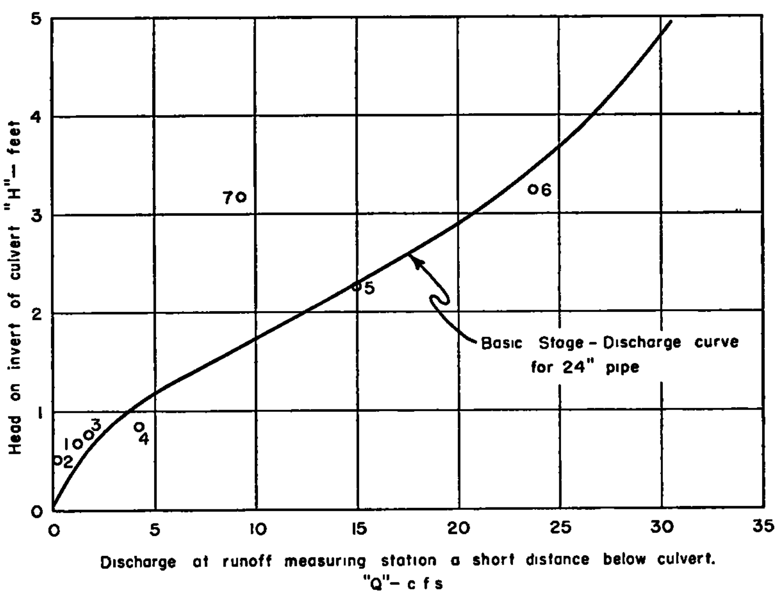

Figure 4. Measured Discharge of 24 in. Vitrified Bell Mouth Culvert Compared with Basic Stage. Discharge Curve, Figure 23 of "Hydraulics of Culverts" by Mavis.

24-in. culvert based on Mavis' Figure 23 is shown in Figure 4. The maximum head for Point 7 may have been affected by a surge in the channel above the culvert.

Large box culverts and even streams with stable natural controls spanned by small bridges can be readily rated by the simple, but ingenious device known as the "velocity-head rod." This device should be given the serious consideration it deserves as a simple means of gaging small streams for which the standard current meter procedure is too elaborate and quite often impractical. The "velocity-head rod" operates on the same principle as the Clausen-Pierce Weir Rule, also called "Hydraulic Measuring Stick." The use of the hydraulic measuring stick was first reported by Hayden (*25*) in 1926. It was more fully described by Lippincott (*26*) in 1929. Lippincott's paper includes results of laboratory tests of this device made by Professor Shoder at Cornell University Hydraulic Laboratory. The results of these tests leave no doubt as to the validity of this hydraulic measuring stick. It is incredible that this simple and accurate instrument should not have come into more general use. Wilm (*27*), faced with the problem of measuring flow in small debris laden streams, developed the "Velocity-Head Rod" which is even simpler than the "Hydraulic Measuring Stick." He describes the rod and reports that

'. . . The average error of this instrument, based on 37 measurements checked against calibrated weirs and flumes, is about ±1 64 percent."

and points out that

". . . Limitations of the rod include inaccuracy for velocities much below one foot per second and in streams with soft, unstable beds. Neither can it be handled well in large, deep streams, or with velocities greater than 8 or 10 fps. It has a practical application within its range of use . . ."

The suggested approach to the hydrologic design of small structures does not involve the rainfall-runoff relationship nor even complete hydrographs (except in special cases which will be discussed presently). Neither is it necessary to secure records for all flows. In the probability analysis of runoff records only peak rates above a predetermined minimum are utilized. Thus, on a 300-acre watershed in a high runoff producing region, it may not be necessary to record flows less than 0.2 or even 0.5 in. per hr (30 or 150 cfs). This means that only a few records per year will have to be obtained at each installation. The few records each year would consist simply of gage heights which can be converted into discharge and runoff by means of appropriate rating tables or discharge coefficients. The important part of this scheme is the selection of the watershed with due regard to soils, physiography and land use. Here is where the highway engineer and the conservationist can make a perfect team in achieving a common goal. The former, who maintains and patrols thousands of miles of highways, should not find it burdensome to install the staff gages and record stages on hundreds, nay thousands, of highway drainage structures.

The conservationist can contribute a vast amount of information needed on the proper selection of watersheds and in delineating the "areas of application."

There is one aspect of design that must be considered. Tilton and Rowe (*28*) suggested that culverts should be designed "to pass a 10-yr flood without static head on crown of conduit at the entrance," and that the barrel and appurtenances should be capable "to pass a 100-yr flood without serious damage to the highway." Design under the second provision calls for a complete hydrograph rather than peak rates only. Conservationists face a similar problem, as, for instance, when it becomes advisable to allow for spillway storage in the design of small reservoirs. Such hydrographs for desired expectancies can be developed by the unit hydrograph method from a limited number of observations of all stages during heavy storms. This would have to be done on selected watersheds for which adequate rainfall records (intensities and amounts) are available, or one or more recording rain gages might be installed for the purpose. Another, slower, but probably more adequate method would be to equip a limited number of installations with water-level recorders. Installations, so equipped, will, over a period of years, furnish the desired design-hydrographs. The controls for such stations may be either suitable culverts or, preferably, precalibrated measuring stations, such as those described in a recent technical publication of the Soil Conservation Service (*29*) and by Villemonte (*30*) in *Engineering News-Record.* The station described by Villemonte appears to be particularly adaptable to box culverts.

The records from the runoff and experimental watershed studies of the Soil Conservation Service and the limited United States Geological Survey data for small streams may serve as a guide in determining whether the capacity of a particular structure is sufficient to carry maximum peak flows from the watersheds under consideration. This information will also help in determining the minimum gage readings to be recorded at each installation. In setting up such a program the experience gained in measuring runoff from small natural watersheds during the last decade should be utilized (*31*).

In closing it may be well to emphasize the following limitations of the suggested approach:

1. It will not result in a simple looking formula, such as $q = Ci$.
2. Curves or tables resulting from this method will be applicable only to areas and conditions represented by the watersheds on which they are based.
3. The design values of peak rates of runoff based on short periods of records will be subject to revision in the light of longer record.
4. Records from hundreds of installations will be required to cover the entire country.
5. It will take at least 5 years of continuous records before an attempt can be made to analyze the data.

On the credit side of the ledger we may list the following:

1. For the limited areas of application, curves and tables for specific conditions will give the desired values directly without involved computations and questionable assumptions.
2. Considering the doubtful validity of the rainfall-runoff relationship, it is not improbable that estimated values derived directly, even from short records of runoff, will prove more reliable.
3. The efforts and expenditures involved in securing the necessary records are negligible.
4. Results from hundreds of watersheds may find much wider application than the design of culverts and similar small structures. They may even constitute an important contribution to some phases of the general field of hydrology.

The objection as to the time required to obtain sufficient records can be met by saying that there is no short cut to victory. My admonition is that, if the suggested approach is acceptable, the necessary action be taken now so that 5 or 10 years hence we shall be analyzing records instead of bemoaning the lack of basic information.

It may seem inconsistent, but prudent, to close by emphasizing that, in spite of what I have said so far, I would be the last man to suggest that present methods including empirical formula and even the "rational method" should be discarded before better information becomes available.

ACKNOWLEDGEMENTS

The runoff studies and experimental watersheds referred to in this paper are a part of the Soil Conservation Service Research, Drainage and Water Control Division, Lewis A. Jones, Chief. The runoff studies were established and the records collected and compiled by several project supervisors and assistants of the Soil Conservation Service Research, under the technical direction of the writer. N. E. Minshall (Madison, Wisconsin), H. K. Rouse (Colorado Springs, Colorado) and H. W. Hobbs (College Park, Maryland), project supervisors, collaborated with the writer in the analyses of the records and in developing the data presented in this paper. Curve 6, in Figure 2, was derived by the writer from records of the Hastings Experimental Watershed, J. A. Allis, project supervisor. In the analyses, all available information from various sources have been utilized to strengthen and verify the results. Thus, published United States Geological Survey records from relatively small drainage areas (less than 50 sq. mi.) in the several "areas of application" and published and unpublished records from the Ralston Creek Watershed at Iowa City (3 sq. mi.) were included in the analyses.

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THE APPLICATION OF AERIAL STRIP PHOTOGRAPHY TO HIGHWAY AND AIRPORT ENGINEERING

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SYNOPSIS

This paper is a report of one of the continuing researches in pavement performance conducted by the Joint Highway Research Project of Purdue University cooperating with the State Highway Commission of Indiana. It presents a method of gathering pavement performance data by the use of aerial strip photography. This method of aerial photography offers a quick, convenient method of making a permanent record of the essential features of pavement performance that heretofore could only be obtained by visual inspection in the field.

Aerial strip photography differs from conventional aerial photography in that a continuous, uninterrupted strip photograph is produced instead of a series of individual overlapping photographs. The continuous uninterrupted exposure of photographic film (as much as 200 ft. in length) is made possible through the use of a specially designed aerial camera which is adapted to low altitude photography at high airplane speeds. Thus, large-scale strip photographs, up to 1 in. equals 25 ft., covering a strip of terrain several miles in length can be obtained in a relatively short time. These features of aerial strip photography make it well suited to highway problems since the scale and coverage of the photograph can be adapted to the required detail and right-of-way width.

This method of gathering pavement performance data quickly and accurately makes a detailed permanent record of performance. A few of the performance details that can be recorded by aerial strip photography are: blow-up patches, cracks, and corner breaks on concrete pavements and base failures and surface patches on bituminous surfaces. These features are recorded with remarkable detail.

Strip photography also permits coverage of performance information from widely separated locations and therefore enhances the study of contributing factors of pavement performance, such as types and sources of materials, and factors of traffic and design. Pavement performance data recorded on strip photographs also may be used by administrative officials in evaluating their maintenance and reconstruction needs.

Aerial strip photography also has several other potential applications to highway and airport engineering including; location surveys of a reconnaissance nature, clearing estimates, property evaluation, and assessment problems. The technique of gathering pavement performance data through the use of strip photography is highly significant in view of the immediate need for performance information in the advanced planning of highway programs.

Research has shown that pavement performance data provide a logical and expedient method of analyzing materials and construction problems encountered by highway and airport engineers. An approach to materials and construction problems from the point of view of pavement performance is well adapted to research methods since it has the distinct advantage of presenting the basic problem under field conditions. Its use permits an