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COMPUTING A DESIGN FLOOD IN THE ABSENCE OF HISTORICAL RECORDS

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COMPUTING A DESIGN FLOOD IN THE ABSENCE OF HISTORICAL RECORDS

by HERBERT RIEHL & HORACE R. BYERS (*)

Summary — A design flood for a Venezuelan river is computed in the absence of rainfall and stream-flow data of more than a few years. From synoptic studies of an area embracing northern South America and the Caribbean, the type of disturbance producing the abundant rains of the area is determined. A disturbance of this type is maximized on the basis of the ratio of energy dissipated through friction to released latent energy represented by rainfall — in other words, the *efficiency* of the system is given its highest reasonable value. The synthetic disturbance is moved over the river basin in a manner most favorable for heavy rain. Certain data available from other rivers are used as a cross-check on the resultant flood values.

Introduction — The purpose of this study was to estimate flood extremes to be used as criteria in the design of a dam on the Boconó River in Venezuela. The Boconó flows to the Orinoco Plain from a *T* shaped area near the northeastern end of the Andes (Fig. 1). The dam site is at a place known as Peña Larga, where the river enters the plain. A simplified outline of the watershed, including smoothed 1000 m contours, is sketched in Figure 2. The basin above the dam has an area of about 1600 sq km.

Although stream flow records of some Venezuelan rivers go back to 1940 or earlier, only two years of such information for the Boconó were available for this study. Before 1952, rainfall records in this part of the country were either nonexistent or intermittent; hence they could not tell the story of rainfall experienced in the area. The practice often followed in hydrometeorology of substituting space for time through superposition of isohyetal patterns from areas up to 1000 km away was impossible because of the short or scattered records everywhere in this part of the world.

Fortunately, and as might be expected, it was found that flood producing rains occurred in connection with weather disturbances with characteristic scale of 1000 km which were detectable on carefully analysed synoptic charts, were of a pattern well known in tropical meteorology, and of frequently repeated occurrence.

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The model cyclone — Synoptic charts on 250 days, mainly in 1952-1954, were treated with streamline methods for the entire area represented in Figure 1. Just enough upper air wind data were available from stations in and around Venezuela

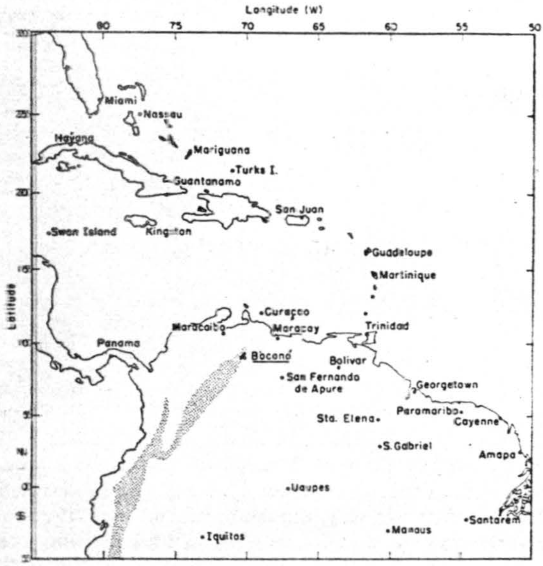

Fig. 1 - *Location of Boconó watershed and of pilot balloon stations used for analysis.* Dotted area above 2000 m.

to construct an adequate picture of the type of disturbance affecting the area in question. It was found that a cyclone that forms in the equatorial trough (RIEHL, 1954) produces the great rains in this region. Other types of storms characteristic of the northern coast, such as studied by FLETCHER (1949), were without importance because of protection by the mountains.

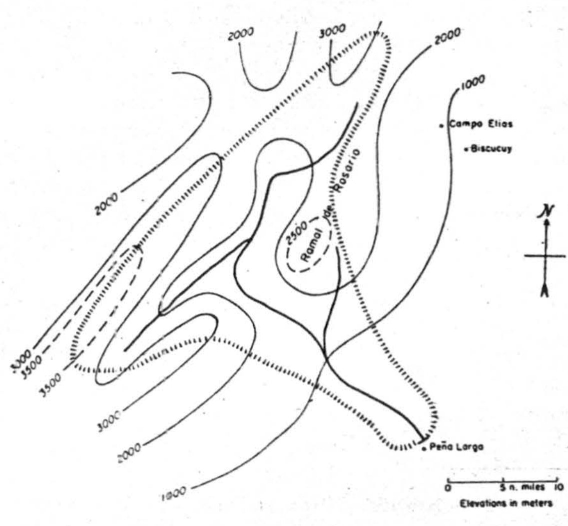

Fig. 2 - *Boconó river and simplified topography of watershed above dam site at Peña Larga.* Stippled line shows limit of basin (area 1600 km²).

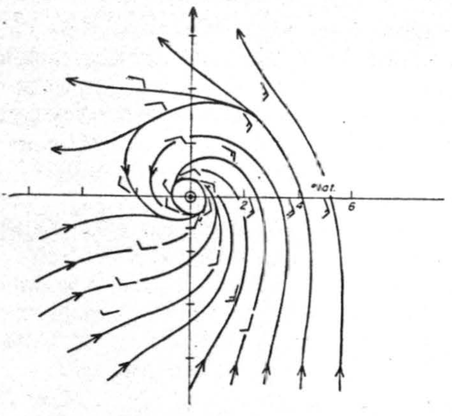

Fig. 3a - *Streamlines for composite cyclone in layer* 950-850 mb.

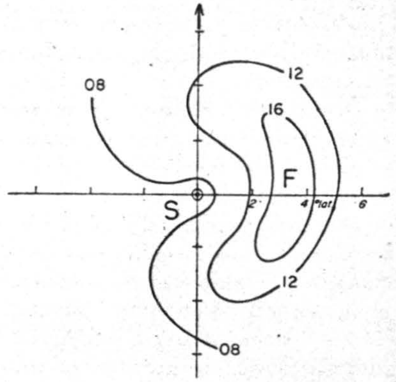

Fig. 3b - *Isotachs (knots) for composite cyclone in layer* 950-850 *mb.* «*F*» denotes fast and «*S*» slow areas.

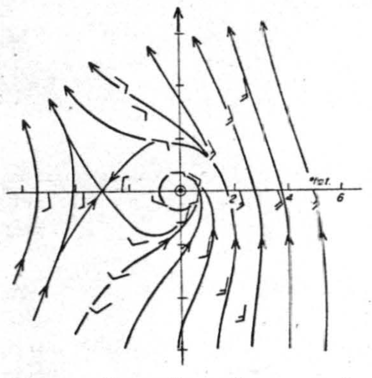

Fig .4a - *Streamlines for composite cyclone in layer* 850-750 mb.

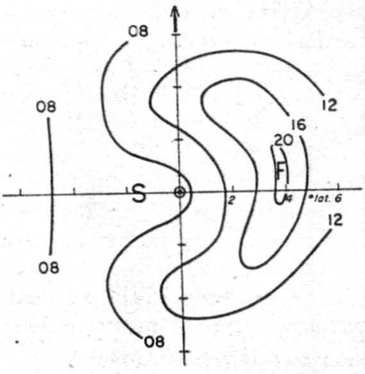

Fig. 4b - *Isotachs for composite cyclone in layer* 850-750 mb.

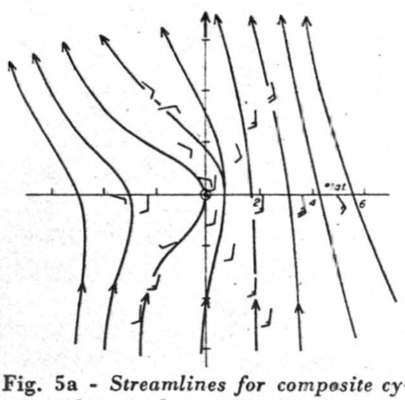

Fig. 5a - *Streamlines for composite cyclone in layer* 750-650 mb.

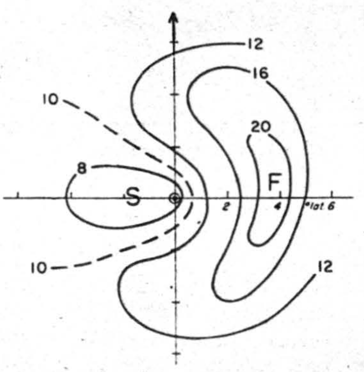

Fig. 5b - *Isotachs for composite cyclone in layer* 750-650 mb.

To arrive at the average equatorial trough cyclone of the Venezuelan interior, nine cyclones with the largest number of pilot balloon observations were chosen for compositing. Mean flow charts were constructed at 2000 ft intervals from 2000 to 10.000 ft and up to 300 n mi from the centers. The composite cyclone, shown in Figures 3, 4 and 5, was represented in the form of streamlines and lines of equal wind speed at various distances from the center.

To determine the vertical velocities, the mass convergence into various sectors of concentric circles about the cyclone was computed. The vertical velocity, w, is related to this convergence by

$$(\rho w A)_p - (\rho w A)_{p_0} = \frac{1}{g} \int_p^{p_0} \oint_s v_n \, ds \, dp \,. \tag{1}$$

Here A is the area of the sector, ρ is the air density, p and p_0 are the pressures at at the top and bottom, respectively, of the air column, g is the acceleration of gravity, s is distance around the boundary of the sector and v_n is the flow component normal to the boundary of the sector, counted positive inward.

At the ground, w is zero, so integration upward from the surface gives the vertical velocity at any pressure-level p as

$$w_p = \frac{1}{\rho_p A_g} \int_p^{p_0} \oint_s v_n \, ds \, dp \,, \tag{2}$$

where p_0 now is the surface pressure. Since in the tropics there are no appreciable gradients of temperature on an isobaric surface, the density at any given pressure, ρ_p, is constant.

An example of the vertical velocities computed in this way for the 650-mb surface in the composite cyclone is shown in Figure 6.

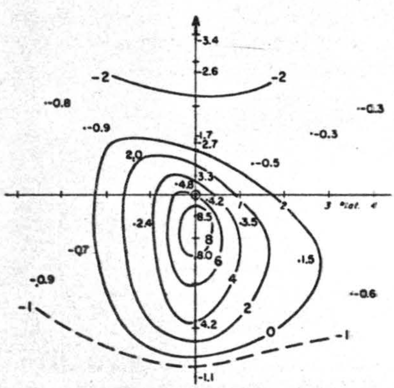

Fig. 6 - *Distribution of vertical velocity* (cm/sec) *at* 650 mb *for composite cyclone.*

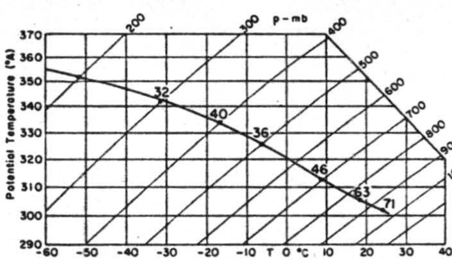

Fig. 7 - *Tephigram at Maracay for May* 1954. Numbers along curve denote relative humidity in per cent.

Precipitation: average storm, flat terrain — If it is assumed that the amount of water that is stored in the form of nonprecipitating cloud particles in each sector remains constant, the precipitation in a sector must be equal to the mass convergence of water vapor into it. For the water-vapor distribution on the outskirts of the model cyclone, a mean of the soundings at Maracay, Venezuela, during May 1954 is used (Fig. 7). During the rainy season, which the set of soundings represents, Maracay has air from a continental source similar to that of the Boconó. We are disinclined to assume greater moisture than in this mean sounding because the vertical-velocity computations have revealed subsidence to be taking place in the outer areas; thus by assuming this undisturbed mean we probably are already maximizing the water-vapor content of the air. In the storm itself, the ascent is taken along the saturated adiabat above the lifting-condensation level.

Since insufficient data were available for obtaining the flow above 650 mb, an assumption was made that 75 per cent of the water vapor flowing upward

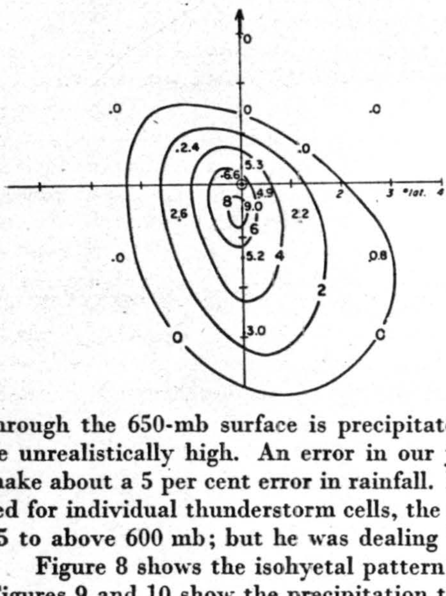

Fig. 8 - *Distribution of precipitation* (mm/3 hours) *relative to composite cyclone.*

through the 650-mb surface is precipitated to the ground. This percentage may be unrealistically high. An error in our judgment of 10 percentage points would make about a 5 per cent error in rainfall. From the data of BRAHAM (1952) computed for individual thunderstorm cells, the percentage might be inferred to be about 35 to above 600 mb; but he was dealing with isolated updrafts.

Figure 8 shows the isohyetal pattern that moves with the average storm, and Figures 9 and 10 show the precipitation that would be experienced at a station on

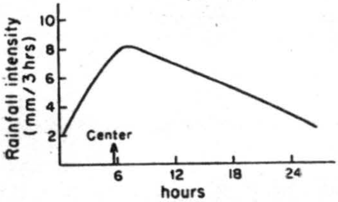

Fig. 9 - *Time distribution of precipitation intensity along line passing through center from top to bottom in* Fig. 8.

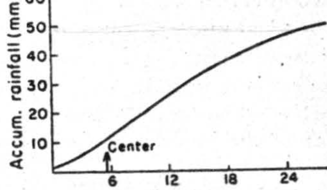

Fig. 10 - *Accumulative precipitation for composite cyclone computed from* Fig. 9.

the direct center path if the cyclone were moving at a speed of 10 kts, which is the average speed of the storms used in computing this average cyclone. It is seen that in this cyclone, over level terrain, the station on course through the center would receive about 50 mm of rain, nearly all in 24 hours.

Effects of the Boconó terrain — The next step, which will not be described in detail, was to move the average storm over the Boconó basin. Figure 11 shows a simplified shape and slope of the basin used in the computation. It is apparent that the greatest upslope components will be associated with southeast winds.

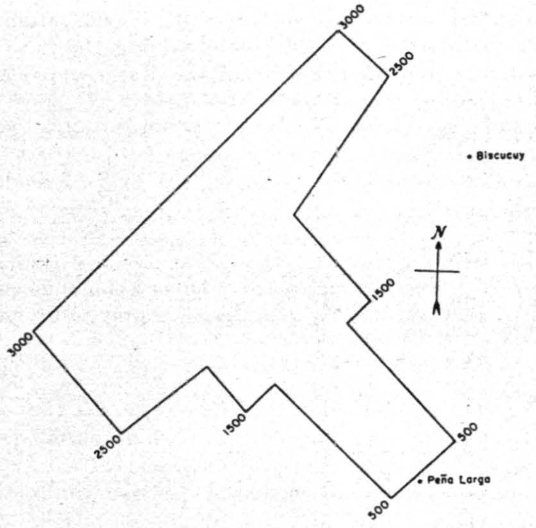

Fig. 11 - *Simplified outline of Boconó basin.* Numbers denote contour heights in meters (cf. also Fig. 2).

As the cyclone approaches from the east or southeast, the low-level winds will parallel the range or actually have a downslope component. The onset of precipitation would be delayed until about the arrival of the center.

Two effects augment the precipitation rate: (1) the upslope component added to the vertical motions computed from the inflow into the area and (2) the increase of moisture in the environment to saturation before it reaches the basin. The latter effect is to be expected from convergence against the mountains as the cyclone approaches. The transport of liquid water and snow across the divide and otherwise out of the basin area has to be subtracted.

The condensation rate over the basin for this average storm is computed to be $3.1 \cdot 10^6$ kg sec^{-1} and the outflow of condensed water is estimated at $1 \cdot 10^6$ kg sec^{-1}, giving a precipitation rate of $2.1 \cdot 10^6$ kg sec^{-1} or $2.1 \cdot 10^3$ m^3 sec^{-1}. The delayed onset of the rain reduces the duration by six hours, but the orographic effects prolong the rain at a diminishing rate, which can only be estimated. For 24-hr period it is deduced that the rain would fall at an average rate of $1.8 \cdot 10^3$

$m^3 \, sec^{-1}$, giving a total depth over the 1600 km^2 of the basin of about 100 mm. The Boconó terrain thus has the effect of doubling the precipitation derived over flat terrain from the average cyclone.

Maximizing the cyclone — The « maximum design flood » obviously will not come from an average storm but from an extreme one. It is necessary to arrive at a limiting factor by which the intensity of a cyclone could be greater than the average. Since the cyclones of the Venezuelan interior are maintained entirely by the thermoconvective process, it appeared logical to maximize on the basis of the possible efficiency with which the released latent energy could perform work against the frictional forces.

The efficiency is given by

$$E = \frac{-F}{H}, \tag{3}$$

where $-F$ is the energy dissipation by the frictional forces and H is the energy gain through the condensation-precipitation process. If $EH > |-F|$, the intensity must increase and if $EH < |-F|$, the intensity must decrease. In all but incipient or rapidly dying storms, these two magnitudes must be very nearly equal. H is determined from the rate of condensation which, in turn, is dependent on the field of flow and the available moisture. The available moisture cannot be maximized further, so the maximizing must come through increasing the flow, that is, through increasing the intensity. The quantity H is obtained quite simply by integrating the precipitation over the rain area and multiplying the total by the latent heat of condensation expressed in mechanical units.

The work done against friction, F, can be obtained from the product of the frictional force and the air displacement in the direction of the force. The frictional force is given by the vertical gradient of the horizontal shearing-stress vector τ, i.e. $\partial\tau/\partial z$. Further, $\tau = \mu \partial \boldsymbol{V}/\partial z$, where μ is the coefficient of eddy viscosity and $\boldsymbol{V}$ is the velocity vector. For unit time, the work F done by friction is $\boldsymbol{V} \cdot \partial\tau/\partial z$. Integrated over the volume α occupied by the cyclone,

$$F = \int_\alpha \boldsymbol{V} \cdot \frac{\partial \tau}{\partial z} \, d\alpha \,. \tag{4}$$

But

$$\boldsymbol{V} \cdot \frac{\partial \tau}{\partial z} = \frac{\partial}{\partial z} (\boldsymbol{V} \cdot \tau) - \tau \cdot \frac{\partial \boldsymbol{V}}{\partial z},$$

so that

$$F = \int_\alpha \frac{\partial}{\partial z} (\boldsymbol{V} \cdot \tau) \, d\alpha - \int_\alpha \tau \cdot \frac{\partial \boldsymbol{V}}{\partial z} \, d\alpha \,. \tag{5}$$

The first of these terms can be integrated vertically from the surface to the top of the cyclone where the shearing stress may be assumed to vanish. We have, then,

$$\int_\alpha \frac{\partial}{\partial z} (\boldsymbol{V} \cdot \tau) \, d\alpha = - \int_A (\boldsymbol{V} \cdot \tau)_0 \, dA \,, \tag{6}$$

where A is the horizontal area occupied by the cyclone. The work per unit time now becomes

$$F = -\int_A (V \cdot \tau)_0 \, dA - \int_\alpha \tau \cdot \frac{\partial V}{\partial z} \, d\alpha \,. \tag{7}$$

The first term on the right denotes the dissipation of kinetic energy by ground friction F_g, the second the internal dissipation F_i. In the first term, τ_0 is the drag exerted on the wind by the ground, given by the well-known relation of hydrodynamics

$$\tau_0 = C_D \rho_0 V_0^2 \,,$$

where C_D is the drag coefficient (*). Since τ_0 is in the same direction as the velocity vector, $(V \cdot \tau)_0 = C_D \rho_0 V_0^3$, where V is scalar windspeed. We may then write for the first integral

$$F_g = - C_D \rho_0 \overline{V_0^3} A \,, \tag{8}$$

where the bar denotes averaging over the area A. From the definition of the shearing stress a substitution can be made in the second integral of Equation (7) to give the total work as

$$F = F_g + F_i = - C_D \rho_0 \overline{V_0^3} A - \int \mu \, (\partial V / \partial z)^2 \, d\alpha \,. \tag{9}$$

A consideration of reasonable values of the coefficients C_D and μ and of the wind field shows that the ground friction is about one order of magnitude greater than the internal friction. DEACON (1953) has shown that C_D is relatively insensitive to the roughness of the underlying surface, but varies between 10^{-3} and 10^{-2} (dimensionless). Over a fairly rough sea with a wind of 12 m sec^{-1} the values were grouped around $2.5 \cdot 10^{-3}$, a value in agreement with that reported by TAYLOR (1915) for a land surface, so it will be used here. For our average cyclone, F_g turns out to be $4 \cdot 10^8$ kilojoules per second. For an estimate of F_i, a value of 50 poises seems reasonable for μ in the lower and middle troposphere. LETTAU (1950), in an analysis of the Leipzig wind profile, obtained 118 poises at 700 m and 70 at 900 m. In the less dense upper air the value should be lower. With a vertical shear of 1 m sec^{-1} km^{-1} or 10^{-3} sec^{-1}, and with the assumption that the cyclone is 10 km deep, one obtains $F_i = 5 \cdot 10^7$ kj sec^{-1} for the entire volume of the cyclone. It is doubtful that one could obtain a value much above 10^8 kj sec^{-1} with reasonable values of the eddy viscosity and shear; it is seen that this term is always likely to be smaller than the ground-friction term.

From experience in studying tropical disturbances, it has been found that the efficiency of large thermo-convective disturbances may reach 2 per cent, with only true hurricanes slightly exceeding this value. Assuming that 2 per cent is the upper limit of efficiency of interest for the present computation, various multiples of the intensity of our average storm were tested for balance. Intensity was defined in

(*) A conventional factor of 1/2 is often retained in the expression, requiring a coefficient of double the value used here.

terms of the wind at 2000 ft, and the internal friction term was not included. The results are shown in Table 1.

TABLE 1 - *Generation and dissipation of energy in thermoconvective cyclones of efficiency* 0.02.

Multiple of « average cyclone » intensity	Frictional dissipation of energy (10^9 kj sec^{-1})	0.02 · generation of latent heat energy (10^9 kj sec^{-1})
1	0.4	1.7
2	3.1	3.4
3	10.6	5.1
4	25.7	6.8

It is seen that for storms more than twice the intensity of the average, the dissipation of energy greatly exceeds its creation. There is an approximate balance for a system of twice the average intensity. The data suggest that the « average cyclone » has an efficiency of less than 2 per cent. Thus, by introducing an efficiency of 2 per cent and balancing the energy equation in a tropical atmosphere with as high a moisture content as is reasonable, the storm conditions have been maximized. This twice-the-average circulation corresponds to a cube-root mean 2000-ft wind of 9.4 m sec^{-1}. With this intensity, we obtain a circulation that approaches that of oceanic tropical storms without hurricane core.

The 24-hr average precipitation rate for movement of the maximized storm over the Boconó at 10 kts in the most critical direction will be $3.7 \cdot 10^3$ m^3 over the basin, or about 200 mm per 24 hr from the foregoing. In arriving at this figure, it was assumed that by doubling the intensity, the orographic effect produced by the mountains would be doubled. This seems reasonable in view of the fact that twice the amount of water vapor would be carried up an exposed slope in a given time.

Characteristics of river discharge — To check the computations and to translate them into the discharge behavior of the Boconó a study was made of data from the Registro Fluviometrico of the Ministerio de Obras Públicas (Dirección de Obras Hidráulicas) of Venezuela. From headwater basins over all of Venezuela, 440 station years of records of river discharge were obtained. For some rivers the duration of record was only 2-3 years, for others, up to 13 years. It appeared that a relation existed between the annual runoff and the maximum 24-hr runoff for the various rivers, shown in Figure 12. The extreme occurrences recorded at different annual discharges have been marked with crosses. The Boconó data fall in the upper part of the diagram, indicating that it carries more water than most other headwater systems in Venezuela.

An attempt was made to draw a limiting line for the upper part of the diagram based on two considerations: (1) the possibility that in sampling 440 station years, one really extreme value was hit upon, fixing one point on the diagram through which the limiting line will pass; (2) an almost linear increase of the maximum 24-hr runoff with the annual discharge, at least for small basins. This increase should diminish with higher annual runoff to allow for more compensation of convection cells and surrounding clear areas as the basin size becomes larger.

This reasoning is, of course, speculative. The line drawn in Figure 12 can serve only as a rough guide. It must also be noted that the data are given for fixed 24-hr periods, and therefore are likely to be underestimates of the maximum runoff that would be obtained using « natural » periods centered with respect to a continuous runoff record. Figure 13 is derived from Figure 12 and shows the amount rather

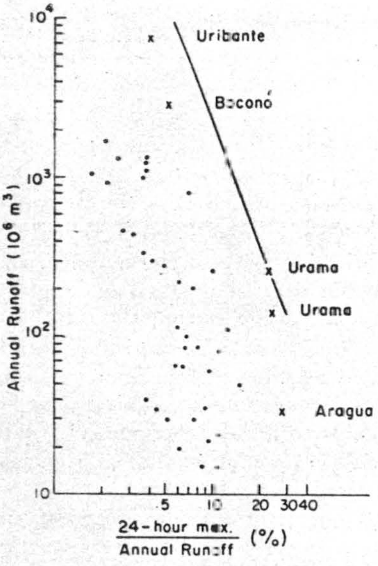

Fig. 12 - *Relation of annual runoff* (10^6 m^3) *and contribution of largest 24-hour discharge to annual runoff* (*per cent*) *for all headwater basins in Venezuela.* Crosses mark highest values observed in different classes of annual runoff.

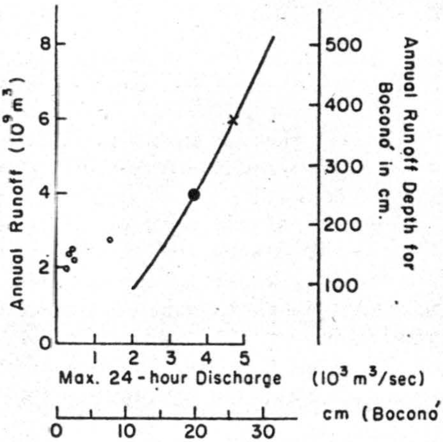

Fig. 13 - *Annual runoff* (10^9 m^3) *against mean rate of maximum 24-hour discharge* (m^3/sec) *for the Boconó* (from Fig. 12). Annual and maximum 24-hour runoff depth in cm are also shown. Dot indicates annual runoff for a maximum daily discharge of 20 cm, cross for a discharge of 25 cm.

than the percentage of maximum 24-hr discharge. The limiting line is the same as in Figure 12. The heavy dot indicates the relation for a maximum daily runoff of 20 cm (200 mm) on the Boconó and the cross the same for 25 cm. Open circles show the five points obtained for the Boconó from 1952 through 1956. The highest observed annual runoff depth was a little under 200 cm. A maximum day's discharge of 20 cm would imply an annual discharge of 250 cm and a 25-cm day would be in a year of 375-cm discharge.

The study gives no decisive clue as to whether 20 or 25 cm per day should be used as a maximum, because of the uncertainty of the line in Figure 12. As a minimum conclusion, however, it does not appear that anything has been brought to light in the discharge data which argues strongly that an estimate for the basin of 20 cm per day for an extreme occurrence is obviously too low or too high.

An investigation also was conducted aimed at determining the ratio of maximum instantaneous discharge to maximum 24-hr discharge. Again, the data for all headwaters of Venezuela were used. Figure 14 shows the plot of ratio against maximum 24-hr runoff; only the largest ratio has been entered for each river.

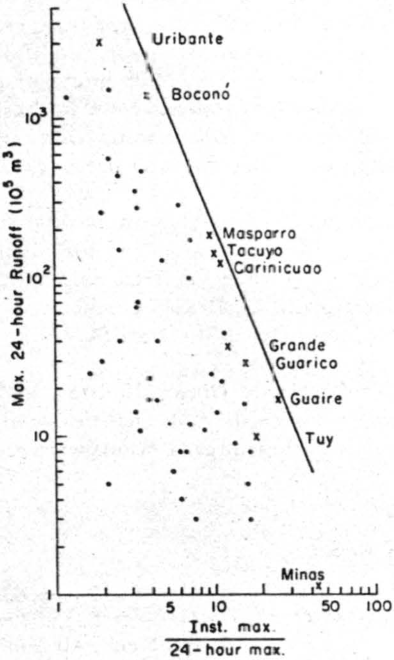

Fig. 14 - *Relation of largest 24-hour runoff* (10^5 m^3) *with ratio of instantaneous peak discharge rate to mean 24-hour discharge rate for largest 24-hour discharge of each Venezuelan headwater basin.*

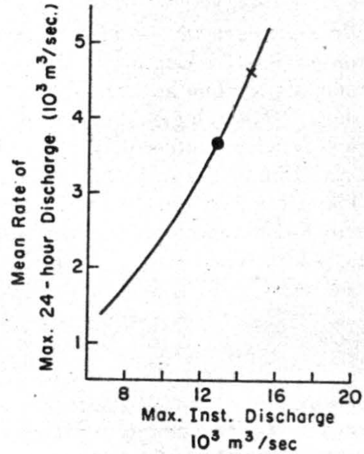

Fig. 15 - *Relation of mean rate of maximum 24-hour discharge for the Boconó* (10^3 m^3/sec) *to the maximum instantaneous rate* (10^3 m^3/sec), *from* Fig. 14. Dot marks 24-hour discharge depth of 20 cm, and cross a discharge depth of 25 cm.

Surprisingly the result is much better than for the daily against annual plot, so that a tentative limiting line can be drawn quite easily. The good fit of so many rivers with diverse location, stream flow and basin structure may be accidental; nevertheless the Figure indicates clearly the magnitude of the ratio applicable to the Boconó. Figure 15 shows the relation between maximum 24-hr and instantaneous discharges, utilizing the limiting line of Figure 14. The highest instantaneous rate increases with the 24-hr discharge, but the curvature is such that this increase diminishes toward higher values. It is seen that for a maximum runoff (and precipitation) of 20 cm per day from the Boconó, the highest discharge rate will be $13 \cdot 10^3$ m^3 sec^{-1}.

Conclusion — The design figure of a depth of 200 mm of precipitation per day over the Boconó watershed above the dam site was obtained from meteorological reasoning. A study of 440 station years of discharge records in Venezuelan headwaters indicates the reasonableness of this value. From a study of these river data, it is concluded that with the occurrence of the 200-mm-perday storm a maximum instantaneous discharge at the dam site of $13 \cdot 10^3 \, m^3 \, sec^{-1}$ would be expected. This value is in fair agreement with unit hydrograph calculations.

Since the soil is likely to be saturated at the beginning, and evaporation is negligible because of the short duration of the storm, complete runoff of the precipitated water may be assumed without affecting the broad limits of accuracy of the computation. Furthermore, in considering a small, compact basin of this type, one is within the same limits of accuracy in assuming that, in the extreme case, the 24-hour discharge will approach the 24-hour precipitation.

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