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Meteorological Estimation of Extreme Precipitation for Spillway Design Floods

Technical Memorandum WBTM HYDRO-5

U.S. DEPARTMENT OF COMMERCE / ENVIRONMENTAL SCIENCE SERVICES ADMINISTRATION

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ABSTRACT

The spillways of most large dams built in the United States in the last 25 years are designed to carry the flood resulting from probable maximum precipitation.

This paper reviews the historical reasons for this particular approach to design in the United States, summarizes the procedures that have evolved for estimating probable maximum precipitation, and examines trends.

Introduction

A subject at the Symposium on Floods and Their Computation is the "computation of maximum flow of rainfall floods in case of availability, absence, or insufficiency of hydrologic data." An important area in which hydrologic data are generally insufficient is in the establishment of the spillway design flood for a major dam. Streamflow data at the dam site are automatically insufficient, since the reliable evaluation of the possibilities for high flows would require hundreds or thousands of years of record under uniform climatic and stream channel conditions. It has become a general practice to derive spillway design floods from an estimate of the probable maximum precipitation upstream, and this practice is the primary subject of this paper.

Many technical aspects of estimating probable maximum precipitation have been covered in other conferences and in published papers (Fletcher 1951; Paulhus and Gilman 1953; Bruce 1959; Gilman 1964; Myers 1966; U. S. Weather Bureau 1947, 1956, 1960a, 1961, 1963a). The WMO (World Meteorological Organization) is nearing publication in its Technical Note series

*Paper presented at International Symposium on Floods and Their Computation, August 15-22, 1967, Leningrad, USSR, sponsored by UNESCO, under title "The Estimation of Extreme Precipitation as the Basis for Design Floods - Resume of Practice in the United States."

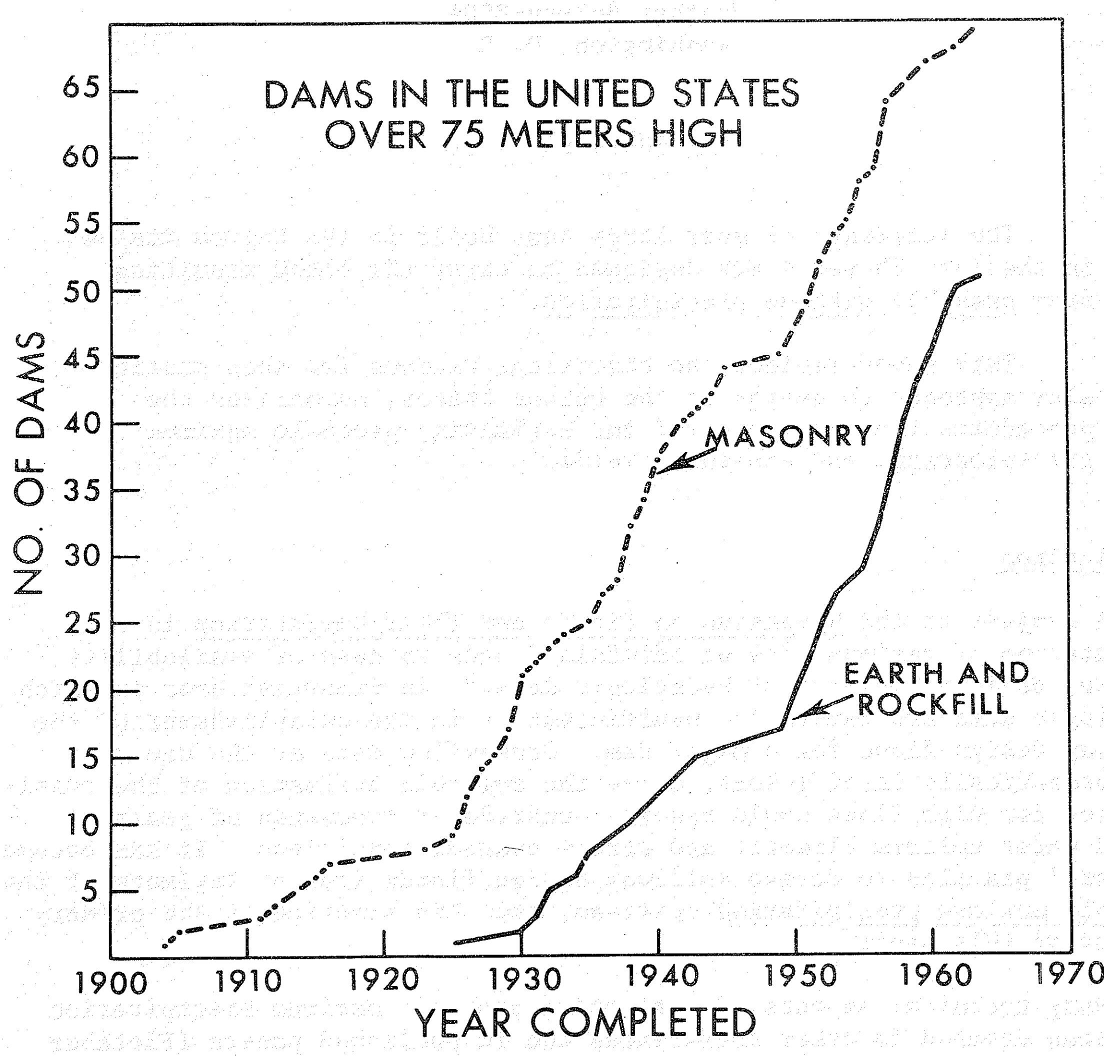
DAMS IN THE UNITED STATES
OVER 75 METERS HIGH
MASONRY
EARTH AND
ROCKFILL
NO. OF DAMS
5
10
15
20
25
30
35
40
45
50
55
60
65
1900
1910
1920
1930
1940
1950
1960
1970
YEAR COMPLETED

Figure 1.

a document on "Estimation of Maximum Floods" which will include in some detail current methods for estimating maximum probable precipitation, while the earlier "Guide to Hydrometeorological Practices" of the WMO (1965) summarizes concisely techniques and applications. Much of usual practice in the United States from the point of view of the engineer has been summarized by Hathaway (1950) and Snyder (1964). Some worldwide aspects of design flood estimation, including the level of accuracy needed at various stages in project planning, have been summarized with examples by Koelzer and Bitoun (1964).

But important to the understanding and appreciation of any cultural or technical development is its historical context. With this in mind, the present paper, rather than being a treatise on current probable maximum precipitation methods, is composed around the evolution of related practices from past to future. The paper is restricted to the evolution of practices in the United States. This is not to ignore developments in other countries, but to keep the paper within bounds as to length and also to restrict it to material most familiar to the author. As an historical source the Transactions of the American Society of Civil Engineers have been particularly valuable.

Dam building in the United States

Dam building in the United States has been continuously active since the second half of the 19th century. From 1872 to 1900 the word "dam" appears in the title to 27 papers in the Transactions of the ASCE. By 1900, the U.S.A. had about a dozen dams over 30 meters high (Mermel 1958), constructed variously for irrigation, water supply, and hydro-power. Dam building in the present century has been nicely summarized in a recent publication of the USSR, "High Dams of the World," (Mandzhavidze and Mamradze 1963) which lists dams over 75 meters high. The progress of dams over 75 meters in the U.S.A. is shown in figure 1, from that source,* supplemented by a few recent ones from the World Register of Dams. (International Commission on Large Dams, 1964).

The first of the high masonry dams plotted on the figure was for water supply for the city of Denver; the second for water supply for the city of New York; the next two, irrigation and power projects of the U. S. Bureau of Reclamation in the semi-arid west. These last were the beginning of the program of large U. S. Government sponsored irrigation projects initiated by a new law, the Reclamation Act of 1902.

Rockfill and earth dams over 75 meters high came two decades later than masonry dams but since about 1950 have been built at an even greater rate.

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*Ponthook Dam, built in 1887, listed both by Mermel (1958) and Mandzhavidze and Mamradze (1963) is omitted from figure 1. This dam, 84 meters high, is only 4 meters in average width and fills a crevice in the rock and impounds but 1.5 million cubic meters of water.

Evolution of spillway design flood determination

The practice in establishing the spillway design flood for high dams in the United States -- and by "high" is not necessarily meant as high as the 75 meters of figure 1 -- has undergone continuous evolution; it can, however, be subdivided into four periods. These periods, like most subdivisions of human progress into distinct eras, overlap, but each period is characterized by a principal emphasis. At no time has any one method of spillway design flood estimation been used exclusively. These periods may be called the early period, the regional flood period, the storm transposition period, and the probable maximum precipitation period.

Early period

In the early period the design engineer for any particular project had to rely primarily on his own judgment. Usually his principal information was the floods of record on the stream with which he was concerned. Much of this information was historical or traditional and in terms of stage of water level only. The corresponding volumetric discharge rates he would have to estimate as best he could. Where possible some reference was made to the floods of adjacent streams for guidance.

In reading the early reports one can sense a confidence by the less cautious that the flood record was stable, that nature had shown what she could do on a particular stream in a relatively few decades. This confidence was later found to be misplaced. The more cautious showed a feeling that major floods were among the imponderables, whose evaluation was impossible by the techniques then available. Some earth dams built during this period have failed from overtopping due to insufficient spillway capacity (Justin 1932). During those days, of course, not only were hydrologic data severely limited, but certain social factors were at least slightly different than today. More dams, though by no means all, were in remote locations where downstream flooding from a failure would not be catastrophic; capital was limited and the investment had to be recovered from relatively local benefits from irrigation, water supply, or power. There was probably more acceptance of the idea that some natural events are so extreme that man is not able to cope with them nor is he responsible for their consequences. (The last point is cited, for example, by Posey 1965 and Snyder 1964, p. 247.) That most of the earliest high dams were masonry structures which can more readily stand overtopping than can an earth dam also put less demand on ultra-safe design.

Regional discharge period

It was early recognized that examining all floods of a region might lead to firmer conclusions as to nature's potential than the limited record on single stream. This type of consideration is now called transposition.

Fuller's work. The era of considering maximum discharges regionally in a systematic way we might date from the presentation in 1913 of a paper to the American Society of Civil Engineers by Fuller (Fuller 1914). Fuller analyzed the discharge records of hundreds of streams and developed what is considered to be the first flood frequency formula (Linsley, Kohler and Paulhus 1949, p. 574; Chow 1964, p. 8-23):

$$Q_T = \overline{Q}\,(1 + 0.8 \log_{10} T) \qquad (1)$$

where
$\overline{Q}$ = mean highest annual flood, in discharge units
Q_T = flood of return period T, same units as $\overline{Q}$
T = return period in years
0.8 = an average empirical coefficient

The study would hardly have been possible without the program that had then been going on a few years of measuring and publishing discharges on a number of streams (primarily by the U. S. Geological Survey). Fuller sought in his analysis regional variations in the empirical coefficient of 0.8 but considered the variations he found too small to be important, excluding semi-arid areas.

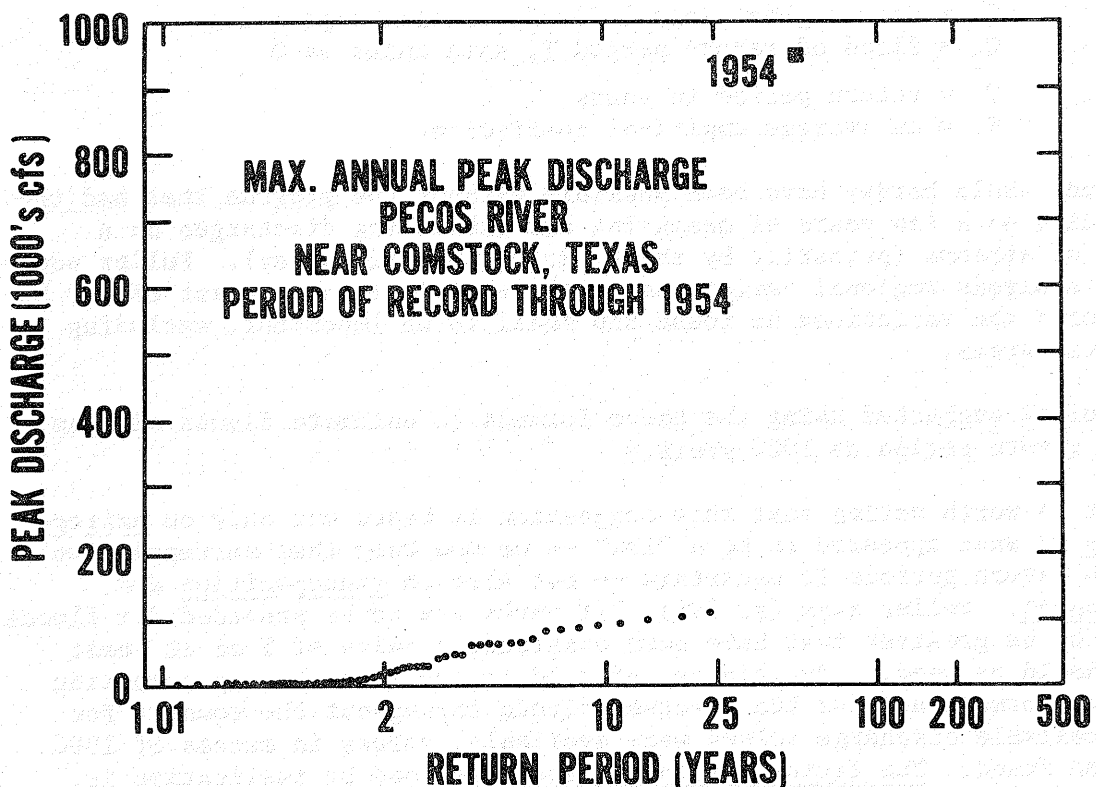
Fuller suggested using the above formula to estimate floods with as long a return period as 1000 years.*

It is worth noting that this suggestion is based not only on extrapolation of what appeared to be a "law" -- we now know that extrapolation to such return periods is uncertain -- but also on transposition and envelopment. Fuller says (p. 594), "If works are to be provided for floods equal to the greatest that have been observed, a value of T of at least 1000 should be used." By this he referred to the fact that by computing from the formula a T for the greatest floods throughout the country for which reliable discharge values were available, values in excess of 1000 had been found. The factor transposed and enveloped by implication is $Q_x/\overline{Q}$, where Q_x is the maximum recorded discharge and $\overline{Q}$ the mean annual flood.

Enveloping formulas related to area. As discharge records lengthened, directly enveloping the records of peak discharges -- normalized for area -- rather than assigning specific frequencies found favor in deriving the "maximum flood." The most famous formulas for this are the so-called Myers' rating** (Jarvis 1926, p. 994), sometimes called the Myers-Jarvis rating,

*This suggestion was repeated as late as 1932. The discharge estimated from Fuller's formula at T = 1000 is recommended in a handbook (Justin 1932, p. 58) as the spillway design flood for certain classes of earth dams, together with a generous freeboard safety factor.

**No relationship to author of present paper.



1954
MAX. ANNUAL PEAK DISCHARGE
PECOS RIVER
NEAR COMSTOCK, TEXAS
PERIOD OF RECORD THROUGH 1954
PEAK DISCHARGE (1000's cfs)
1000
800
600
400
200
0
1.01
2
10
25
100
200
500
RETURN PERIOD (YEARS)

Figure 2.

in which peak discharges are proportional to the square root of the area drained, and to a coefficient that varies with region and geology, and Creager's equation which uses a different function of the area (Creager and Justin 1950, p. 63). The Myers-Jarvis rating formula is:

$$Q_{max} = C\sqrt{A} \qquad (2)$$

where

Q_{max} = maximum discharge

A = drainage area

C = empirical coefficient varying with climate and topographic and geological characteristics. (Also depends on units of Q_{max} and A).

This form of the rating formula appears to have been developed by Jarvis from an earlier formula by Myers, a railroad construction engineer, relating drainage area in acres to required culvert cross-section.*

Note that the factor transposed and enveloped in using these formulas for spillway design floods is the ratio of peak discharge to a certain function of drainage area. By transposing the largest observed values of this ratio within a particular geological and climatological domain, it is assumed either that these values approach the largest that can prevail or that they provide an adequate degree of safety for the intended purpose. There is an analogy in this procedure to probable maximum precipitation estimate procedures which will become apparent later.

Statistical frequency analysis. This era was also marked by the development of formal statistics in its application to hydrologic problems, including maximum floods. Most noteworthy are the work of Hazen (1930), Horton (1936), and that great statistician who recently (1966) passed from the scene, E. J. Gumbel. Developing a spillway design flood for an important dam by straight frequency analysis of discharges at or near the dam site even from a long record, was a meteor that glowed brightly but briefly and then waned. The problem is illustrated dramatically in figure 2. There is no possible way to predict the 1954 flood peak from the previous 53 years of record on the Pecos River (International Boundary and Water Commission 1932-1954, U. S. Geological Survey 1901-1954), though the occurrence of the 1954 flood in a basin of normally rather low flow is readily comprehended when one examines the precipitation storm that produced it.

After some major floods in the New England States (northeastern U.S.A.) the Boston Society of Civil Engineers examined this question. The Society had at its disposal the longest flood records in the United States, some extending back 100 years. Nonetheless, they concluded in a 1942 report

*Personal communication from W. B. Langbein, U. S. Geological Survey.

that assignment of return periods to the extreme observed floods on a river was difficult and dubious, and it would therefore be even more difficult and dubious to extrapolate to the long return period that would be required for a spillway design flood of a major structure (Boston Society of Civil Engineers 1942). This was not intended to downgrade the power of statistical analysis for many ancillary purposes.

Storm transposition period

The method. The storm transposition period in spillway design flood determination was relatively brief in the years it spanned, roughly the 1930's, and the method was not universally adopted by any means even during that period. But it is a very important conceptual milepost. In this method historical storms of the surrounding region are moved to a basin of interest. They must be of such type that it is considered little more than accident that they occurred where they did instead of over the basin. They are, therefore, an indication of what might happen over the basin in the future. The transposed factor here is simply storm rainfall. A prophetic view of this era dates to 1913 when the chief engineer of the Miami, Ohio Conservancy District, in participating in lively discussion on Fuller's paper already referred to, proposed the desirability in some cases of determining the "maximum possible flood" by computing it from the maximum rainfall to be expected, by the "rational" (that is, physical reconstruction) method (Morgan 1914).

One impediment to adopting this proposal at that time was the lack of adequate systematic rainfall data. Another impediment in those days was the lack of precision in available means of computing runoff and flood hydrographs from rainfall.

The chief developers and advocates of the storm transposition method in the 1930's were an engineer with design responsibilities with the Corps of Engineers, Gail Hathaway, and a consulting engineer who was later head of the River Forecasting Service of the Weather Bureau, Merrill Bernard. They presented this method as a powerful tool for engineers in determining events which "could happen" over the basins with which they were concerned but cautioned that this does not necessarily yield a "limiting" storm (Bernard 1936, p. 230-231).

Advantages and disadvantages of method. Advantages of transposition of storms over the transposition of discharges are rather obvious: (a) Rainfall is much less dependent on underlying topography than is peak discharge; its transposition therefore is more physically realistic and accurate. (b) Precipitation records are in many instances longer and more comprehensive than discharge records. (This does not apply to ancient historical floods for which there is a history of floodmarks but not of the rainfall.) (c) The isohyets of a storm may be centered precisely over a basin, or in a number of different positions over a basin, a flexibility not available in discharge transposition. Thus the observed events of the past can be used to reconstruct more numerous, and more severe, hypothetical events with rain than with discharge. (d) Volume of hypothetical flood flow, as well as peak, is obtained. This is necessary for some applications (Bailey and Schneider 1939).

The chief disadvantage of storm transposition vs. discharge transposition is that one ends up with rainfall and still has the problem of converting it to streamflow. This problem was much ameliorated, compared to earlier times, by development of the unit hydrograph method of converting rainfall to a streamflow hydrograph (Sherman 1932a, 1932b) and subsequent refinements. If we are dealing with a stream on which there are no discharge measurements an additional transposition is required, namely transposition of unit hydrographs from similar basins. This physical reconstruction of a storm permits variation of another natural condition, namely the infiltration rate, through assumption of the prior state of the soil with respect to moisture.

Application of method. The most specific reference to the use of the storm transposition technique for peak discharge in the design of projects in readily available published literature is the discussion by Hathaway, of a paper by Bernard in the *Transactions* of the ASCE (Hathaway 1944). These projects were mostly somewhere in the central United States, where conditions are especially favorable for this approach. Storm types are similar over large areas, and topographic influences are slight, thus transposition of storms over considerable distances is reliable. Precipitation data are reasonably adequate and some very outstanding storms and floods have occurred which provide a fairly high degree of safety if transposed to a study basin and centered over it. The Tennessee Valley Authority (1961) in the late 1930's used the Myers-Jarvis rating to establish peak design rate of flow (plus generous freeboard) and storm transposition for flood volume.

The culmination of the storm transposition method was a paper published in 1939 (Bailey and Schneider 1939). This paper also initiated the generalized chart approach carried forward in the next period, the PMP period. The authors of that paper took advantage of a recently completed compilation of volumetric rainfall data (Miami Conservancy District 1936) to be discussed later, supplemented by station records from the Weather Bureau, and plotted on maps the largest storm rainfall values for selected area sizes and durations, such as 1500 square miles in 2 days or less. They then constructed enveloping isohyets, recognizing that precipitation potential decreases from south to north and from the coast inland. Some of their results are shown in figure 3. The isohyets were smoothed and spaced by plotting the rainfall data along straightline profiles in various

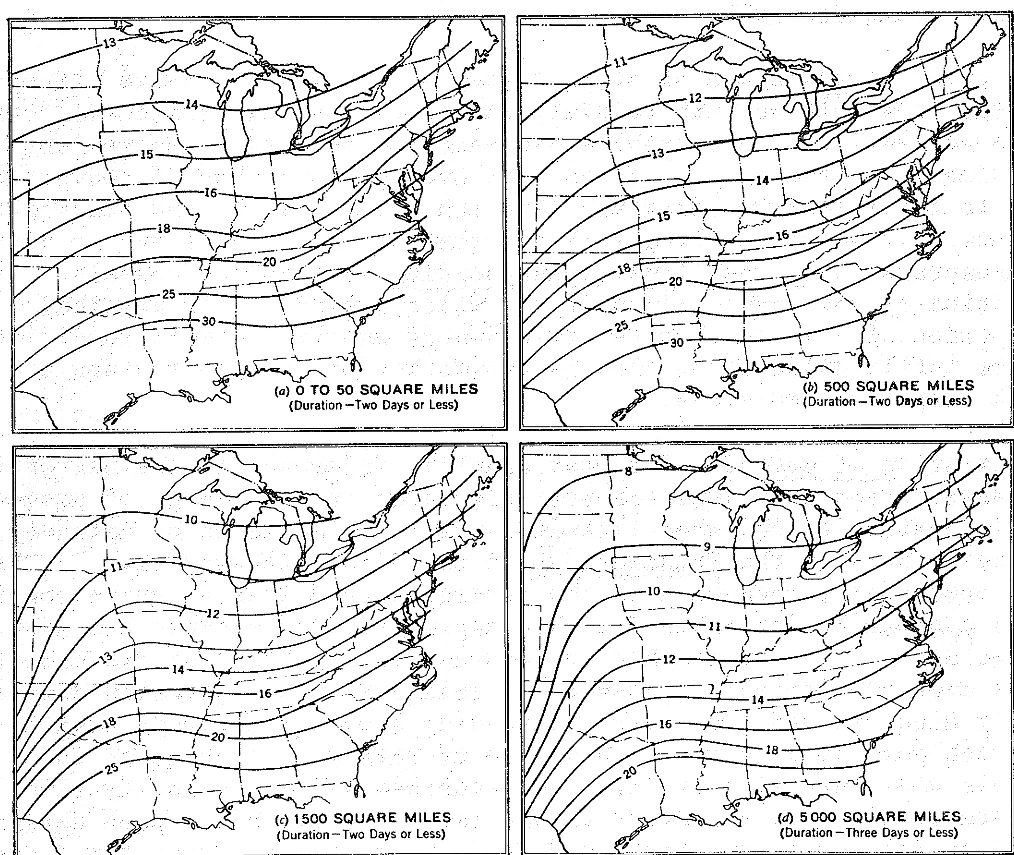


Figure 3. Enveloped storm rainfall, inches. From Bailey and Schneider 1939.

directions, then enveloping with smooth curves. Values from the envelopes are then transferred to the map. This enveloping procedure provides an implicit transposition. The transposition factor of course is storm rainfall.

Interlude

It can be expected that meteorologists will be a minority at the Symposium on Floods and their Computation while engineers may form a majority. The author as a meteorologist pays tribute to the engineering profession at this point by noting that every pioneer named up through the transposition period except Gumbel, was a civil engineer. The later partnership between engineers and meteorologists was yet to come.

Probable maximum precipitation (PMP) period

New laws in the 1930's broadened the responsibilities of the United States Government for flood control, navigation, and multi-purpose projects, as well as other aspects of stream management such as soil erosion control, and quickened the pace of dam building.* This was stimulated in part by the policy of expanding public works construction as a counteraction against the great economic depression of those years. This quickened pace increased the pressures for consistent, safe, but not exaggerated spillway design flood standards. Funds were made available for broad studies, since dam building had now transitioned from a project-by-project emphasis to a continuous program. Engineers turned to meteorologists to ask if limiting rates of precipitation could be established on a rational basis, making use perhaps newly introduced of air-mass analysis concepts then gaining favor and upper-air values of wind, temperature and humidity then becoming more commonly observed by airplane and balloon soundings (Hathaway 1939).

Physical limitations on precipitation. Physical limitations in meteorological terms on rate of precipitation over a basin were soon classified as follows (Showalter and Solot 1942; U. S. Weather Bureau 1941):

(1) A limit on the humidity concentration in the air that flows into the space above a basin.

(2) A limit to the rate at which wind may carry the humid air into the basin.

(3) A limit on the fraction of the inflowing water vapor that can be precipitated.

*The evolution of legal developments and Federal policy in water resources development and control up to that time is concisely summarized by Saville 1939.

Each of these limitations is handled in a quite different way to estimate the probable maximum precipitation over a basin. The application is different for regions where topography has little direct effect on storm precipitation than it is for regions of marked orographic control of precipitation. Regions of limited topographic influence will be considered first.

Definition of PMP. At this point it is appropriate to digress and define probable maximum precipitation (hereafter abbreviated PMP). A good definition of PMP emphasizing its historical conceptual basis which has the status of appearing in a glossary (American Meteorological Society 1959) is, "The theoretical greatest depth of precipitation for a given duration that is physically possible over a particular drainage area at a certain time of year. In practice this is derived over flat terrain by storm transposition and moisture adjustment to observed storm patterns." Another definition more operational in nature and emphasizing application would be: "PMP is that magnitude of rainfall over a particular basin which will yield the flood flow of which there is virtually no risk of being exceeded." It is understood that in a few climatic regions a concomitant condition to the PMP in producing this flow is a high rate of snowmelt. The words no risk appear in this definition because a principal purpose of PMP estimates is to guide an engineer in designing the spillway of an earthfill dam above a population center, a dam which under no circumstances must be subjected to the danger of overtopping. The word virtually is added as recognition that nothing in life is completely and absolutely safe. Definitions and their implications have been discussed in detail by G. N. Alexander (1965).

Maximum moisture. Generally, in estimating PMP, the moisture content of the atmosphere is evaluated in terms of the liquid equivalent of the total water vapor in a vertical column, commonly called precipitable water, as described in the papers cited in the second paragraph of this paper. Estimating precipitable water from surface dew point is covered in the papers. The maximum value of the precipitable water in an air mass is imposed by the sea-surface temperature in the region where the air mass acquires its characteristics. Simply stated, if the dew point in the air exceeds the sea-surface temperature, vapor will condense on the sea instead of evaporating from it. Thus the maximum moisture content of the atmosphere available for formation of storm precipitation varies regionally and seasonally, depending on temperatures of adjacent oceanic source regions.

As a practical matter, the asymptotic value of air dew point at sea is not the sea-surface temperature, but somewhat less. Further, dew points tend to decrease, at least in cool climates, with increasing distance from the oceanic source. Thus in practice the limiting value of atmospheric moisture has been assigned on a climatological basis (Showalter and Solot 1942). The maximum observed values of dew point, at different places and seasons, from a record of 25 to 50 years, are considered near enough to the maximum to be expected in a probable maximum storm. Surveys of maximum dew points for various individual studies have been incorporated into maximum dew point maps covering the United States (U. S. Weather Bureau 1960b). Sea-surface temperatures have been used as an auxiliary guide to smoothing coastal regions of such maps (U. S. Weather Bureau 1961, par. 4.15).

Experiments have been conducted recently in determining maximum moisture from direct observation by radiosonde rather than by estimation from surface dew points. Twenty years of upper-air data suitable for this purpose are now on punch cards. No specific procedures have crystallized yet.

Maximum inflow wind. Intense precipitation over broad areas in the eastern U.S.A. is always supported by an inflow of tropical air from a southerly direction. The original concept of a limit on the moisture-importing wind was to approximate the boundaries of a basin by a rectangle enclosing equal area, then estimate the maximum inflow across the southern boundary of this rectangle. The average wind through a deep layer is intimately related to atmospheric pressure and temperature, through the geostrophic, hydrostatic, and thermal wind equations. Limitations on horizontal temperature gradients in the middle atmosphere, which are produced by advective and dynamic processes, limit the wind. Direct evaluation of this wind inflow limitation was made in only one major study outside of the mountainous west, an estimate of maximum possible precipitation over the 50,000 square kilometer basin above the often-flooded city of Pittsburgh, Pennsylvania (U. S. Weather Bureau 1941), and then only as a check on a storm transposition and envelopment method. This was because obstacles were found in relating the precipitation limit to the wind inflow limit across a single boundary. Over small basins, the effective inflow (as recognized by Showalter and Solot) is radial; the inflow from one direction is not an effective limit on precipitation. Over a basin large enough to insure that the inflow from the direction of the moisture-bearing wind is a limit on precipitation, the limit may be too high and is more theoretical than practical because the optimum efficiency of conversion of water vapor into precipitation assumed at the next step cannot necessarily prevail throughout so large a basin.

Another view of the wind inflow problem -- stating the same thing as above in different geometric terms -- is that precipitation is limited by the rate of horizontal convergence of the air. Convergence has been notoriously elusive in attempts to measure it, and as yet there are no adequate techniques for measuring it over basin sizes requiring spillway design floods.

The solution to these difficulties has been to use storm precipitation itself as the effective measure of convergence, by the adjustment of storms. This will be described after discussion of the last of the three physical limitations named earlier.

Maximum conversion of water vapor to precipitation. Essential facets of the precipitation production progress are that humid air converges at low levels, rises through tall or deep clouds, and exits from the storm system at a high level. This is shown schematically in figure 4, depicting this for humid air at two different temperatures. The surface dew points are 60°F. (16°C.) and 75°F. (24°C.) respectively. The fraction of the water vapor that must be given up by the air on cooling adiabatically as it rises from one level to another is a closely known physical quantity* and increases with temperature for a specific lift. A model was developed assuming that the lower third of the cloud is inflow, the upper third outflow, and the middle third experiencing only the associated vertical velocity (Showalter and Solot 1942). Maximum height of cloud is determined climatologically from observations of highest cloud tops and physically by considering clouds in great storms as extending to the tropopause. The assumed maximum cloud height increases with temperature. The precipitation yielded by this model increases about 9 percent for a 1°C. increase in dew point.

This model has been used to calculate effective precipitable water, namely that part of the water vapor which is condensed out by processing through the cloud, as a function of dew point, just as total precipitable water is related to dew point in storm situations. The theoretical maximum rate of precipitation averaged over a rectangular basin according to the inflow limit approach would be the product of the maximum inflow velocity, the length of the inflow boundary, the maximum effective precipitable water in the inflow, divided by the basin area.

The difficulties with the inflow limit approach have already been pointed out. The present use of the model, as for some years past, is to adjust storms to maximum moisture, as described in the next paragraph.

PMP for non-mountainous regions. PMP estimates in the United States vary in detail but, exclusive of regions of high mountains, the following steps are standard: (1) Maximize the rainfall depths of intense storms for moisture by the model that has been described. The depths are multiplied by the ratio of the precipitation yields associated respectively with dew points observed in the tropical air flowing into the storm and the climatological maximum dew points in the vicinity of the basin. (2) Transpose to the study basin the maximized values of those storms which are of a type that might be expected in the basin. (3) Carry out the foregoing separately for various durations and area sizes of rainfall. Determine enveloping values by constructing smooth depth-duration and depth-area envelopes of the transposed maximized values.

*We omit here, as is the custom in this type of hydrometeorological work, the whole very complex process of condensation of water vapor into cloud particles (ice or water) and their later coagulation into precipitation (snow or rain). These processes have been summarized from the hydrometeorological point of view by Gilman (1964). All vapor in excess of saturation is assumed converted into rain.

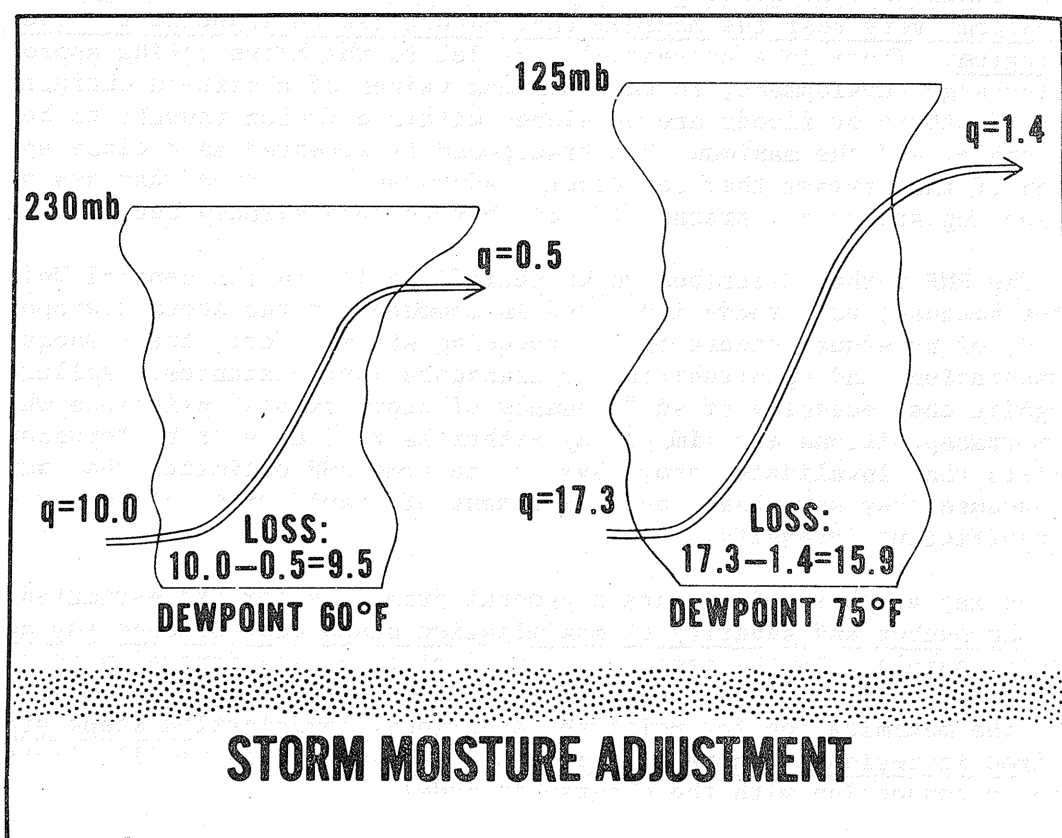


Figure 4. q is specific humidity in gm kg^{-1}.

It is very important to note the assumptions implicit in this procedure. This is a combined transposition, maximization, and envelopment method. The factor transposed to the basin is the three-dimensional wind flow of the historical storms, that is, their convergence and vertical motion. This is unmeasured but is indicated by the precipitation. It is assumed that sufficient very intense storms have been detected and have been transposed to the basin that at least one of them contained a convergent wind "mechanism" very near the maximum that nature can be expected to produce in the region. There is a conceptual parallel to the Myers rating approach to discharge envelopment, in that maximum values of a certain characteristic of storms or floods are enveloped within a region thought to be applicable, and the maximum thus transposed is accepted as a close approximation of the maximum that can occur. Advantages and disadvantages of transposing storms vs. transposing discharges have already been pointed out.

The PMP method described works satisfactorily in the central United States because, as already indicated in comments on the storm transposition period, of numerous intense flood-producing storms there, their adequate documentation, and opportunities to transpose long distances. Failure to recognize the necessity of an "adequacy of storm sample" principle where storm transpositions are limited by either lack of data or by topographic barriers that invalidate them, have led to some PMP estimates that were too low because they were based on envelopment of insufficient storms or storms of insufficient intensity.

We may at this point state a general principle for PMP estimates which is: the number and severity of maximization steps must balance the adequacy of storm sample. In the central United States, having generally an adequate storm sample for transposition, but one additional maximization step is used, the maximization for moisture, additional maximization steps are required in regions of more limited storm samples. This is illustrated below in connection with the orographic model.

PMP in orographic regions. Along the entire West Coast of the United States a long north-south chain of generally high mountains lies in the path of the prevailing westerly winds from the Pacific Ocean. Precipitation is strongly orographic, largely caused by the lift imparted to the air by the mountains. This region is hydrologically a very active one with flood control, irrigation, water supply and hydro-power all receiving great attention. A succession of reports investigate PMP in considerable detail in this important region (U. S. Weather Bureau 1943, 1947, 1961, 1966). This orographic influence gives a basis for a wind model with maximized inflow, illustrated in figure 5. Assuming laminar flow of air over any particular mountain cross section, one can calculate the lift of the air, the levels at which rain and snowflakes are formed, and their drift with the air before they strike the ground. Such models are verified by reproducing approximately the precipitation in observed storms and are then used for estimating PMP by introducing maximum values of moisture and wind as inflow at the foot of the mountains. Maximum moisture is evaluated just as in non-orographic regions.

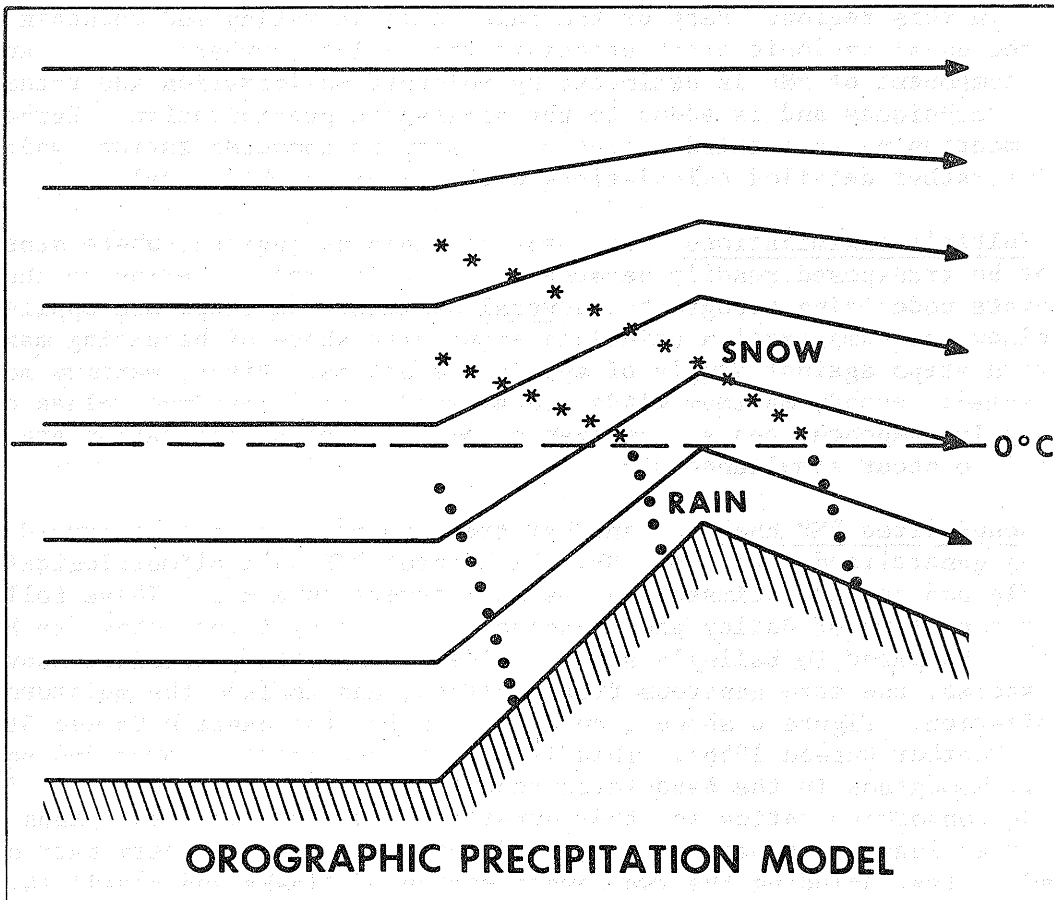


Figure 5.

Evolution of practice in this area includes the following. Estimating maximum winds through the depth of the atmosphere has shifted from extrapolations from surface winds, to calculations from pressure gradients, and then to envelopment of upper-air wind data as successive classes of data have become available. Another evolutionary step is recognizing that orographic rainfall, while dominant, is not the sole characteristic of storms in this region. Part of the rain falls on valley and mountain alike from the usual cyclonic storm processes that exist anywhere. This general storm component of PMP is estimated by moisture maximization and transposition techniques and is added to the orographic precipitation. Perhaps worth mentioning as a third evolutionary step is computerization, which permits rather detailed calculations with the orographic model.

Multiple maximizations. In these mountainous regions, where storms cannot be transposed readily because of their intimate relation to the immediate underlying topography, several maximization steps are applied to follow the compensation principle enunciated above of balancing maximization steps against sample of applicable storms. First, maximum moisture is assumed; second, maximum winds are assumed; third, maximum values of an orographic component and a convergence component of precipitation are considered to occur simultaneously.

Generalized PMP charts. Another trend to mention is that toward drawing generalized charts of PMP, which treat PMP as a climatological variable and depict estimated values as isohyets on a map. These follow from the pattern of Bailey and Schneider (1939) except that they are PMP values. Compared to Bailey's and Schneider's maps, they consider many more storms, use more generous transposition, and include the moisture maximization. Figure 6 shows such a PMP map for the eastern United States (U. S. Weather Bureau 1956). This is for 24-hour rainfall over 200 square miles. Nomograms in the associated report, one for each zone of the figure, provide conversion ratios to other durations and sizes of area. Maps of PMP for at least some basin sizes and durations now cover every part of the United States including the two newest states of Alaska and Hawaii (U. S. Weather Bureau 1956, 1960a, 1961, 1963a, 1963b, 1966). Refining some of these for more detailed correspondence to topography and extension to larger basin sizes is the emphasis in current work.

The generalized chart approach to depicting PMP is particularly pertinent where there are a number of potential dam projects for small or medium size drainages. Advantages of generalized charts as compared to individual project studies are: (1) the data are available when needed quickly for a feasibility or appraisal report; (2) consistency in estimates from project to project; (3) probability of more thorough study and greater reliability of general level of values than may be possible for an individual project; (4) suitability for publication in engineering handbooks. Weather

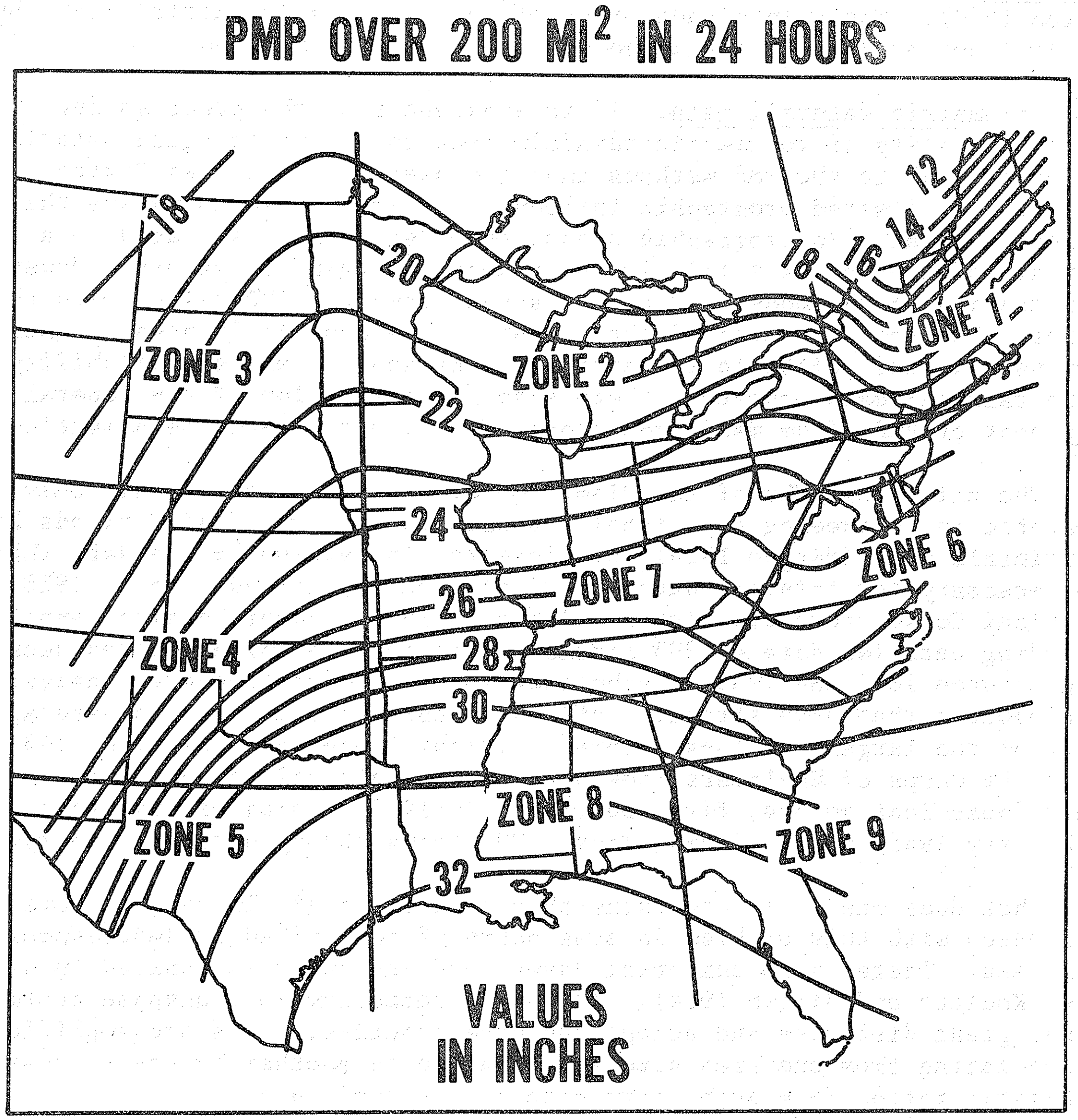


Figure 6. From U. S. Weather Bureau 1956.

Bureau PMP maps for example have been reprinted in the Handbook of Applied Hydrology (Gilman 1964) and in Design of Small Dams (U. S. Bureau of Reclamation 1960). The main disadvantage of such studies is initial cost, but the cost per project is not large when several are involved.

Volumetric rainfall data. It is apparent from the paper so far that the availability of volumetric rainfall data as a climatological statistic is fundamental to the PMP methods that are used in the United States. For the areas of limited orographic influence, observed rainstorms are the beginning point. In orographic areas, more dependence is placed on a theoretical model which is initially independent of rainfall values. However both testing of the model and comparison of computed PMP values with the highest observed rainfalls of the region -- the last influences judgment at various optional points in the estimation process -- makes availability of storm rainfall data important there also. The addition of the general storm component of PMP, from maximized storm values, has already been mentioned.

The chief engineer of the Miami Conservancy District was not only prophetic in foreseeing a rational approach to spillway design floods based on rainfall data (Morgan 1914) but pioneered in developing the data that are necessary for this approach. Replacing an earlier edition of 1918, the Miami Conservancy District published in 1936 a comprehensive report including detailed data on 283 storms in the eastern United States occurring between 1891 and 1933. Techniques for depth-duration-area analysis were evolved that have strongly influenced current practice and were applied to 72 of the largest of these storms. (Miami Conservancy District 1936). Later the Corps of Engineers took up this work and refined and extended it. Their loose-leaf volume, first published in 1945, (Corps of Engineers, U. S. Army 1945) now includes almost 700 storms throughout the country.

What does one do if one lacks this type of data? Indeed, we have been confronted with this problem in some parts of the United States, especially in Alaska. There is no universal answer and ingenuity is applied in various ways (Koelzer and Bitoun 1964). It may be necessary to transpose storm values great distances and accept the uncertainties. Data are amplified by extrapolating from one area size and duration to another by use of characteristic ratios from such storm data as are available.

As a first reference for appraisal in warm climates, one can consider the published values of maximum observed worldwide point rainfalls (Paulhus 1965) or the maximum observed areal values in the United States. A table of the latter appears in Gilman (1964) and Myers (1966).

PMP statistical method. An interesting variation of the foregoing PMP method is an attempt to approach the PMP statistically. This idea comes from Hershfield (1961). He proposes that the 24-hr. PMP at a precipitation observing point be estimated from the generalized frequency equation (Chow 1964, p. 8-23) in the form:

$$X_{max} = \overline{X} + KS_n \qquad (3)$$

The data required for this evaluation are the maximum observed daily precipitation during each year of record. $\overline{X}$ is the mean of this series and S_n is the standard deviation of the series. X_{max} is the desired PMP. K is a constant to be determined empirically by an enveloping process. Hershfield evaluates K individually from 2645 station records in the United States and elsewhere by substituting the largest observed rain value at each station for X_{max} and calculating the corresponding K. Details are given in his paper. The largest worldwide value of K thus found was 15. This value is then proposed for K in estimating PMP. Note that the transposed factor in this method is the <u>maximum observed value of K, namely the number of standard deviations that must be added to the mean of the annual series to give the extreme of it</u>.

Similarities to Fuller's frequency equation are immediately apparent. The mean of the annual series, in this case of maximum 24-hr. rainfalls instead of peak annual discharges, is used as the reference base in order to compare records in different regimes; then the variation from this is studied with the variation factor transposed and applied to the point of interest. Hershfield avoids the extrapolation from short record to long return period and attaches no frequency to X_{max}.

Like other schemes depending on empirical coefficients, Hershfield's equation is a concise and convenient way of getting an approximate answer when the initial ignorance of the quantity to be estimated is great. It fails to yield a precise answer upon close examination because of lack of universal transposibility of any one value of K.

<u>The next period</u>?

<u>Successor to PMP</u>? The four periods in spillway design flood and design storm estimation enumerated in this paper have each led to progressively greater spillway design floods. Will some other period yet to come lead to even higher estimates? The feeling of the author of this paper is that in general the answer is "no." Transposition, maximization, and envelopment of transposed and maximized storm data <u>when fully exploited</u> by present PMP methods, and based on reasonably adequate data seem to yield estimates that are close enough to what nature can ultimately produce. Of course it cannot be <u>proved</u> that future storms will not change opinions on this; <u>only present</u> feelings can be reported. The primary task to which workers in the U.S.A. now address themselves is to <u>refine</u> PMP rather than go to still higher standards generally, for example, by depicting greater detail in topographic regions.

This does not mean that design floods <u>for individual projects</u>, will not continue to rise. An example from the U.S.A. would be some minor flood control dams in forested areas that were once regarded as not requiring spillways of PMP capacity because the little-populated little-used character of the downstream valley made some risk acceptable. More and more of such structures are being designed virtually for PMP in view of our increasing population and the likelihood downstream of large summer vacationing populations during the high rainfall potential season. Thus more and more structures are built at or close to PMP standards without necessarily changing the standard.

Taking a worldwide view, there are reasons to expect a continued rise in standards for spillway design floods of both large and small dams. This is reflected in the history of the United States and would be in response to a normal associate of economic growth, namely, both willingness and ability to allot a greater segment of public funds expended on these projects to ultimate safety. Increasing populations and increasing occupation of flood plains also create pressures in this direction.

Maps of PMP. Continued dependence on maps which portray PMP as a climatological variable is anticipated. Construction of these has been found to require a large initial investment in hydrometeorological studies but to pay off in ultimate convenience, reliability and security. Of course there is inevitably a large measure of individual judgment in such charts, but this judgment is guided by scientific knowledge and thorough analysis.

Volumetric rainfall data. Such PMP estimates are properly based on comprehensive analysis of volumes of rainfall as a climatological variable and continued emphasis on such analysis is foreseen. Computer techniques likely will facilitate assemblage of such data in the future. It is not inconceivable that radar will make a contribution to areal analysis of rainfall though the specifics are not in sight. If applied in other countries, this does not necessarily have to be done in the enveloping depth-duration-area table method of the United States (Corps of Engineers, U. S. Army 1945) though this method seems to work fairly well. Someone may evolve some other method. The point is that rainfall volumes, not just point values, unquestionably are needed, not just for spillway design, but for other water resources projects.

Tropical methods. Certain important aspects of present PMP methods are more suited to middle latitudes than the tropics. Hydrologic studies of the Panama Canal region have shown this. One such aspect is the moisture maximization of storms, which adjusts storms upward to a rare event, the extreme influx of humid tropical air. It is empirically observed that high rainfalls are associated with high dew points. In much of the tropics very high atmospheric moisture is present most or all of the time in the rainy season, and there is neither theoretical nor empirical reason to relate rain potential to the minor fluctuations in humidity that occur. Hopefully, rapidly improving data and increased attention from tropical areas will give insight into the causative features that distinguish extreme tropical rains from ordinary rains and lead to storm maximization procedures indigenous to the tropics.

Similar remarks might be made about the orographic rainfall model, (fig. 5). The essence of this model is quasi-laminar flow. Yet the role of mountains in producing tropical rain may be more to stimulate convection in unstable air than to produce lift of the laminar type, thus requiring a different model for maximization.

Union of methods for large basins. The final trend envisioned is a closer union of hydrology, meteorology, and statistics in estimating spillway design floods of main-stream structures draining tens of thousands of square kilometers. Introduction of storm transposition was a big step forward in that it greatly expanded the hypothetical events available to the design engineer as clues to the future. Computers and associated technology now open the way for an even greater expansion of hypothetical events on large complex basins as well as simple ones.

Essential to the envisioned approach is a hydrologic model of the stream investigated with virtually unlimited flexibility of converting snowmelt and rainfall events of various intensities and placements to runoff and stream hydrograph, programmed for a computer. The nearest approach to this so far in the United States is the Columbia River Basin model of the Corps of Engineers (Rockwood 1961, Rockwood and Nelson 1966).

With such a model available, the flood hydrograph consequent to any desired number of precipitation events can be calculated, varying precipitation as to timing, intensity, placement within basin, and combination with factors such as infiltration rate and state of reservoir drawdown. This flexibility and comprehensiveness would permit --

A posteriori instead of a priori selection of factors to be maximized in the design flood, based on their revealed influence on the flood hydrograph. For example, placement of precipitation centers at the most critical location in a basin -- very significant for large basins -- could be given equal consideration with maximization of the total precipitation volume.

Treatment of meteorological factors and hydrologic factors as a single package from which to select a balance of maximization steps.

A probabilistic description of at least some factors, such as early rainfall antecedent to the main storm, now handled by assigning a single arbitrary, if reasonable, value.

To carry out the above would require specification by the meteorologist of a whole spectrum of hypothetical severe rainstorms (and snow if important) in isohyetal form, based on maximization, transposition, and combination of observed or synthetic storms, for trials in the hydrologic model.

There are yet no examples of storm data treated this way; the problems are formidable and may limit progress. Perhaps computers can assist. The "adequacy of storm sample" principle applies here, as an analysis, no matter how complex, restricted to minor storms can lead only to gross underestimate of potential. To attempt all of this is a challenge.

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