

SESSION ON
HYDROLOGY

Presiding:

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- The Application of Hydrometeorology to Engineering
Problems* MERRILL BERNARD
- The Present Trend in Evaporation Experiments* CARL ROHWER
- Current Technique in Rainfall-Runoff Analysis* W. G. HOYT

THE APPLICATION OF HYDROMETEOROLOGY TO ENGINEERING PROBLEMS

by

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At 10 a. m. of January 27, 1937, flood waters marked the highest stage in the 65 years of record on the Ohio River at Louisville, Kentucky, submerging the gage on the river bank to a little more than its 57-foot mark, which, at Louisville, is 29 feet above flood stage.

Immediate concern in this city was centered upon the reported stages upstream at Cincinnati, Parkersburg, and Pittsburgh; but in fact the scene of the impending flood had been laid more than a month before in remote tropical and polar regions.

What were the many circumstances combining to bring the river to the particular stage of 57.15 feet at Louisville? It is not too difficult to identify them and their beginnings and to attempt an evaluation of the immediate forces that created, transported, and finally concentrated the myriad of water particles within the narrow dimensions of the Ohio River flood channel during the nearly 30 days of almost continuous rainfall from December 28, 1936, to January 25, 1937.

Let us begin at the river gage where observed stages become the measure of river discharge out of the vast "moving" storage in the channel system of the Ohio above Louisville. Maps of the basin are deceiving in that they give the impression that there are large areas from which storm water flows off as a sheet. In reality, almost as quickly as rain falls, its run-off assembles into small flows that combine into a system of connected channels of appreciable dimension. If, then, the Ohio River system be divided to its very headwaters into reaches of like channel and slope characteristics, we may proceed downstream, solving the storage equation successively from reach to

reach; that is, considering the discharge into the head of any reach for a given period of time as equalling the discharge out of it, after adding lateral inflow and adjusting for changes in storage volume.

At the headwaters of the innumerable small tributaries of the river we have reached the source of the river flow—rainfall. Here we must pause to take into account the difference we shall find in the amount of water accounted for as river discharge and that measured as rainfall. If we could identify the actual rainfall that produced the river flow for the 24 hours embracing the flood peak on January 28th, we should find little difference for heavy antecedent rains had long since occupied all available surface pondage and had reduced infiltration to the capacity limits of the soils comprising the basin.

The flood, as streamflow, becomes a ribbon of flowing water occupying the channel and flood plain of the river and is marked on the map by a meandering line of insignificant width giving a much less impressive picture than the isohyetal map of the rainfall which blankets the whole of the basin and shows that rain fell to a depth of two feet or more over appreciable areas.

Here the meteorologist takes up the analysis, carrying it back to the source regions of the warm, moist, tropical air and the cold, dry, polar air that moved inward to meet over the Ohio Valley, there to be held in deadlock for nearly a month by a warm anticyclone off the South Atlantic Coast, and an upper level cold cyclone over the plains region.

The picture of the storm as the meteorologist sees it is presented in the following three figures. Fig. 1 is the synoptic weather map for 7:30 a. m., of January 21st, the day of heaviest rainfall. The synoptic map pictures the weather "on the ground", as it is measured by surface observations of pressure, temperature, humidity and wind. The synoptic map shows in addition to the familiar "highs" and "lows" the position of cold and warm fronts that separate the air masses of differing characteristics. Fig. 2 shows pressure and temperature at five kilometers above sea level. The marked temperature gradient of from -35° C. at Cheyenne to -6° C. at Nashville is one of the important meteorological factors accounting for the excessive rainfall on this day. The complete reversal of the circulation pattern over central United States, from anticyclonic at the surface to cyclonic at five kilometers, has an important bearing on the results to follow

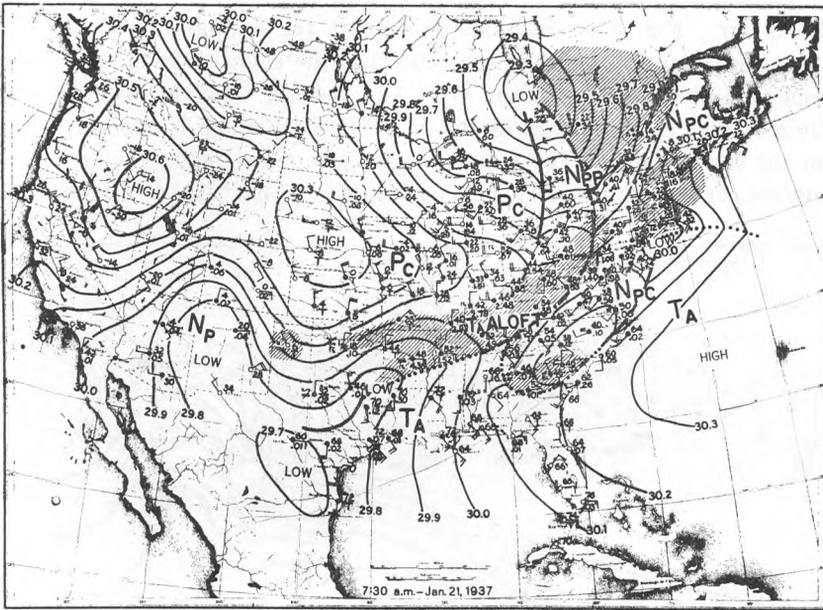


FIG. 1.

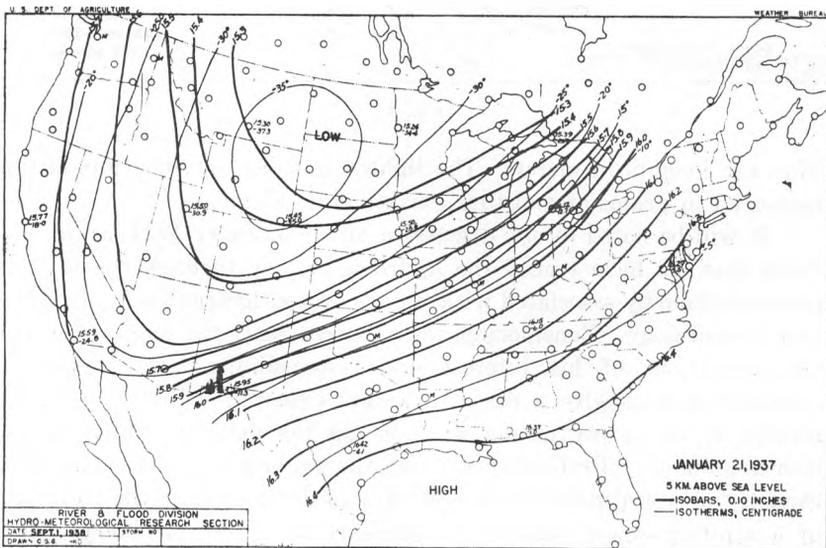


FIG. 2

in causing the warm moist Gulf air to be pushed up over the stable Polar air. Fig. 3 is the isentropic chart for January 21st. It reveals the extensive moist tongue entering the country from the maritime moisture sources of the Gulf and moving upslope towards the Ohio Valley, an important factor in forecasting which is not apparent on the surface map. The isentropic map is one showing factors in a surface of constant potential temperature, (305° C.). The heavy

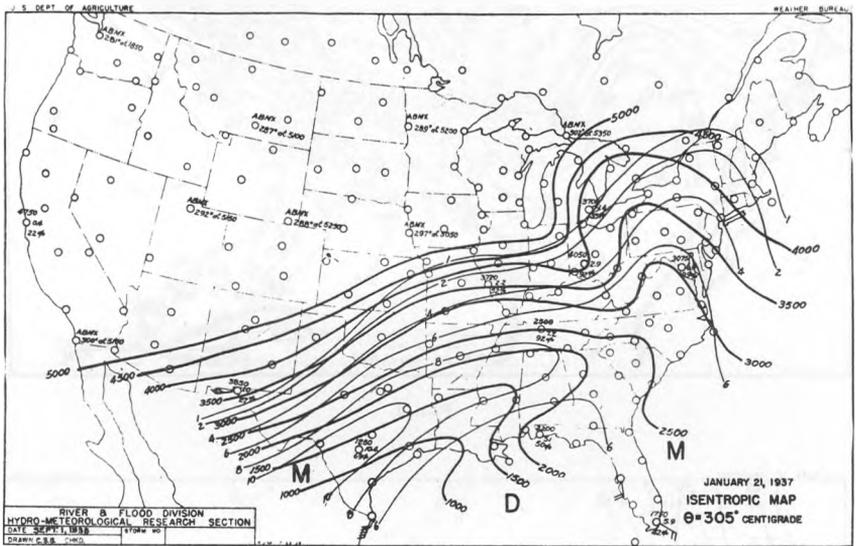


FIG. 3.

lines are heights in meters. The lighter lines are specific humidities measured in grams of moisture per kilogram of air.

It will be noted in our discussion of the January 1937 storm and flood that we have traced the hydrologic cycle through the several phases ordinarily associated with the sciences of hydraulics, hydrology, and meteorology. Considering these, where may the engineer place the limitations of his interest and responsibility? All fields of engineering must give a place to water; either in utilizing and conserving it, or in preventing or reducing the damage caused by its over-abundance. Problems involving the water supply of a city; the capacity of a spillway; the height of a protection wall; the elevation of a sanitary sewer outlet; the necessity to place machinery above flood stage—all are provisional in character and if real security and

economy are to be injected into their solution every facility at hand must be utilized.

In approaching these problems the first, and often the gravest, limitation lies in a paucity of precipitation and streamflow data. The length of record is found too short to have great statistical significance; the number of rainfall stations is too small to give adequate areal significance to average depths; and the quality and character of the records are not adaptable to the solution of problems on the smaller watersheds.

The length of hydrologic records over the country has doubled approximately within the scope of our professional lives, and we hope our technical knowledge has kept pace. We have experienced the inadequacies of the older empirical formulas and are beginning to have the "feel" of newer and more rational methods of predetermining flow rates and volume.

Until recently, the engineer-hydrologist has not been interested particularly in the causes of precipitation. Rather has it been important to him to know its variations in terms of rate, duration, and areal extent; its variation with changes in elevation and locality; seasonal differences to be expected; the periodicity with which like phenomena can be expected to occur; and finally, the relation of precipitation to the resultant phenomena of infiltration, transpiration, evaporation, and run-off.

Sciences so closely allied as meteorology and hydrology can not long remain sharply separated. The continual search for supporting facts will carry one investigator into the field of the other. The objectives of both entail an unrelenting search for physical and statistical relationships, and closer correlations of the factors which are of importance in improving the means of forecasting meteorologic and hydrologic events such as storms and floods.

The engineer, therefore, has every reason to be interested in hydro-meteorology, and he should project his knowledge beyond that segment of the cycle embracing falling rain and run-off only. Also, in the light of a woefully inadequate record of hydrologic data, both as to length and geographical extent, he could improve his statistical analysis by including in his correlations a consideration of the principal causal factors that are now the everyday tools of the air-mass analyst.

Engineering technique for planning the utilization of water has

developed more rapidly than that for flood control. The staggering quantities of water involved in the latter, and the great cost of control works required, have provided the incentive to support design with the refinements, security, and economics inherent in more rational procedures among which hydrometeorology is finding a place.

The utilization of hydrometeorology in engineering can be illustrated in its application to flood control problems, taking a case in which the greatest possible flood must be provided for in the capacity of a spillway to be built in a dam above a developed valley area.

Again we must acknowledge the limitations which hedge about our first steps in this new field. Our records of storm and flood are short and our knowledge of meteorologic and hydrologic relationships elementary. We have paid dearly for those inadequacies, not so much in the failure of the works we have built, but in the admittedly extravagant factors of safety which have characterized design in the past.

Our records of streamflow are shorter, less extensive, and not so dependably subject to interpolation as our records of precipitation. This accounts for recent trends to storm rainfall as the basis for flood estimation, for the meteorological background of the storms that produce rains of flood proportions has been found to add materially to the interpretability of our shorter precipitation records.

The storm and accompanying rainfall are phenomena recognized as having physical limits within fairly well defined regions of meteorologic homogeneity. Current studies indicate that the likelihood of all the meteorological factors combining at their maxima in a single storm is of remote probability within such a region and that for such a combination to occur in a critical position over a selected, relatively small basin within the region approaches an impossibility. Therefore, if such a limiting or enveloping storm is to be considered beyond the probability of experience in a single storm period of continuous rainfall, its estimation, or forecast, must rest upon the synthesis of the determinable factors at their upper limits.

The almost complete absence of hydrologic data on many basins for which important flood control works must be designed has stimulated the development of a method of flood flow estimation based upon storm transposition, assuming that any of the great storms that have occurred in a given region could have with equal probability

occurred in critical position over a particular basin. It is believed sound to assume that, looking into the future, every basin within a region will ultimately experience for every duration the greatest intensity of which the region is susceptible. It seems logical to assume, further, that in bringing to a particular basin through transposition every great storm that has occurred in the region within the record period, the storm-record for the basin has been extrapolated into the future a considerable, though indeterminable period. If now the greatest depths for selected durations are taken from the transposed storms and combined (that is, the greatest 6-hour depth from Storm No. 4, the greatest 12-hour depth from Storm No. 1, the greatest 18-hour depth from Storm No. 3, etc.) the synthesized storm resulting will envelop all individual storms capable of occurring over the basin.

The steps in the determination of the maximum possible rainfall for a basin are as follows:

1. A review of the history of floods, rainfall, and climate for the meteorologically homogeneous region in which the basin is located.

2. Analysis of physiographic controls of climate, semi-permanent centers of meteorological action; and large scale abnormalities in the general atmospheric circulation and their effect on storm sequence in the region.

3. Study of source regions of moisture laden air and possible trajectories of such air over the basin; and sources of cold air north and west of the basin.

4. Analysis of the seasonal precipitation trends in the region and their relation to flood possibilities over the particular size of basin under consideration.

5. Generalized analysis of all storms of record occurring in the region.

6. Detailed analysis of the outstanding storms reviewed.

7. Determination and classification of storm types.

8. Transposition of priority storms to the basin and their modification for intervening influences.

9. The preparation of mass curves of rainfall for all stations in the storm area from the original station records. From these the excessive rates and their time of occurrence are determined and checked with the meteorological analysis which gives the time of passage and the intensities of frontal movements over the station.

10. The preparation of isohyetal maps for all storms found to contribute maximum depths for selected durations within a period fixed by the conditions of the basin study.

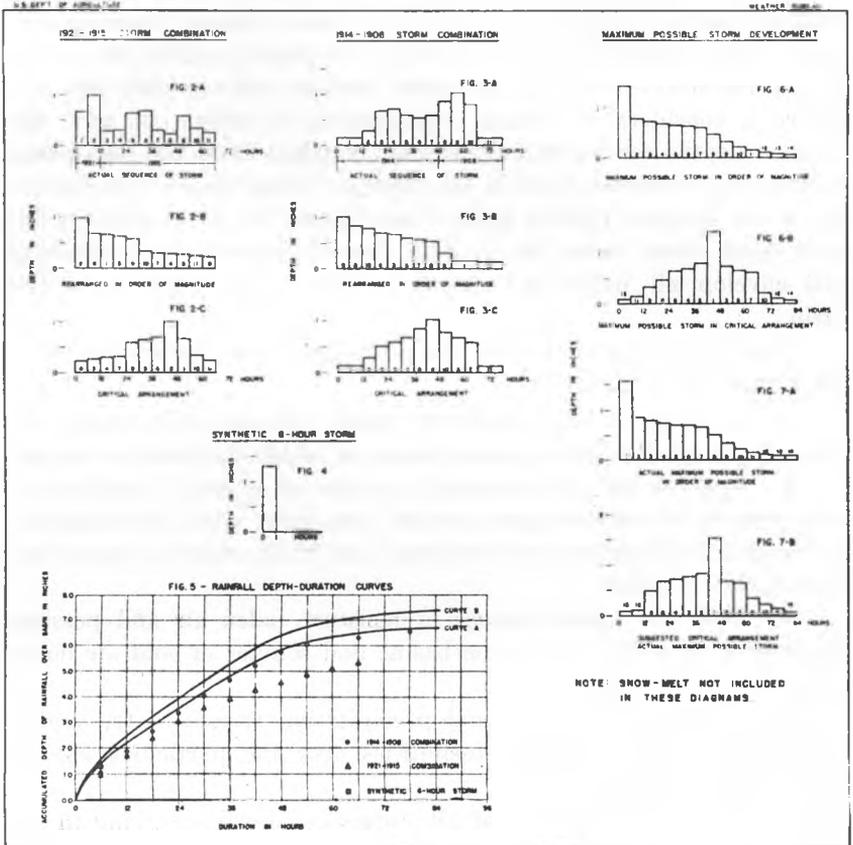


FIG. 4.

11. The preparation of limiting depth-duration and limiting depth-area curves for the basin.

12. The determination of the critical pattern for the design storm.

13. If the basin is too large to be treated as a unit, the determination of the areal distribution of the maximum possible depths to facilitate flood routing and the application of unit hydrographs.

Steps in the synthesis of the design storm are shown in Fig. 4.

The forecasting of floods is of interest to engineers, not only in the technical aspects of an important public service but as the means of more securely organizing construction at elevations subject to flooding. The practicability of utilizing available meteorological facilities and modern techniques in forecasting floods is illustrated in the following description of a forecast formulation. Figs. 5 and 6 show graphically the sequence of events as they could have been anticipated in forecasting the storm and flood of January 29—February 3, 1939, on the Shenandoah Basin above Millville, West Virginia.

Studies of rainfall-streamflow relations for the basin indicate an initial run-off coefficient of about 10 per cent. The figures show the increase in the run-off coefficient values as the storm progressed and as this factor would be reflected in the discharge of an "index" watershed or some other readily available indication of diminishing infiltration capacity.

The synoptic weather situation as of 7:30 a. m., January 28, points to an outbreak of precipitation in the West Gulf area moving northeastward toward the Appalachian Region.

The situation at 7:30 p. m., of the 28th indicated a rapid northeastward movement of a well defined moist tongue accompanied by copious rainfall.

Another area of cyclogenesis becoming evident at this time lies off the South Atlantic Coast and is producing rainfall in the Carolinas and on the Georgia coast.

At 7:30 a. m. of January 29th the principal area of precipitation has entered the Appalachian Region. Rains continue along the South Atlantic Coast. The situation now indicates the necessity for preparedness at the forecasting center.

Weather conditions at 7:30 p. m. confirm the forecaster's judgment as to the seriousness of the situation; justify the call for general reporting from rainfall stations throughout the basin; necessitate the issuance of cautionary warnings; and warrant a trial estimate of rainfall to be expected in the next period.

The material in the hands of the forecaster, period by period, is displayed in Figs. 5 and 6. From rainfall up to 7:30 a. m. of the 30th it was possible to formulate an approximate forecast of peak stage. This was modified from data received at the end of the rainfall period 1:30 a. m., January 31st. However, it is to be noted

ILLUSTRATION OF AN IMPROVED METHOD OF HEADWATER FORECASTING.

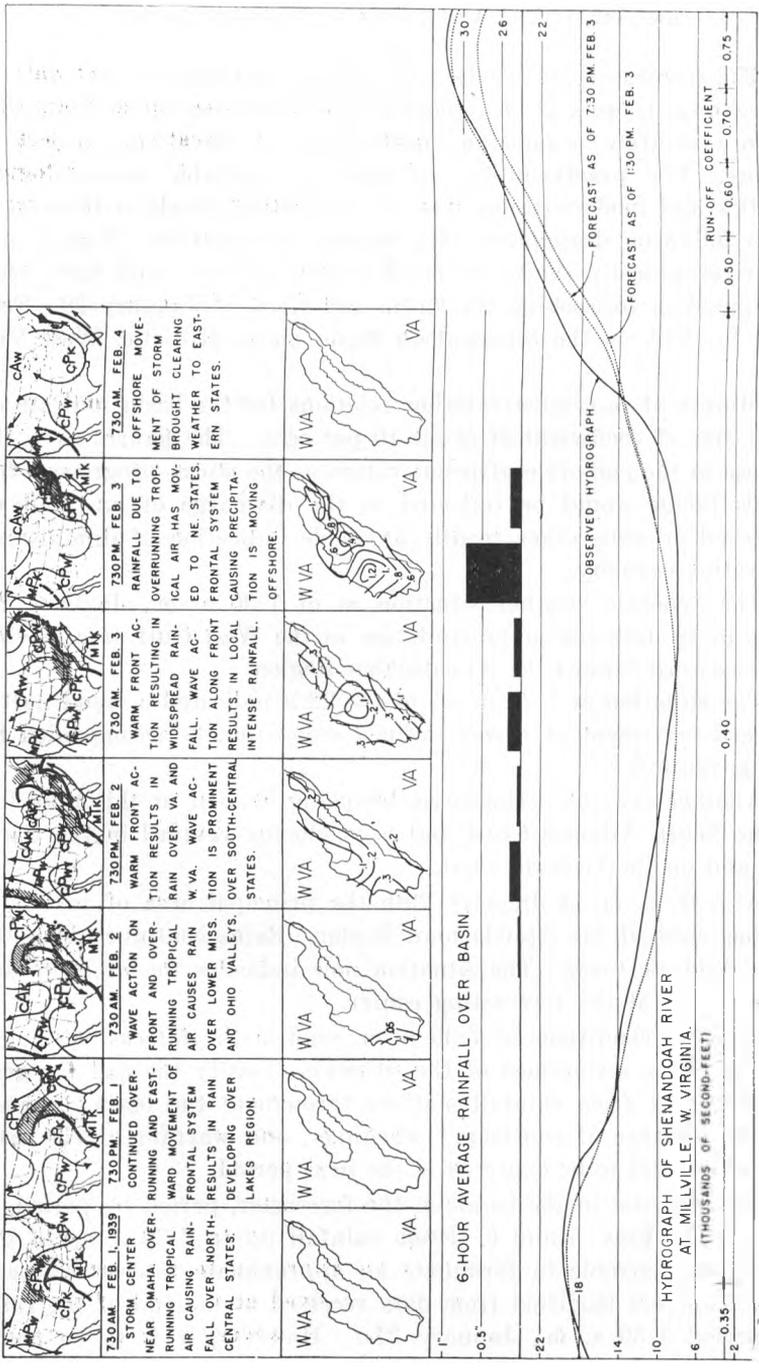


FIG. 5.

ILLUSTRATION OF AN IMPROVED METHOD OF HEADWATER FORECASTING.

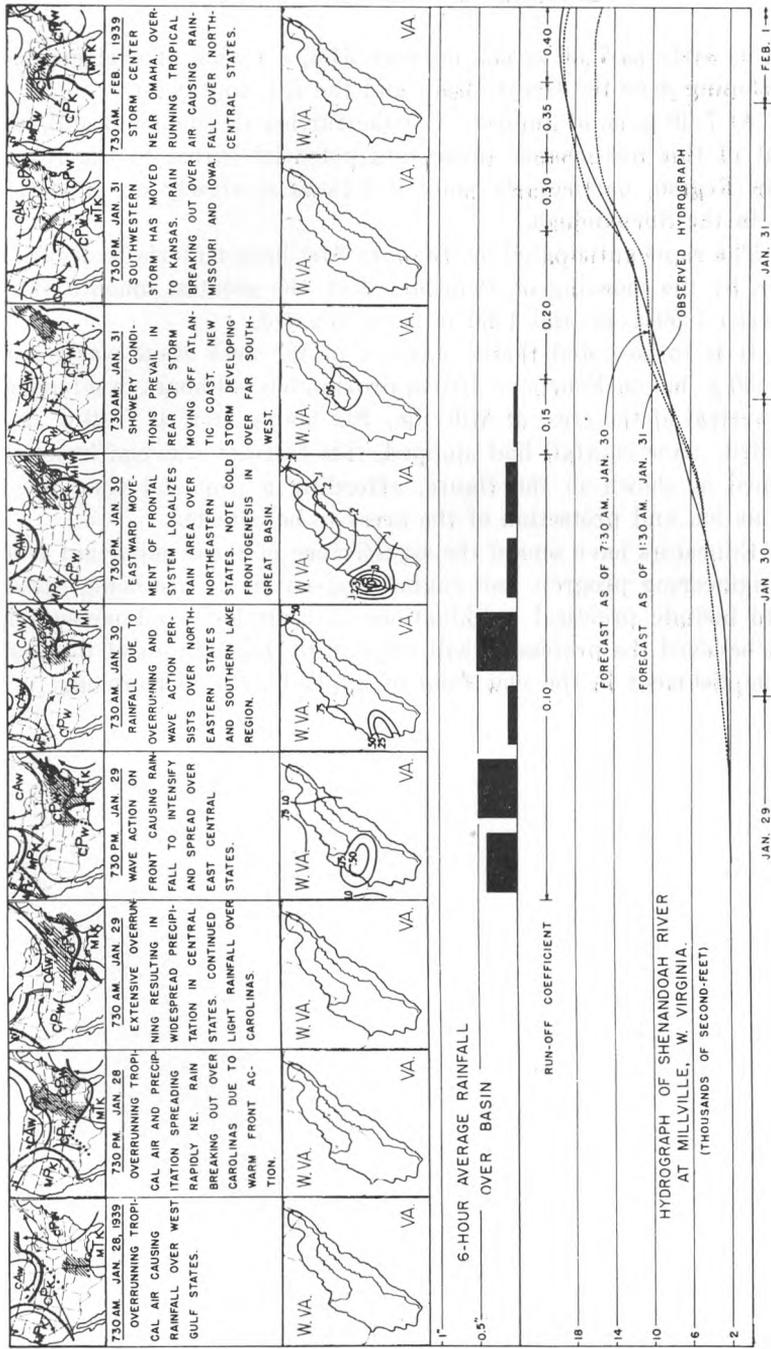


FIG. 6.

that as early as 7:30 a. m., January 31st, a region of cyclogenesis is developing over the Great Basin and the far Southwest.

At 7:30 p. m. of January 31st the further development and movement of this disturbance presents a potential threat to the Appalachian Region, particularly since it follows so closely an appreciable rise in the Shenandoah.

The rains anticipated on January 31st have materialized over the basin by the morning of February 2nd, the greatest amount falling between 7:30 a. m. and 1:30 p. m. of the 3rd.

It is to be noted that a forecast of the peak stage was possible at 1:30 p. m., on February 3rd, approximately 40 hours in advance of the arrival of the crest at Millville. Six hours later, at 7:30 p. m., of the 3rd, after rainfall had stopped, this forecast was confirmed and refined as shown in the figure, affording a practical time for the evacuation and protection of the areas to be affected.

Educators have sensed the significance of these important trends in engineering progress and engineering curricula are being expanded to include practical combinations of hydrology and meteorology. It is believed the profession will respond to the stimulus of increasing accomplishment in the new field of applied hydrometeorology.