U.S. DEPARTMENT OF COMMERCE
WEATHER BUREAU

HYDROMETEOROLOGICAL REPORT NO. 38

METEOROLOGY OF FLOOD-PRODUCING STORMS IN THE OHIO RIVER BASIN

Washington
May 1961

HYDROMETEOROLOGICAL REPORTS

(Nos. 6–22 Numbered Retroactively)

*No. 1. Maximum possible precipitation over the Ompompanoosuc Basin above Union Village, Vt. 1943.
*No. 2. Maximum possible precipitation over the Ohio River Basin above Pittsburgh, Pa. 1942.
*No. 3. Maximum possible precipitation over the Sacramento Basin of California. 1943.
*No. 4. Maximum possible precipitation over the Panama Canal Basin. 1943.
*No. 5. Thunderstorm rainfall. 1947.
*No. 6. A preliminary report on the probable occurrence of excessive precipitation over Fort Supply Basin, Okla. 1938.
*No. 7. Worst probable meteorological condition on Mill Creek, Butler and Hamilton Counties, Ohio. 1937. (Unpublished.) Supplement, 1938.
*No. 8. A hydrometeorological analysis of possible maximum precipitation over St. Francis River Basin above Wappapello, Mo. 1938.
*No. 9. A report on the possible occurrence of maximum precipitation over White River Basin above Mud Mountain Dam site, Wash. 1939.
*No. 10. Maximum possible rainfall over the Arkansas River Basin above Caddoa, Colo. 1939. Supplement, 1939.
*No. 11. A preliminary report on the maximum possible precipitation over the Dorena, Cottage Grove, and Fern Ridge Basins in the Willamette Basin, Oreg. 1939.
*No. 12. Maximum possible precipitation over the Red River Basin above Denison, Tex. 1939.
*No. 13. A report on the maximum possible precipitation over Cherry Creek Basin in Colorado. 1940.
*No. 14. The frequency of flood-producing rainfall over the Pajaro River Basin in California. 1940.
*No 15. A report on depth-frequency relations of thunderstorm rainfall on the Sevier Basin, Utah. 1941.
*No. 16. A preliminary report on the maximum possible precipitation over the Potomac and Rappahannock River Basins. 1943
*No. 17. Maximum possible precipitation over the Pecos Basin of New Mexico. 1944. (Unpublished.)
*No. 18. Tentative estimates of maximum possible flood-producing meteorological conditions in the Columbia River Basin. 1945.
*No. 19. Preliminary report on depth-duration-frequency characteristics of precipitation over the Muskingum Basin for 1- to 9-week periods. 1945.
*No. 20. An estimate of maximum possible flood-producing meteorological conditions in the Missouri River Basin above Garrison Dam site. 1945.
*No. 21. A hydrometeorological study of the Los Angeles area. 1939.
*No. 21A. Preliminary report on maximum possible precipitation, Los Angeles area, California. 1944.
*No. 21B. Revised report on maximum possible precipitation, Los Angeles area, California. 1945.
*No. 22. An estimate of maximum possible flood-producing meteorological conditions in the Missouri River Basin between Garrison and Fort Randall. 1946.
*No. 23. Generalized estimates of maximum possible precipitation over the United States east of the 105th meridian, for areas of 10, 200, and 500 square miles. 1947.
*No. 24. Maximum possible precipitation over the San Joaquin Basin, Calif. 1947.
*No. 25. Representative 12-hour dewpoints in major United States storms east of the Continental Divide. 1947.
*No. 25A. Representative 12-hour dewpoints in major United States storms east of the Continental Divide. 2d edition. 1949.
*No. 26. Analysis of winds over Lake Okeechobee during tropical storm of August 26–27, 1949. 1951.
*No. 27. Estimate of maximum possible precipitation, Rio Grande Basin, Fort Quitman to Zapata. 1951.
*No. 28. Generalized estimate of maximum possible precipitation over New England and New York. 1952.
*No. 29. Seasonal variation of the standard project storm for areas of 200 and 1,000 square miles east of 105th meridian. 1953.
*No. 30. Meteorology of floods at St. Louis. 1953. (Unpublished.)
No. 31. Analysis and synthesis of hurricane wind patterns over Lake Okeechobee, Florida. 1954. .35.
No. 32. Characteristics of United States hurricanes pertinent to levee design for Lake Okeechobee, Florida. 1954. .60.
No. 33. Seasonal variation of the probable maximum precipitation east of the 105th meridian for areas from 10 to 1,000 square miles and durations of 6, 12, 24, and 48 hours. 1956. .40.
No. 34. Meteorology of flood-producing storms in the Mississippi River Basin. 1956. $1.25.
No. 35. Meteorology of hypothetical flood sequences in the Mississippi River Basin. 1959. .35.
No. 36. Interim report on probable maximum precipitation in California. (In preparation.)
No. 37. Meteorology of hydrologically critical storms in California. (In preparation.)

* Out of print.

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U.S. Department of the Army
Corps of Engineers

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PREFACE

On assignment from the Office of the Chief of Engineers, Department of the Army, the Hydrometeorological Section of the U. S. Weather Bureau undertook a comprehensive examination of the meteorological aspects of flood potential of the Ohio River. The purpose of this meteorological study was to serve as an aid to the Corps of Engineers in their planning and design of Ohio River Projects.

The meteorological study consists of two parts. The first phase, an appraisal of the important synoptic features of significant Ohio Valley rainstorms, is covered in chapter I. The second phase, comprising chapter II, is a critical meteorological evaluation of sixteen Ohio River hypothetical flood sequences.

Chapter I

METEOROLOGY OF EXCESSIVE RAINS IN THE OHIO VALLEY

General circulation features

The general circulation features for any significant rainstorm must be such that an adequate continuing supply of moist air is provided along with the means for lifting this moist air. For major Ohio River rainstorms the primary controlling features in the type I case are:

(1) A High centered well off the coast of the eastern United States the clockwise circulation of which transports air with a high moisture content into the vicinity of the Ohio Valley.

(2) An equally matched area of high pressure and cold air centered over the general region of the Northern Plains or possibly north of the Canadian border. This feature in combination with (1) aids in the formation of a quasi-stationary frontal zone in the vicinity of the Ohio Valley.

(3) A major trough aloft (approximately 20,000 feet) over the western United States resulting in a wind flow directed from the southwest toward the northeast over the surface frontal position.

The above features are shown schematically in figure 1-1 depicting the quasi-stationary frontal type conducive to major flood-producing rains in the Ohio River Valley.

Somewhat different general circulation features result in another type of potential heavy rain producer in the Ohio Valley shown schematically in figure 1-2 and designated as type II. In this type the controlling features take the form of a more south-to-north wind flow aloft with the trough line in a more easterly position. The center of the surface Atlantic High is usually further to the north but with an extension to the south in the form of a ridge of high pressure which acts as a block to the eastward motion of the surface Low.

The two schematic synoptic patterns are to be considered as ideal patterns for a two- or three-day period of rain. For a shorter period within the two-or three-day storm the synoptic pattern may approximate one of the two ideal patterns or may be best represented by some intermediate pattern. A typical sequence through a two- or three-day period might well be a quasi-stationary frontal situation culminating in an occluding Low west of the Appalachians in conjunction with an intensifying eastward moving trough or low-pressure center aloft.

Physical processes involved in heavy rainfall

The general circulation synoptic features described in the above two ideal types act in a manner that brings about the efficient processing of a generous supply of moist air. The hydrologically significant timing of the concomitant heavy rains results in Ohio River floods.

Of primary importance is the presence of a High somewhere off the East Coast, which under proper conditions will result in a generous transport, from warm southerly waters, of air with moisture and other characteristics conducive to heavy precipitation. Typically this inflow of moisture concentrates in a jet 2,000 to 3,000 feet above the surface.

Substantial lifting and cooling of the moist tropical air is necessary for significant condensation and rainfall. A great many factors can contribute to lifting of the moist air but the two basic ingredients are significant horizontal convergence of the air, tending to force air upward, and the inherent instability of the air upon which the convergence acts.

The proximity of fronts separating strongly contrasting air masses are frequently important factors in heavy rain situations for several reasons. First, convergence-favoring isobaric patterns are usually found in the vicinity of fronts. Fronts may also provide the slight amount of lifting necessary to bring about the turbulent overturning of moist tropical air with resulting heavy rainfall. In addition the potential energy represented by two contrasting air masses on opposite sides of a front is instrumental in rain production as this potential energy is converted into the kinetic energy of a developing disturbance. Not only does this developing disturbance increase the moisture inflow, but it also generally results in a rain-enhancing concentrated increase in convergence.

A primary function of an upper level southwesterly flow over the surface front is to keep the zone of rain-enhancing factors relatively fixed over the Ohio Valley. Furthermore, the southwest-to-northeast orientation of the upper-air flow helps to produce the most critical orientation of isohyetal patterns for the Ohio Valley.

Optimum combination of flood-producing synoptic types

In order that an Ohio River flood take place, neither the quasi-stationary character of type I nor the intensifying low pressure character of type II should become overly dominant. A certain degree of the quasi-stationary character is needed in order that successive bursts of rainfall continue to <u>fall in the basin</u>. Although some fluctuation of the zone of heavy rain <u>is allowable</u>, the development of an intense Low becomes self-defeating if it occurs too soon. This is true because the same development that enhances the moisture transport, convergence and therefore rain, at the same time also pulls in drier air cutting off the moisture supply. The effective marriage of the two types is perhaps best seen in the famous

March 1913 storm and Ohio flood. Here the situation retained a quasi-stationary frontal character for a sufficiently long enough period to significantly concentrate the rainfall within the basin. The storm then culminated in an intensifying low-pressure disturbance, which at the same time, cut off the moisture supply, but not until enough rain over a long enough period had been distributed over the basin in a way so as to produce the final flood crest.

Synoptic features aloft should be such that they complement or enhance the surface rain-producing factors. Again the over-predominance of the character of a particular feature may be self-defeating. For example, a deep trough or low-pressure center to high levels is conducive to a deep layer of converging air favoring heavy rain. However, if pronounced southerly flow exists to high levels a stabilizing effect is introduced which is not the case with neutral or cold advection aloft.

Discussion of major rainstorms

The storms which are discussed hereinafter either have resulted in Ohio River floods or, if they had occurred in a different location, or with more favorable run-off conditions, could have resulted in Ohio River floods. The individual storms are discussed in the order in which they appear in the hypothetical sequences of chapter II. The synoptically more significant features of the storms are emphasized particularly in regard to those features which characterize the general Ohio River flood-producing types illustrated in figures 1-1 and 1-2.

Storm of January 5-25, 1937. In discussing the flood-producing rainfall characteristics of this storm Swenson* emphasizes that "the critical portion of the storm, made up of a series of closely related downpours which persisted for several days at a time without moving very far ... contributed much to the severity of the flood." Also, "the final period [January 13-25, 1937] was comprised of a series of heavy, and almost continuous, rains centered almost directly over the Ohio Valley and these rains were the immediate cause of the record-breaking flood to follow."

The sweep of cold dry air over the Gulf of Mexico was noticeably absent in January 1937 so that a warm moist current was nearly always readily available. Also present were above-normal pressures in the extension of the Bermuda High off the southeast coast and a ready supply of abnormally cold air over the northwestern portion of the United States. Tied in with these features was the typical quasi-stationary frontal zone oriented generally southwest-to-northeast through the Ohio Valley. Cyclonic development of varying intensity took place along this frontal zone in the January 1937

*Bennett Swenson, "The Ohio and Mississippi River Floods of January-February 1937," Monthly Weather Review Supplement No. 37, U. S. Weather Bureau, 1938.

storm. The general northeastward movement of these low-pressure systems was obedient to a steering by the prevailing southwesterly winds aloft.

In addition to the above-mentioned discussion by Swenson an additional rather detailed discussion of the January 1937 storm can be found in Hydrometeorological Report No. 34*, pp. 21-24.

Storm of January 3-16, 1950. The relative persistence of winds aloft from the southwest was an important feature of the prevailing circulation during the January 1950 storm and was indicative of a deep trough aloft over the western United States. Surface features during this storm period ranged from a quasi-stationary front with minor waves with little development to intense developing Lows.

During this storm period extremely cold air invaded the northwestern portion of the United States and the Northern Plains while very warm moist tropical air flowed northward from the Gulf across the eastern portion of the country.

A more detailed synoptic discussion of the January 3-7 period of this storm can be found in Hydrometeorological Report No. 34*, pp. 54-56.

Storm of March 23-26, 1913. The storm resulted in a southwest-to-northeast rainfall pattern with a rainfall center of 11.16 inches at Bellefontaine, Ohio.

As pointed out in Hydrometeorological Report No. 2**, page 44, the March 1913 storm is considered most representative of the quasi-stationary front type (figure 1-1) because of sharp temperature contrasts, wave action, pronounced inflow of moist air from the south and unusually heavy rainfall. Many of the important features of this heavy rain-producing type such as the typical above normal pressure off the southeast coast and contrasting cold air and high pressure into the Northern Plains, are illustrated in the surface weather map for March 25, 1913 (figure 2-3B).

Following the rather rapid northeastward movement of a Low to just north of the Great Lakes on the morning of March 24 (figure 2-3A), the following cold front moved slowly and finally became quasi-stationary on March 25. A significant low pressure development brought an end to this storm (figure 2-3D).

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*Hydrometeorological Section, U. S. Weather Bureau, "Meteorology of Flood-Prodicing Storms in the Mississippi River Basin," Hydrometeorological Report No. 34, July 1956.

**Hydrometeorological Section, U. S. Weather Bureau, "Maximum Possible Precipitation Ohio River Above Pittsburgh," Hydrometeorological Report No. 2, 1941.

The most important feature of this storm was that for a period of two days strongly contrasting air mass currents remained relatively fixed thereby permitting a persistence of rainbursts over the same general region.

Storm of March 24-26, 1904. An elongated isohyetal pattern in this storm stretched from northern Arkansas to central Ohio. Most of the precipitation occurred in a 24-hour period beginning late on March 24. Washington, Indiana recorded a fall of 7.2 inches.

The March 1904 storm represents a differing type from those discussed previously in the sense that the main precipitation was associated with an intense low pressure disturbance in the central portion of the United States (figures 2-4B and 2-4C). In this storm important factors for rain in the Ohio Valley were a strong inflow of moist unstable air and the existence of a large temperature contrast that became particularly effective in connection with an important cold front that moved into the Ohio Valley on March 25. In addition to thunderstorm activity in connection with this front, a wave which moved rapidly along the front slowed its forward progress enhancing and prolonging the rainfall.

A more thorough discussion of this storm may be found in Hydrometeorological Report No. 34*, pp. 24-25.

Storm of March 16-18, 1936. An isohyetal pattern oriented generally north-to-south featured this March 1936 storm with several separate centers of rainfall. A total fall of over six inches at Romney, West Virginia occurred mostly in a 24-hour period beginning the evening of March 16.

This storm of March 1936 was one of a series of deepening Lows with marked northward components of motion that characterized the month. The storm of March 16-18 moved north-northeastward near the Middle Atlantic Coast (figures 2-5B and 2-5C). Most of the important features of this storm are the same as those which characterize the ideal occluding Low type depicted in figure 1-2.

The intense upper air cyclonic circulation that accompanied this March 1936 storm favored the abnormal by large northward component of motion of the surface Low and concomitantly resulted in a very active flow of moisture northward through a deep layer of the atmosphere. A quasi-stationary inverted V-shaped low-pressure trough became established to the north of the Low center. The concentration of precipitation was in this zone of pronounced and persistent convergence. Thus the deep layer of converging moist air displayed in this March 1936 storm was its most important feature. Augmenting the moisture inflow in this case was the intensification of the pressure gradient by a combination of the intense Low moving up along the

*Hydrometeorological Report No. 34, op. cit.

Atlantic Coast and building high pressure off Nova Scotia. The accompanying marked pressure gradient aloft was associated with extremely low temperatures and pressures over the Mississippi Valley.

Storm of April 25-28, 1937. The total isohyetal pattern in this April storm had an orientation similar to that of the March 1936 storm just discussed. Large rainfall centers in this April storm occurred at Clear Springs, Maryland and Big Meadows, Virginia with most of the rainfall in a 24-hour period beginning the morning of April 25.

This storm falls under the general type II classification of Hydrometeorological Report No. 2* as consisting essentially of an occluding primary low-pressure system to the west of the Appalachians. As with the March 1936 storm a pronounced cyclonic circulation prevailed aloft in this April storm.

In the April 1937 storm the primary occluding Low was centered in the Wisconsin-Iowa area on April 24-25. One integral feature of the April 1937 synoptic picture for this storm period was the increase of pressure to the west of Hudson Bay, which prevented any further northward motion of the Low. Another significant feature was the development of a secondary low-pressure system which took place near the South Atlantic Coast. The persistence of high pressure over Hudson Bay and extending southeastward across New England resulted in a very slow motion of the coastal Low northward. Finally by the morning of April 27, the secondary Low had amalgamated with the remnants of the original occluding Low west of the Appalachians, rather than following the more usual northeastward track at sea.

Persistence of the Hudson Bay High, for most of the last half of April 1937, was a prominent synoptic feature and one that should be preserved in hypo sequences since the blocking action of the high pressure is closely associated with the subsequent slow movement of the Low and the accompanying long persistence of precipitation.

Storm of March 12-14, 1907. The main rainfall area in this storm extended from southern Indiana across southern Ohio and into extreme southwestern Pennsylvania. A rainfall center of nearly 8 inches was located in southwestern Ohio. In a 24-hour period on March 12-13 Cincinnati received over 5 inches of rain.

This storm comes under the classification of the quasi-stationary frontal type. It, however, was a less pure variety than the March 1913 storm. In the March 1907 storm the front generally maintained some slow eastward component of motion as waves moved northeastward. Rainfall was appreciably enhanced by the convergence associated with wave action. An intensifying wave moved from Arkansas to New York State from March 13 to

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*Hydrometeorological Report No. 2, op. cit.

March 14 while a less intense wave moved northeastward along the front during March 14.

The unusualness of the March 1913 storm is an important distinguishing point when comparing the March storms of 1907 and 1913. The central pressure of the High in the Atlantic at the beginning of the March 1913 storm was fully ten millibars higher in pressure than was the case in March 1907. A survey of the Historical Weather Maps* showed the month of March 1913 to be outstanding in regard to persistent high pressure in the Atlantic. Using the criterion of three or more consecutive days with a closed central isobar of 1035 mb or higher to select persisting high pressure cases, a total of twenty days were found with pressure of 1035 mb or higher in March 1913.

Although the period of March 12-15, 1907 was a high zonal index** situation, prior to and following this period conditions characteristic of low zonal index** prevailed. Before the heavy rain in the March 1907 storm the synoptic situation in the eastern United States on March 10-11 consisted primarily of a northeastward-moving Low which occluded off the Middle Atlantic Coast with high cells oriented generally north-south ahead of and to the rear of the Low.

Storm of January 7-11, 1930. Persistently heavy rains with no significant lulls in the rainfall for nearly 48 hours was a distinguishing characteristic of this January storm. Nearly 11 inches of rain fell at Arkadelphia, Arkansas in this storm with a secondary center at Brownsville, Tennessee totaling 9.23 inches.

In this storm a strong Bermuda High with an extension over the Southeast was equally matched by a cold High extending into the Northern Plains. This combination resulted in a southwest-to-northeast front through the Ohio Valley. Widespread rainfall within the colder air was indicative of a significant trough aloft over the western portion of the country similar to the one depicted in the quasi-stationary frontal type of figure 1-1.

In addition to the above prevailing large-scale features, the other rain-producing features which seemed to have been important in this storm were an active flow of moist air northward into the frontal zone and the inverted-V-isobaric configuration which existed from the lower Mississippi Valley into the western portion of the Ohio Valley. The latter synoptic feature is one which is an efficient rain producer in that such an isobaric configuration favors pronounced convergence.

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*U. S. Weather Bureau, "Daily Synoptic Series Historical Weather Maps, Northern Hemisphere Sea Level", January 1899 to June 1939, Incl.

**High zonal index (low zonal index) represents a situation in which the westerly component of wind in middle latitudes is stronger (weaker) than normal.

The rainfall in this storm ended as drier air invaded the Ohio Valley with the southeastward movement of the Northern Plains High.

<u>Storm of February 2-7, 1883.</u> Rainfall totals of 3 to 6 inches occurred during the period of February 2-7 including centers at Bowling Green, Kentucky, and Wellsboro, Pennsylvania.

The tracks of low-pressure and high-pressure areas for February 2-7, 1883, indicate that a major trough aloft, over the western portion of the country, was a feature of this storm period. Specifically this is borne out by the positions of a developing Low which moved from southwestern Tennessee on February 3 northeastward across the eastern Great Lakes to extreme northern New York State by the morning of February 4. This Low was followed by a strong High which dipped southeastward from the Dakotas on February 3-4, 1883 to extreme northeastern Kansas. On February 5 this High turned sharply in crossing Missouri and moved off rapidly eastward as another Low was beginning to develop in Kentucky. This second Low deepened rapidly on February 6-7 while moving northeastward, once again to a position in northeastern New York State by the morning of February 7. The High following this second Low took a course similar to the previous High. It initially plunged further south (as far as northwestern Arkansas late on February 7) in conjunction with the pronounced deepening of the Low which moved northeastward into southern Ohio by the morning of February 9, indicating that the large-scale feature of southwesterly flow aloft still persisted.

<u>Storm of January 1-3, 1907.</u> In the January 1907 storm the bulk of the rain occurred between 6 p.m. CST on January 1 and 6 p.m. CST January 3. The 3-inch isohyet covered southern Indiana, northwestern Kentucky, the southern tip of Illinois and Missouri, the western end of Tennessee and diagonally across Arkansas from northeast to southwest.

This storm period might be classified in the quasi-stationary frontal category in so far as rainbursts were intensified by wave action on a front that moved northward from the Gulf and became quasi-stationary in the Ohio Valley. However, the broader scale synoptic features were not in conformity with the classical quasi-stationary frontal type. In the January 1907 storm the necessary pressure gradient and flow of moist air from the south was brought about by a combination of a ridge of high pressure along the East Coast and a Low which moved from Colorado early on January 1 to the vicinity of Lake Superior by late on January 3. By the morning of January 4 a northwesterly flow of drier air brought an end to the precipitation.

<u>Storm of January 10-11, 1913.</u> The typical southwest-to-northeast isohyetal pattern resulted from the rainfall in this storm. The 3-inch isohyet extended from extreme northeast Texas to north-central Kentucky. A total of 7.39 inches of rain fell in less than 36 hours at New Madrid, Missouri.

The significant factors favoring heavy rain in the January 1913 storm were the plentiful supply of moist unstable air, the movement inland of a weak disturbance from the Gulf of Mexico and the arrival of a cold front which increased the overturning of the moist air thereby accentuating the precipitation. A more detailed discussion of the timing of these events may be found in Hydrometeorological Report No. 34*, pages 25-27.

The January 10-11, 1913 storm followed another major rainstorm in the Ohio Valley (January 6-8, 1913) that ended as dry air overspread the area and to a little beyond the middle of the Gulf of Mexico. Following this earlier storm a significant flow of moist air northward from the Gulf became established in the clockwise flow around the western periphery of a reinforced Bermuda High. The opposing mass of cold air, typically extending into the Northern Plains in the quasi-stationary frontal type (figure 1-1), was brought about in this storm period as a Low moved eastward and then northeastward from Colorado to across the Upper Mississippi Valley.

Storms of May 6-12, 1943 and May 15-20, 1943. The period May 6-20, 1943 was quite unusual in that it was comprised of two very heavy storms centered over the same general area with only a short rainless period intervening. The first had a rainfall center of 25 inches in 48 hours at Warner, Oklahoma while more than 17 inches fell within a 12-hour period near Mounds, Oklahoma in the second storm. Both of these storms are covered in a detailed manner in Hydrometeorological Report No. 34* pages 48-53.

The prevailing weather pattern during the rains of May 1943 may be classified as a quasi-stationary frontal situation favored by a persistent high-pressure ridge over the Southeast balanced by cold air and high pressure extending from Canada into the Northern Plains. An investigation of prevailing conditions during the heavy rain in May 1943 showed the pressure in the Jacksonville, Florida area to average several millibars above normal. This is typical of many winter storms as, for example, those of January 1930 and January 1937.

Specifically, considering these May 1943 storms jointly the smaller scale features which were significant in the heavy rain included a strong southerly jet of high moisture content, a frontal boundary with large temperature contrasts, wave activity of varying intensity and at times the important convergence-producing inverted-V isobaric configuration.

Storm of July 25-August 3, 1875. The area of 5 inches or more of rain in this storm extended in a west-to-east band about 200 miles wide from west of the Mississippi River in northeast Missouri across southern Indiana to extreme southwestern Pennsylvania. Several periods of rainfall from July 25 to August 3 resulted in an accumulated total of 12.06 inches at Kenton, Ohio.

The rainfall from this storm was caused principally by wave action and resulting convergence along a quasi-stationary frontal zone oriented generally west-to-east. A minor wave moved across the Ohio Valley and into

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*Hydrometeorological Report No. 34, op. cit.

the St. Lawrence Valley on July 28-29. This was followed by a more important Low that centered along the Kansas-Missouri border on the morning of July 31. This Low subsequently deepened as it moved into northern Kentucky by the evening of August 1. Its eastward motion thereafter was slowed as rising pressure ahead of the Low extended southeastward over New England. This slowing down of the Low prolonged the precipitation well into August 2 in Ohio.

Storm of October 3-6, 1910. This storm resulted in the typical southwest-to-northeast rainfall pattern. Golconda, in southern Illinois, received the heaviest rainfall with a four-day total of 15.2 inches.

An intense High over New England on October 13 in conjunction with a north-south trough of low pressure in the Plains States set the stage for this storm in the form of pronounced flow of moist tropical air from the Gulf of Mexico. On October 4 the High moved to a position off the Atlantic Coast with its clockwise circulation effectively continuing to transport moist tropical air northward as evidenced by a 24-hour rainfall of 4.50 inches at Cairo, Illinois. Showers and thunderstorms occurred primarily in the warm air to the east of a trough and frontal zone which, on the morning of October 4, extended from eastern Oklahoma to upper Michigan.

On October 5 the High off the Atlantic Coast weakened at the same time pressure was increasing over the western portion of the United States. The result was the eastward movement of an active frontal system. On October 5 increased shower and thundershower activity occurred primarily ahead of this eastward-moving cold front but wave activity along the front later helped to extend the rainfall area so that some rain fell within the modified polar Pacific air to the rear of the cold front. Rainfall ended when high pressure and dry air prevailed over most of the Ohio River Basin by the morning of October 7.

Storm of October 2-7, 1941. The October 2-7 period produced an extensive rainfall area extending in a southwest-to-northeast pattern from Oklahoma to Michigan. Of primary concern to the Ohio River Basin was the northeasternmost one third of the isohyetal pattern with a rainfall center of 11.29 inches at La Porte, Indiana.

During this storm period a rather persistent synoptic pattern prevailed aloft consisting of a ridge of high pressure over the southeastern states and a deep trough aloft over the western portion of the United States. This pattern resulted in a continuing supply of moist tropical air being transported into the Ohio River Basin since south or southwest winds persisted through a deep layer of the atmosphere. The more important fronts during this storm extended from the Texas-Oklahoma area to the southern Great Lakes. Increased convergence, associated with frontal movements and wave activity along the fronts, was primarily responsible for the heavier rainfall bursts in this storm. Two important waves during this storm period took approximately the same path from Kansas to upper Michigan - one on October 2-3 and the other on October 4-5.

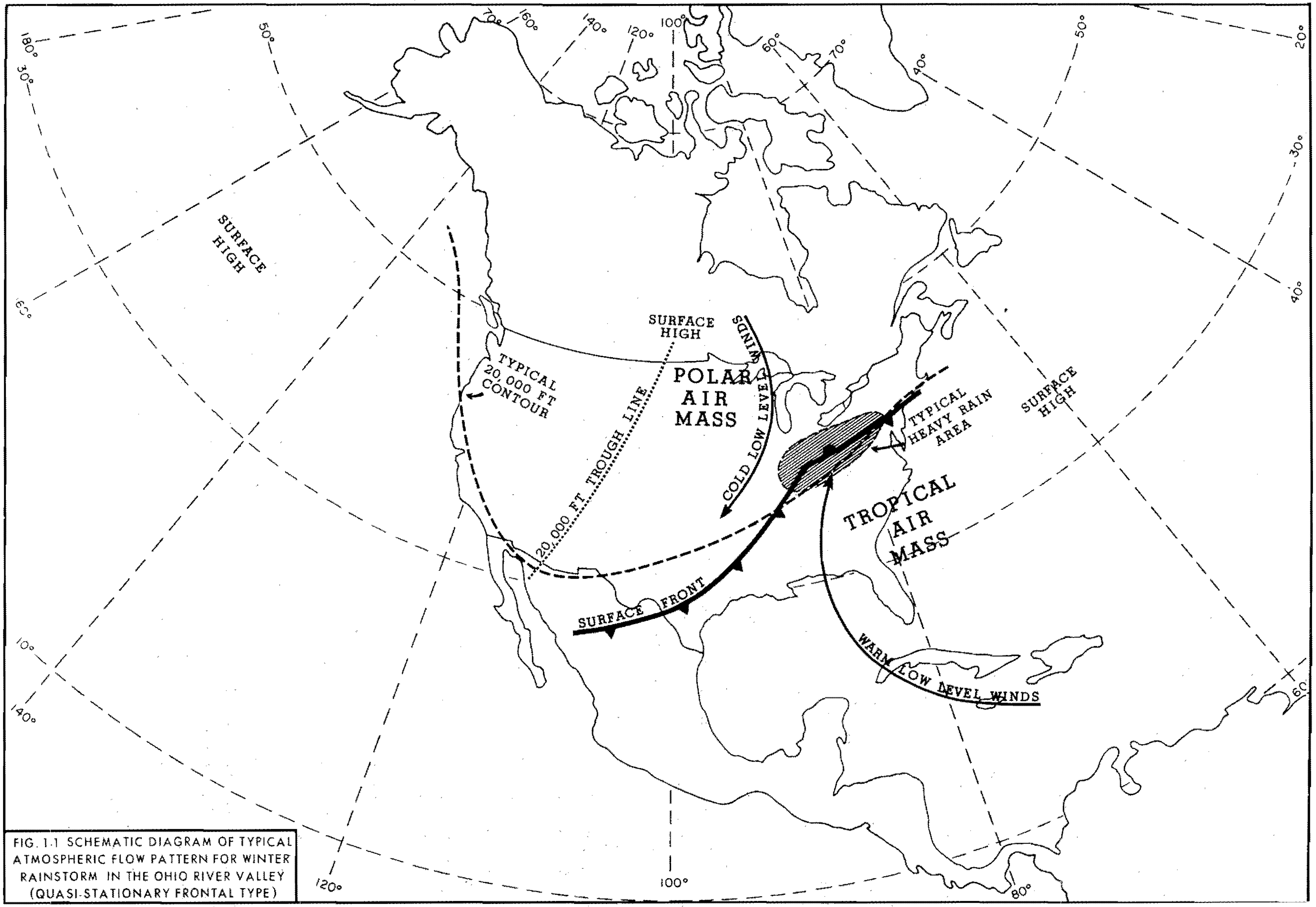

FIG. 1.1 SCHEMATIC DIAGRAM OF TYPICAL ATMOSPHERIC FLOW PATTERN FOR WINTER RAINSTORM IN THE OHIO RIVER VALLEY (QUASI-STATIONARY FRONTAL TYPE)

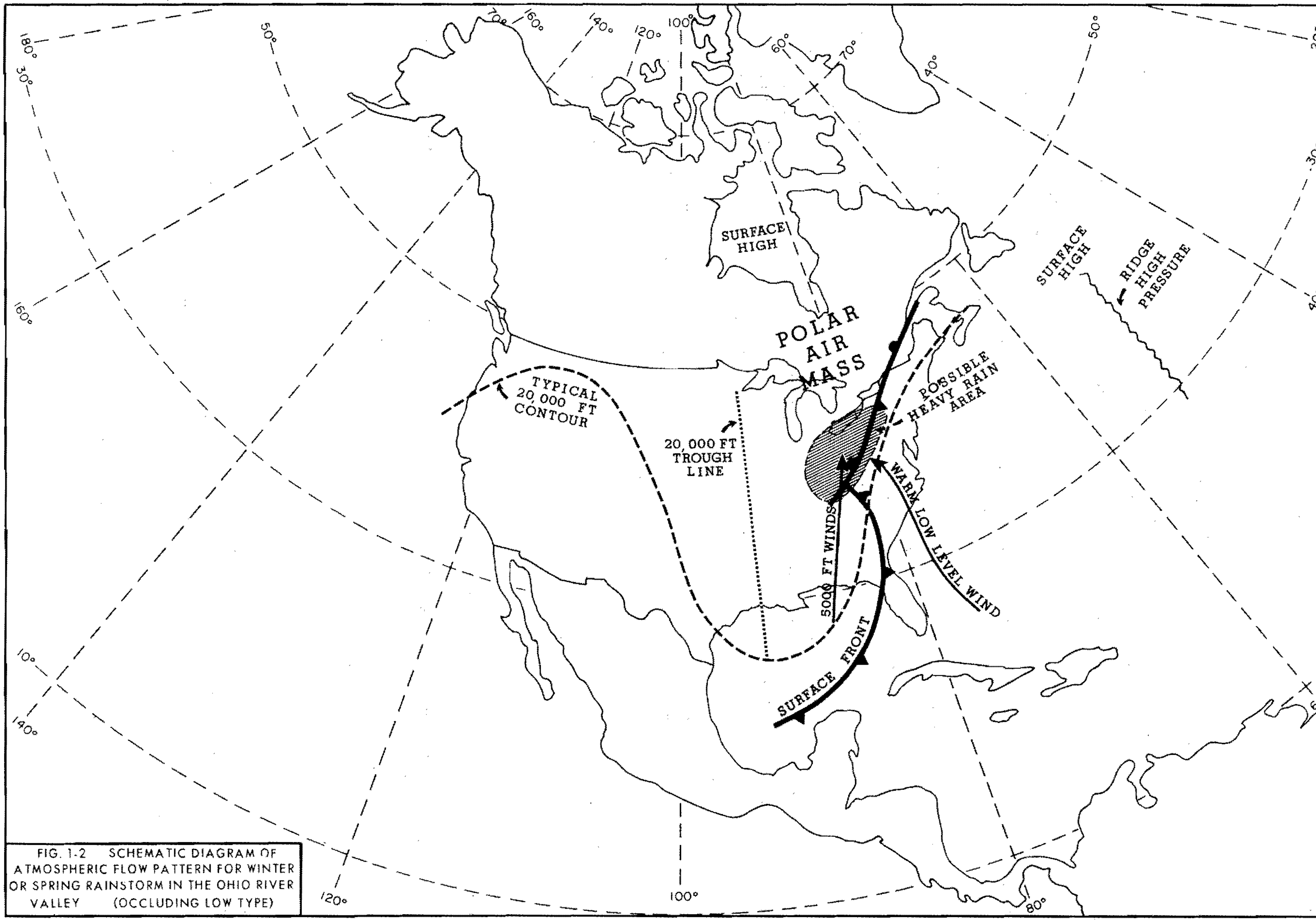

FIG. 1-2 SCHEMATIC DIAGRAM OF ATMOSPHERIC FLOW PATTERN FOR WINTER OR SPRING RAINSTORM IN THE OHIO RIVER VALLEY (OCCLUDING LOW TYPE)

Chapter II

OHIO RIVER HYPOTHETICAL FLOOD SEQUENCES

Hypothetical flood sequence technique

A thorough discussion of the technique involved in determining hypothetical flood sequences is found in Hydrometeorological Report No. 35*. Basically the technique involves putting two hydrologically significant storms together in a way that does not violate meteorological knowledge concerning repetition of significant storms. As used in this report a "storm" refers to a period of rainfall determined to be hydrologically significant. A given storm ceases with the occurrence of a lengthy period of no precipitation, or, hydrologically insignificant precipitation.

Once it has been determined that a particular storm can reasonably follow the other storm in the sequence, it then remains to be shown how short a time interval between storms is reasonable. It has been found that this is best accomplished by consideration of historical analogues of the desired synoptic sequence and more generally of particular synoptic features so that a meteorologically reasonable evolution from the end of one storm to the beginning of the other is possible. Both area of occurrence and the variety of weather processes involved had to be considered thoroughly in the determination of the reasonableness of the following sixteen hypothetical flood sequences. Hypothetical maps of surface weather features are included for a few of the more significant and difficult sequences. Some of the storms are used in place, while in other cases isohyetal patterns are moved geographically and, in some cases, rotated.

Detailed specification sheets for each hypothetical flood are included at the end of the chapter, pages 44-58.

HYPO-FLOOD NO. 1

Storms in sequence and transposition

Hypo-Flood No. 1 is a combination of two January storms, that of January 5-24, 1937 (OR 5-6)** followed by the storm of January 3-16, 1950. A discussion of these storms may be found in chapter I, on pages 4 and 5. Data sheet No. 1, page 44 also pertains to this sequence.

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*Hydrometeorological Section, U. S. Weather Bureau, "Meteorology of Hypothetical Flood Sequences in the Mississippi River Basin", Hydrometeorological Report No. 35, 1959.

**Storms will be referred to by the storm assignment numbers in "Storm Rainfall in the United States", Corps of Engineers, Department of the Army, 1945.

In the January 1937 storm the isohyetal pattern with a rainfall center at McKenzie, Tennessee is moved a distance of 240 miles toward the east-northeast. Such a transposition of the observed rainfall pattern results in a more hydrologically critical placement of the rain.

The 240-mile transposition is considered meteorologically reasonable primarily because of the fact that rainfall centers at the transposed location are as likely from quasi-stationary frontal situations as they are in the area of actual rain occurrence in the January 1937 storm. During the period of 1946-1955 nine of the ten heaviest January 24-hour rainfalls in the Ohio Basin above Louisville, Kentucky were of the same synoptic type as one or more of the bursts during the critical part of OR 5-6, from January 17, 1937 through January 24, 1937. Furthermore, this transposition keeps most of the rainfall within a topographically homogeneous region. A small portion of the rainfall pattern is placed in a region of somewhat less moisture potential due to the partial depletion of the lower level moisture by the flow of air across the southern extremities of the Appalachians. However, this depletion is not sufficient to require a rainfall reduction due to transposition.

In this hypo-sequence a four-day interval is used between the ending of the rain on January 24, 1937 and the beginning of the rain on January 3, 1950. Such an interval has been demonstrated to be meteorologically reasonable in Hydrometeorological Report No. 35*. Since the transposition of the January 1937 storm has also been shown to be reasonable, Hypo-Flood No. 1 for the Ohio above Metropolis is meteorologically reasonable.

HYPO-FLOOD NO. 22

Storms in sequence

The factors which make storm combinations reasonable are partly clarified by discussing a combination that was rejected. This hypo-sequence begins with the storm of March 16-18, 1936 (SA 1-27) followed after four intervening days by the storm of March 23-27, 1913 (OR 1-15). The Hydrometeorological Section did not regard this sequence as sufficiently reasonable meteorologically to indorse its use. The weather maps for March 1936 show the month to have been one with occluding Lows with pronounced northward motion a prominent feature. Such development is closely associated with rather intense low-pressure troughs aloft which occasionally reach the proportions of closed circulations to 20,000 feet and higher. It is not uncommon for such an over-all weather pattern to persist or to repeat itself over an extended period of time, as was the case in March 1936.

Recurring high pressure areas oriented more or less north-south over the western Atlantic seem to have been another synoptic feature closely tied in with the strong northerly motion of Lows in March 1936. The blocking action of these Highs prevented any substantial eastward motion of the Lows. In March 1913, on the other hand, a more nearly east-west alignment of the Atlantic High developed, setting up a quasi-stationary frontal

*Hydrometeorological Report No. 35, op. cit.

pattern oriented northeast-to-southwest from New England to Texas. Along this front, which separated sharply contrasting air masses, a deepening northeastward-moving storm finally developed.

Basically, the synoptic dissimilarity of these storms makes it unreasonable for the March 1936 storm to be followed by the March 1913 storm with only four intervening days. To check on this a series of hypothetical surface weather charts were constructed, forcing the features of the 1936 storm to evolve into the pattern of the 1913 storm after 2, 3, 4, 5, 6, and 7 days. For elapsed intervals up to at least five days the forced evolution is meteorologically unreasonable, that is fronts and pressure systems move at unrealistic speeds, are modified too rapidly, etc. Specifically in objection to this sequence can be mentioned the building back of the Bermuda High in the Southeast and the necessity of going from a nearly stationary major trough in the East in the 1936 storm to a High of maximum extent westward and northward in the 1913 storm.

The actual sequence of events in March 1936 suggests strongly that a much more logical hypothetical sequence would be to have the March 16-18, 1936 storm essentially repeat itself, especially, since this requires relatively minor adjustments to what actually did occur in March 1936. Such a hypothetical sequence is discussed under Hypo-Flood No. 22A.

HYPO-FLOOD NO. 21

Time interval between storms

This sequence combines two March storms, OR 1-15 of March 23-26, 1913, followed after three intervening days by UMV 2-4 of March 24-26, 1904. Data sheet 2 pertains to this sequence. The March 1913 storm is discussed on pages 5-6 and the March 1904 storm on page 6, of chapter I.

The period of significant rain in the March 1913 storm ended when cooler and drier air plunged southward and southeastward across the Gulf of Mexico, cutting off the supply of moisture. This is quite typical of this synoptic type. A minimum time interval of three days is necessary for the return of a moist flow of the flood-producing magnitude after the end of a storm of the March 1913 type in which the drier air reaches all the way to the Yucatan Peninsula. The three-day rainless time interval following the March 1913 storm is the minimum that permits a sufficient southward push of cold and drier air over the Gulf to retain the essential dynamics of the storm.

Transposition of OR 1-15

The transposition of the Bellefontaine, Ohio, center in the March 1913 storm is meteorologically sound since the quasi-stationary front along which the rain-producing cyclonic activity occurred, a common meteorological type over much of the United States, could just as well have been in a more easterly position without affecting significantly any major features of the general atmospheric circulation patterns prevailing at the time. This transposition, however, does bring the isohyetal pattern into the more mountainous region to the east. A barrier depletion adjustment is therefore reasonable for the portion of the storm transposed into the mountainous area.

Transposition of UMV 2-4

It is also meteorologically plausible for the March 1904 storm to have occurred further east. An example of a similar synoptic situation with the occluding Low occurring further to the east can be found in the maps for March 14-17, 1902. This transposition does not put the isohyetal pattern sufficiently in the mountains to require a barrier depletion adjustment.

Barrier depletion adjustment

The "geographical relocation adjustment" makes allowance for differing precipitable water in the atmosphere at the place of storm occurrence and at the tranposed position because of distance from the sea and similar factors. This adjustment does not substantially take care of depletion in precipitation due to the mountains. Where transposition is into the mountainous regions an additional barrier depletion adjustment is required. The following barrier reduction values were determined for the March 23-26, 1913 storm:

Zone 1 = 0.93
Zone 2 = 0.91
Zone 3 = 0.86
Zone 4 = 0.82

The orographic depletion zones are outlined on figure 2-1. These adjustment factors for the various zones are to be applied to the transposed precipitation in addition to all other adjustments.

In determining the orographic depletion for transposition of an isohyetal pattern into the Appalachian Mountains the reasonable assumption is made that a quasi-stationary frontal synoptic situation with prevailing inflow from the south could just as well have occurred with the moist inflow from the southwest, over lower barriers. Such an assumption is based on synoptic evidence that winds from either the southwest or south are logical with rainbursts associated with quasi-stationary fronts. Using southwesterly winds results in smaller orographic depletion than would be the case with southerly winds.

Considering a flow of air from the southwest, barrier heights were determined for such a wind. This resulted in the construction of zones oriented southwest to northeast with an assigned barrier height for each strip, representing the amount of moist inflow cut off by the mountains with a southwest wind. The following steps were followed for each zone in determining the percentage of remaining inflowing moisture:

(1) The zone with its assigned barrier height was marked on the isohyetal map in transposed position.

(2) The isohyetal map was returned to the place of occurrence and the mean elevation of the zone at rainfall-in-place noted.

(3) The precipitation was reduced by the amount of moisture in a column represented by the difference between elevations in (1) and (2). The remainder is the available moisture.

a. Figure 3 of Hydrometeorological Report No. 23* is used for this computation by entering the abscissa representative storm dew point and reading off percentages of moisture above 1000 mb lying above the elevations for (1) and (2).

b. The reduction factor for the barrier is then the ratio of: Percentage for (1) to percentage for (2).

The representative 12-hour dew point used in the adjustments for the March 1913 storm was 67°F, the same value as used in the Tennessee and Cumberland Basin Study**, and in the Mississippi River Basin Study***.

Surface weather maps

Surface weather maps covering this hypothetical sequence are shown in figures 2-3 and 2-4, pages 62 and 63.

HYPO-FLOOD NO. 23

Storms in sequence

This sequence is a combination of the same storms and rainless interval as in Hypo-Flood No. 21. The March 1904 storm has a 200-mile east-southeast transposition instead of the east-northeast transposition in Hypo-Flood No. 21. The meteorological reasonableness of this sequence for factors other than the transposition of the 1904 storm as used in Hypo-Flood No. 23 is pointed out in Hypo-Flood No. 21. Data sheet No. 3, page 46 pertains to this sequence.

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*Hydrometeorological Section, U. S. Weather Bureau, "Generalized Estimates of Maximum Possible Precipitation over the United States East of the 105th Meridian", Hydrometeorological Report No. 23, 1947.

**Lower Cumberland Reservoir Project. Memorandum to Office of Corps of Engineers from Hydrometeorological Section dated November 9, 1955.

***Hydrometeorological Report No. 34, op. cit.

Transposition of the March 1904 Washington, Ind., rainfall center

Transposition of the Washington, Ind., center 200 miles east-southeastward to Hazard, Ky., is meteorologically reasonable, as was the 200-mile east-northeastward transposition in Hypo-Flood No. 21. Most of the rain associated with the Washington, Ind., center occurred on March 23 as waves formed on the cold front while it moved through the area of interest.

A search of storm rainfall patterns for the Ohio River Basin disclosed two examples that support an isohyetal pattern such as that in the March 1904 storm occurring with a center near the desired area of transposition. There is the storm of December 4-8, 1924, with a center at Brownsville, Ky., and that of March 21-23, 1929 with a center at Rock Island, Tenn. The 1924 storm retains the feature of an occlusion with marked northward motion. Also in both of these storms, as in the March 1904 storm, the greater portion of the rain occurred in a 24-hour period. These examples are sufficient justification for considering the transposition meteorologically reasonable. The reasonableness of the time interval as set up in the sequence is not altered by this transposition nor does the transposition alter the reasonableness of using conditions prior to March 28, 1945 as antecedent conditions.

Depletion for barrier

Although meteorologically reasonable, the transposition of the Washington, Ind., rainfall center to Hazard, Ky., brings the rainfall pattern into the Appalachians sufficiently to require an adjustment for the cutting off of some lower-level moisture due to the barrier. The procedure for determining these adjustment values is outlined in Hypo-Flood No. 21. Figure 2-1 is also applicable to this Hypo-Flood sequence. The following barrier reduction values were determined for the March 24-26, 1904 storm:

Zone 1 = 0.93
Zone 2 = 0.86
Zone 3 = 0.81
Zone 4 = 0.77

HYPO-FLOOD NO. 22-A

Storms in sequence

This hypothetical sequence begins with the antecedent snow cover of March 9, 1936, occurring on March 15 of Hypo-Flood date. Storm SA 1-27 of March 16-18, 1936, is then hypothetically followed by a repeat of this same storm after an interval of 3 days. Data sheet 4, page 47 pertains to this sequence. The March storm used in this sequence is discussed on pages 6-7 chapter I.

Analogues of northward moving or retrograde Lows

A number of factors of the March 1936 weather support the reasonableness of a storm of the March 16-18, 1936 type repeating itself. First, as pointed out under Hypo-Flood No. 22, March 1936 was a month of a rather persistent synoptic type in which deepening Lows with marked northward motion were a dominant feature, particularly during the latter two-thirds of the month. It is not difficult to find occurrences of the persistence of this synoptic type in the months of March and April. For example, the prevailing weather in April 1932 presents a good analogue for the March 1936 persistence of type. During the period April 10-13, 1932 a Low displayed a westward component of motion across the mountains into the Great Lakes area. After two days another storm was underway which also had a retrograde (east-to-west) motion but, in this case, the occurrence took place further to the east. Still a third major low-pressure development showed marked northerly motion, eventually looping back into New England from a position several hundred miles to the southeast. Each of the three developments in April 1932 occurred successively further to the east, representing the more normal course for such developments to take.

A second important point demonstrated by the weather of March 1936 is that successive Lows with marked northward motion need not follow a set pattern, particularly regarding the position of their tracks. Following three significant low-pressure developments in the eastern portion of the country in March 1936 the major activity then shifted westward. In setting up sequences, then, of successive Lows with marked northward motion, the most probable train of events, is for the storm to occur successively further to the east, but it is not unreasonable to expect a storm to repeat in the same region or to expect the occurrence of the second storm further to the west. Another example of this type of occurrence is demonstrated in the period of March 9-16, 1912, when three deepening Lows developed successively further to the west.

Precipitation patterns and justification of sequence

The first one of the pronounced low-pressure developments in March 1936 covered the period from March 11 through March 13 and produced a rainfall center of more than six inches in a 24-hour period on March 11-12 in New Hampshire. It is interesting to note that in a subsequent 24-hour period on March 18-19, a strikingly similar isohyetal pattern occurred, centered over the same general New England area. This demonstrates what can take place regarding successive repetition of a rainfall pattern, practically in the same place. Following the March 16-18 storm period was yet another significant development on March 20-22 with perhaps the only hindrance to heavier precipitation from this storm being that its development took place a little too rapidly to allow an adequate return flow of sufficiently moist air.

Sequence 22-A, therefore, is considered meteorologically reasonable, with March 16-18, 1936 repeating itself after three intervening rainless days. Although it becomes increasingly difficult to retain a snow cover beyond the middle of March, it is, nevertheless, meteorologically reasonable to assume the snow cover of March 9, 1936, occurring as of March 15 with no synoptic modifications deemed necessary for making this adjustment in time.

Surface weather maps

Actual and hypothetical weather maps of surface synoptic features for this sequence are shown in figures 2-5 and 2-6, pages 64 and 65.

HYPO-FLOOD NO. 30

Storms in sequence

This sequence begins with SA 1-27, using the period of rainfall of March 16-18, 1936 followed after 3 days by SA 5-13 of April 25-28, 1937. Data sheet 5, page 48 pertains to this sequence. The April 1937 storm is discussed in chapter I, page 7. The individual centers of rainfall in the April 1937 storm showed some relationship to the orography. In the April 1937 storm the major portion of rain fell between 6:00 a.m. EST April 25 and midnight EST April 26. Pronounced low-pressure circulations aloft were associated both with this storm type and that of March 1936. For this and subsequent numerous additional reasons this Hypo-Flood sequence is meteorologically reasonable. Persistence of the Hudson Bay High for most of the last half of April 1937 was a prominent synoptic feature of the April 1937 weather and one that must be preserved in the sequence since the blocking action of high pressure is needed for the subsequent slow movement of the Low.

Analogues of necessary synoptic features

Blocking action of high pressure. February 17, 1952, through February 20, 1952, is a good illustration of the transition from an intensifying Low near the East Coast to the building of high pressure over the Hudson Bay region with a ridge building southward across New England. Another feature in this storm supporting the combination of the March 1936 and April 1937 storms is that the building high pressure was followed by a Low that had difficulty moving across the Great Lakes region against the prevailing high pressure to the northeast. With the primary occluding Low essentially blocked, a secondary Low formed by February 21 creating a synoptic picture similar to that of April 1937. Movement of the secondary in the 1952 situation was not of the sluggish type of April 1937. Furthermore, in February 1952 the primary Low although weakened, retained its identity as it finally moved to the Hudson Bay region by February 23. This contrasts with the continued dominance of the Hudson Bay High throughout the remainder of the month of April 1937. Such differences are to be expected in a February analogue for an April situation, since the Hudson Bay High normally might be expected to be a more dominant and slower-moving feature in April when that region becomes the cold source for the lower-level intensification of high pressure systems.

An example of a similar transition occurring in the month of April is found in the maps for April 4-7, 1933. Here, after an intensifying low-pressure system near the East Coast had passed, the synoptic pattern evolved into a situation similar to that of April 1937. A greater strengthening of the High across New England than actually occurred in this 1933 case would need to be postulated, coincident with the more sluggish movement of the secondary development along the Coast. Such a strengthening of the ridge over New England and simultaneous slowing down of an East Coast Low is meteorologically reasonable. One feature of the March 1936 storm that is modified is the pronounced retrograde (east-to-west) motion into Canada.

With the necessary modifications, the map for April 23, 1937, might be substituted for March 19, 1936. For this transition we can assume that the major trough aloft, which was not far removed from the East Coast in March 1936, retrogrades westward so that the Low in Missouri in March 1936, shows a normal slowing down while turning toward a more northeasterly course. The meteorological reasonableness of such a westward regression of the southwesterly flow aloft is covered in Hypo-Flood No. 22-A. The postulation of the long-wave trough retrograding westward also makes meteorologically reasonable the shifting of the East Coast Low to an eventual, more normal, northeasterly path rather than allowing it to follow through with a retrograde motion into Canada. With the retrogression of the long-wave trough to a position toward the center of the country, it is meteorologically reasonable for the steering current aloft over the Northeast to come from a more westerly or northwesterly direction, since a tendency then exists for anti-cyclogenesis at a position downstream from the upper trough position.

Actually, tropical air was more readily available on April 23, 1937, than it was on March 19, 1936. However, the idea of the return of sufficiently moist air to give a rain of a flood-producing type in three days following March 19, 1936, has already been covered in Hypo-Flood No. 22-A where an additional day is added to the two-day interval between significant developments that actually did occur in March 1936.

Analogues to March 1936 - April 1937 sequence

The maps for March 5-6, 1907, offer a good example of the building of high pressure north of the Great Lakes out of a complex synoptic pattern in the eastern portion of the country. Allowing for a pronounced High extending southward into northern Canada, and other necessary adjustments, the period March 19-23, 1899, offers a fairly good analogue to the development of a situation corresponding to the March 1936-April 1937 sequence.

It is quite conceivable that if the Low in March 1936 is allowed to move off to the northeast (as was the case in the March 1899 situation) then the remainder of the March 1899 series of maps might be modified to follow through in the manner of the April 1937 storm. In March 1899 the second occlusion occurred west of the one beginning the sequence, but it would be necessary to have it occur even further west in order to give the ridge of high pressure over New England the opportunity to become somewhat more pronounced and persistent, as was the case in April 1937.

March 13-16, 1939, is an example of a pronounced occluding Low near the East Coast, followed by an occluding Low in the Great Lakes area. With adjustments, it is not difficult to visualize the April 1937 developments subsequent to the map for March 14, 1939. Of primary importance is the maintaining of high pressure in the Hudson Bay region with a ridge of high pressure extending across New England. Examples in the month of March of the April 1937 type of development can be found in the synoptic surface maps for March 28-30, 1900, and March 5-8, 1914.

The synoptic series of maps just discussed provide sufficient evidence to demonstrate that Hypo-Flood No. 30 is a meteorologically reasonable sequence. Additional support might be found in the near-repeat of March 19, 1936, on March 22, and the fact that the maps of March 24-25, 1936 were not too significantly different from those of April 25-26, 1937. Thus, Hypo-Flood No. 30 as set up with a three-day interval is meteorologically reasonable.

<u>Transposition of storms</u>

To justify the occurrence further west, the synoptically verified conclusions reached in Hypo-Flood No. 22-A can be used for considering the meteorological reasonableness of transposing the March 1936 storm 85 miles west-northwestward as required in the sequence. Since the low-pressure center moved across the Appalachians to the northwest between March 19-20, 1936, it is reasonable to assume that a westward component of motion could just as well have taken place sooner. In effect, this would also have shifted the main body of the precipitation westward. The November 1950 storm serves as an analogue for the desired motion and makes it possible to postulate a westward shift of the rainfall pattern.

While transposition of this storm is reasonable, the peak isohyetal centers, having been augmented by orographic lifting along the eastern slopes of the Appalachians, must, in the transposed position, be reduced for the barrier. Adjustments for barrier depletion due to transposition must also be computed for the transposed April 1937 storm. As long as this depletion due to orography is allowed for, the April 1937 storm may likewise be transposed the desired 135 miles to the northwest. The added distance in transposition, however, makes the meteorological justification of such a move more difficult than if the transposition were restricted to less than 100 miles, since the latter would keep a substantial portion of the precipitation within the more mountainous area. It can be reasoned, however, that, given a persistent moist flow from the Atlantic, the necessary combination of rain-augmenting factors could so combine in a storm like that of April 1937 as to produce the rain center in the less mountainous region of west-central Pennsylvania, with due allowance, of course, for the subtraction of the orographically augmented portion of the precipitation.

An example of an important northward-moving storm producing much precipitation on the western portion of the Appalachians is that of November 25-27, 1950. The storm of September 10-13, 1878 (OR 9-19) is another good example of how a significant isohyetal center can occur to the west of the Appalachians in a northward-moving storm which draws some of its moisture supply from the Atlantic. In such storms synoptic features, such as an inverted-V-trough, produce non-orographic convergence that becomes important in increasing the rainfall to the extent that it overwhelms the orographic control.

Reduction of precipitation in transposing across Appalachians

A common characteristic of storms occurring east of the Appalachians with inflow from the south or east is the intensification of the rainfall due to lifting on the ridges of the Appalachians as, for example, the Blue Ridge. The storms involved in this sequence are of this type and to be transposed to the Ohio Basin, the rainfall amounts should be reduced. Since no tested objective method of removing the orographic contribution to rainfall has been developed up to the present, an approximation, based upon the depletion of precipitable water in a storm by the barriers, has been used for these storms. The location of the generalized Appalachian barrier has been determined and divided into two parts, zone I with an average height of 3200 feet and zone II, 2000 feet. Figure 2-2 shows the barrier and the two zones of reduction. This barrier height is applicable for inflow directions from the south through east. For the March 1936 storm the reductions to be applied to the precipitation amounts transposed over the barrier are 32% and 21% for the 3200 foot and 2000 foot barriers, respectively. These percentages were determined by using figure 3 of Hydrometeorological Report No. 23* with maximum dew point. For a ten-mile band to the west of the barrier, the adjustment can be gradually reduced to zero. This will permit smoothing where the unadjusted and adjusted isohyets meet and has merit in that an approximation to "spillover" is introduced.

The same reduction factors were used in the April 1937 storm. Basic to this procedure is the idea that the March 1936 storm might be looked upon as typical for computations of orographic depletion. The results derived are thus considered applicable to other transposable storms of

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*Hydrometeorological Report No. 23, op. cit.

similar inflow characteristics. The dividing line between the two reductions for transposition of the April 1937 storm to the northwest is also shown on figure 2-2. The lines forming zones I and II in each case are constructed parallel to the direction of transposition.

HYPO-FLOOD NO. 22-B

Storms in sequence

The meteorological discussion of Hypo-Flood sequence No. 22-A adequately covers the reasonableness of this sequence without transposition. In Hypo-Flood No. 22-B however, the isohyetal center is shifted 100 miles west and 40 miles south. Data sheet 6, page 49 pertains to this sequence. Again the period of March 9-16, 1912, might be cited as a synoptic example of occluding Lows occurring successively further to the west, indicating that such sequences do occur, although they are not what is most frequently observed. Other synoptic justification for such a sequence may be found in the Historical Weather Maps* for the periods of March 6-9, 1942, and March 19-23, 1899. These examples help support the reasonableness of the occurrence of the repeat of the March 1936 storm further to the southwest, which, in turn supports the transposition of the isohyetal center.

Transposition synoptics

With the reasonableness established for the second of two occluding Lows occurring further west, the question remains whether the region some 100 miles west of the Romney, West Virginia, center might experience a storm of the March 1936 type. Meteorological support for the reasonableness of such an occurrence is dealt with in Hypo-Flood No. 30. As long as a reduction factor for precipitation volume is applied for transposition across the Appalachian ridges, it is reasonable to transpose the March 1936 storm, as proposed in this sequence, to a region for which the storm potential for this type is less. Actually in the March 1936 storm the combination of rain favoring factors in conjunction with the retrograde motion of the storm was such that isohyetal centers of greater than five inches did occur west of the higher ridges. This demonstrates that in such a storm convergence-producing factors other than orography are sufficiently operative to give a substantial rainfall center downwind of the higher ridges, giving added synoptic justification for the reasonableness of transposing the Romney center westward and southward in this Hypo-Flood sequence.

*Daily Synoptic Series Historical Weather Maps, op. cit.

The storm of March 12-15, 1918 (OR 3-10) was centered over the region of desired transposition, but here a low-pressure disturbance moving northeastward from the central portion of the country was responsible for the precipitation. This was typical of many synoptic cases that were looked into indicating that an important isohyetal center in central West Virginia is most likely to result when the moist inflow is from a southwesterly direction.

There have been a few notable storms of record which have produced significant isohyetal centers to the west of the Appalachians even though drawing some of their moisture supply from the Atlantic. As pointed out in Hypo-Flood No. 30, page 24, the storms of September 10-13, 1878 and November 25-27, 1950 are two which fit into this category. In the November 1950 storm some of the heaviest precipitation amounts occurred in central West Virginia. Actually in the March 1936 storm itself there were substantial centers of rainfall to the west of the higher portions of the Appalachians. It is not difficult to visualize these centers of rainfall occurring even further west simply by postulating a westward displacement of a relatively fixed zone of convergence in the form of an inverted-V trough extending northward from the Low center.

Barrier depletion

A barrier depletion for moisture is required in this March 1936 storm in moving the isohyetal pattern across portions of the Appalachians. For this, the values for depletion determined for the same March storm in Hypo-Flood Study No. 30 should be used in conjunction with the orographic depletion chart for south through east winds (figure 2-2) showing the generalized barrier and the line paralleling the path of transposition that divides the depletion correction into two zones. Further discussion of the techniques used in depletion of the rainfall for transposition across the mountains can be found in Hypo-Flood No. 30.

Barrier reductions of 32% for zone I and 21% for zone II are to be used in accordance with figure 2-2 and a WSW transposition.

HYPO-FLOOD NO. 24

Synoptic features of March 23-26, 1913 storm

This sequence consists of OR 1-15 of March 23-26, 1913 essentially repeating itself after three intervening rainless days, but with the second occurrence taking place nearly 125 miles to the southeast. The 1913 storm culminated in the greatest flood of record on the upper Ohio. During March 1913 pressure in the Bermuda High was well above normal for most of the month, which in itself, is ample justification for allowing a persisting Bermuda High while the March 1913 storm repeats itself. Data sheet 7, page 50 pertains to this sequence.

Analogues of important synoptic features of March 1913 storm

A search of the Historical Weather Maps* for March disclosed other examples of situations with persistent well above-normal Bermuda Highs but none as pronounced as that of March 1913. Above-normal pressure prevailed during a substantial portion of March 1949 in the Atlantic including the period March 1-12 and March 19-24. Ten of the first eleven days of March 1903 had well above-normal pressure in the Bermuda High region of the Atlantic. Slightly over half of the March historical weather maps surveyed showed at least one period of three days or longer with pressure above 1035 mb in the Bermuda High region. Of the years in which this did occur, nearly half showed a repeat in the same month.

The presence of temperature well below normal in the Montana area might also be considered a persistent feature since below zero readings prevailed for at least four days prior to the storm itself. Previous to the storm period of March 23-26 in 1913 a supply of cold air and high pressure had been persistently maintained in northwestern Canada and Alaska beginning March 11 with only an occasional outbreak of cold air into the United States. Along with the final deepening low-pressure system in the eastern United States on March 26, 1913, a marked inflow of warmer air was observed to take place in western Canada. The beginning of a storm such as the March 1913 storm requires an extensive area of cold air extending into the United States from Canada. Thus, if we are to have this storm repeat itself we must consider the problem presented by this inflow of warmer air into western Canada at the end of the March 1913 storm.

A survey of March Historical Weather Maps* was made to determine how quickly a supply of cold air and high pressure might build in western Canada following a tendency for marked warming in that area. Several rather good examples of such development were found. One of the better examples for our purposes concerns the period of March 1-3, 1939. The map for March 1, 1939, shows a synoptic situation favorable for warming in western Canada similar to that for March 27, 1913. Unlike the 1913 situation, though, the 1939 example is one in which cold air and rapidly rising pressure follows. An important feature in 1939 that was absent in 1913 was the reorientation of the Pacific High to a north-south direction.

Other important features in the March 1939 situation that are necessary ingredients for repeating the March 1913 sequence, beginning with March 24, are the pronounced inflow of air from a southerly direction and the presence of very cold air in a High extending into the Northern Plains. (Both of these features are prominent on the map for March 4, 1939.) Using

*Daily Synoptic Series Historical Weather Maps, op. cit.

the March 1-4, 1939 sequence it is not difficult to visualize the elimination of the problem introduced by the marked warming in western Canada closing that particular storm period. In addition, the period of March 22-24, 1926, might be cited as an example of marked strengthening of high pressure and cold air in western Canada. Significant warming and a Low with a central pressure lower than 995 mb on March 22 was replaced in 48 hours by a High with a central pressure greater than 1040 mb. In application to this hypo-sequence, in order that the March 1913 storm repeat itself, modifications would have to be made in the form of keeping the Pacific High oriented in a more or less north-south direction and of allowing a strengthening of high pressure and the extension of cold air southward from northwestern Canada. Without modification of the morning map for March 27, with regard to the cold front which drove clear across the Gulf, a minimum of three days would be necessary to bring back moisture of a flood-producing type.

For reasons given hereinafter, Hypo-Flood No. 24, as set up in this sequence, is meteorologically reasonable. Additional discussion of the March 1913 storm may be found in Hypo-Flood No. 21 and in chapter I, pages 5-6.

Analogues of synoptic sequences

Historical Weather Maps* for the months of February, March and April were searched for synoptic justification for Hypo-Flood No. 24. Essentially, this Hypo-Flood sequence calls for a quick repeat of a particular synoptic pattern which, in itself, is not meteorologically unreasonable in the light of empirical evidence of the important part played by the persistence or repeating of synoptic types in meteorological processes. The period of March 16-19, 1923, is a good example of a quick repetition of the over-all synoptic features covering the United States. In addition to being a good example of a repeating synoptic situation, both March 16 and March 19, 1923, might serve as reasonable analogues for the map of March 27, 1913. With the addition of a short period of time for minor adjustments, such as allowing the higher temperatures and dew points to make additional progress northward in the vicinity of the Mississippi Valley, the surface map for March 21, 1923, can be considered a substitute map for that of March 23, 1913. In the March 1923 instance, as in March 1913, a rather pronounced low-pressure system dissipated as it moved from the Plains States, thereby allowing the necessary quasi-stationary frontal setup to evolve. Actually, in 1923 no significant Low development on this frontal system took place. Nevertheless the necessary ingredients seem to be present, especially if it is assumed that the southern portion of the minor trough crossing the western portion of the country on March 22, 1923, were to become the activating mechanism for such a development when it reached the quasi-stationary front to the east. March 8, 1899, could be used as an analogue for March 27, 1913, with the primary modification consisting of the retention of high pressure in Northern Canada. The March 10, 1899, map, with modifications, can then be substituted for March 23, 1913.

*Daily Synoptic Series Historical Weather Maps, op. cit.

The search of March Historical Weather Maps* disclosed around ten additional instances which bore some resemblence to the synoptic situation for around midnight of March 26-27, 1913. However, in these other cases the necessary adjustments for use in this hypo-sequence were more severe than for the March 1923 case cited above. The feature in the March 1923 situation that is difficult to find in other cases is the pronounced Low which dissipates in the Plains enabling the establishment of a quasi-stationary frontal situation. The following through of other features in some of these examples is sufficiently similar to the March 1913 case to lend added support to the reasonableness of Hypo-Flood No. 24.

Historical analogues for transition from well-developed Low to a quasi-stationary front

The maps for February 11-13, 1949, show a situation in which a pronounced northeastward-moving Low off the Atlantic Coast and another intense Low with central pressure of less than 995 mb in the Northern Plains evolve into a northeast-southwest oriented quasi-stationary frontal situation. On January 20-21, 1937, a very-rapidly-developing situation in which the pressure dropped about 50 mb in 24 hours southeast of James Bay, evolved in just 24 hours more into a northeast-southwest oriented quasi-stationary frontal situation. Another example is found in April 1931. Here an East Coast Low, with marked northward motion on April 1-2, evolved by April 4 into a quasi-stationary front oriented southwest-northeast across the Middle Atlantic States. The developing Low which brought the March 1913 storm to its end was not as extreme a development as the unusual northward-moving type in April 1931.

Thus there is empirical support for a synoptic situation in which quite pronounced high-and low-pressure developments in the United States give way, or evolve, in a relatively short period of time into a quasi-stationary front oriented southwest-northeast.

Transposition of center at Bellefontaine, Ohio, to Athens, Ohio and barrier depletion

The transposition of the Bellefontaine, Ohio, center in this hypo-sequence is sufficiently similar to the transposition of the same rainfall center in Hypo-Flood No. 21 so that the same conclusions apply, namely, that it is a reasonable transposition, provided that the necessary depletion for barrier is made. In addition to the support for reasonableness given in Hypo-Flood No. 21, the storm of March 12-15, 1918 (OR 3-10) might be mentioned. This storm is placed in classification I (quasi-stationary front) in Hydrometeorological Report No. 2**, and in this particular storm the

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*Daily Synoptic Series Historical Weather Maps, op. cit.

**Hydrometeorological Report No. 2, op. cit.

rainfall center is southeast of Bellefontaine, Ohio, at Charleston, West Virginia. It is equally plausible, therefore, for such a storm to occur so that the rainfall center will be near Athens, Ohio.

Computation of the barrier depletion for moisture intercepted by the mountains for the transposed storm were made in accordance with the procedure outlined in Hypo-Flood No. 21, resulting in the following values for barrier depletion (or more correctly the percentage of moisture remaining):

Zone 1 = 0.95
Zone 2 = 0.91
Zone 3 = 0.86
Zone 4 = 0.82

Figure 2-1 is also applicable to this hypo-sequence.

Surface weather maps

Figures 2-7 and 2-8 pages 66 and 67 show the actual and hypothetical surface weather maps derived for this sequence.

HYPO-FLOOD NO. 20

Storms in sequence

Hypo-Flood No. 20 combines two March storms--SA 1-27 of March 16-18, 1936, followed after three intervening rainless days by OR 1-7 of March 12-15, 1907. The 1936 storm occurs in place, while in the 1907 storm the isohyetal center which occurred at Clarington, Ohio is transposed approximately 150 miles to the northeast. Data sheet 8, page 51 pertains to this sequence. The March 1936 storm is discussed on pages 6-7 and the March 1907 storm on pages 7-8 of chapter I.

Historical analogues to combination of two storms

One rather good analogue was found in the search of historical maps. This was in April 1929 with the map for April 17 being substituted as an analogue for March 18, 1936. An important feature that was maintained in the April 1929 case was the slower-than-normal motion of the primary Low. April 20, 1929 then becomes a fairly good analogue for March 12, 1907, and the 1929 situation follows through in a manner quite similar to the March 1907 storm. Both cases, although approaching a quasi-stationary front set-up, exhibit continued eastward translation of the systems in spite of some wave development. Warm moist air appears readily available in April 1929 as was the case in March 1907. In April 1929 the Hudson Bay High was more prominent, effectively blocking the wave development, but such a differing feature is to be expected in April and does not represent a serious problem.

Some additional support for the reasonableness of Hypo-Flood No. 20 is found in a synoptic situation in February 1953, in which February 15, 1953, is substituted for March 18, 1936, and, then, by postulating a more rapid motion in the ensuing 24 hours, the map for March 19, 1936, closely resembles that of February 16, 1953. Actually, in 1936, between March 18 and 19, the Low moved less than half normal speed for that season and location*, while at the same time the similarly - located Low on February 15, 1953, moved at a greater-than-average speed. Simultaneously, with a more rapid withdrawal of the March 1936 Low, we would postulate the development of high pressure in the Northern Plains (more in line with what occurred in February 1953) making it easier to go into the March 1907 sequence. March 12, 1907, is then substituted for February 18, 1953. Since the return flow of moisture was slow, in February 1953, some additional time may be necessary to allow for this.

A distracting feature is that the February 1953 situation does not follow through with the desired quasi-stationary front pattern. However, in spite of this, and also in spite of the fact that a more logical sequence results from the high index situation following the low index, this hypo-sequence is nevertheless considered meteorologically reasonable.

Transposition synoptics

The transposition of the Clarington center in the March 1907 storm 150 miles to the northeast is predominately parallel to the Appalachians. In this type of synoptic situation, comprising a southwest-northeast front along which a wave develops, it is reasonable to have an isohyetal center concentrated 150 miles further to the northeast. There is no significant over-all effect on the general atmospheric circulation patterns when such a change of position of isohyetal center is made. A search of similar type storms in the region showed that the storm of June 15-18, 1920, produced a rainfall center near the area of transposition of this March 1907 storm. The transposition is considered meteorologically reasonable and, furthermore, the orographic control on the precipitation pattern is not changed significantly enough to require any barrier adjustments.

HYPO-FLOOD NO. 2

Storms in sequence

This hypo-sequence combines the January 1937 storm and the storm of January 7-11, 1930 (LMV 2-22). Data sheet 9, page 52 pertains to this

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*E. H. Bowie and R. H. Weightman, "Types of Storms of the United States and Their Average Movements", Monthly Weather Review Supplement, No. 1, November 1914.

sequence. The sequence, except for the transpositions and rotations, is the same as that designated as Hypo-Flood No. 2 in the Tennessee and Cumberland Basin Study* where the basic storm combination has already been declared meteorologically reasonable. The January 1937 storm is discussed on pages 4-5 and the January 1930 storm on pages 8-9 of chapter I.

Controlling synoptic features

It is of particular interest to this sequence that a survey of the January Historical Weather Maps** since 1899 showed that January 1930 and January 1937 were two of a total of only three Januarys in which persistent, well-above-normal pressure existed simultaneously in both the Atlantic and Pacific high-pressure regions. The criterion used in this survey was the existence of a closed isobar of 1035 mb or greater on three or more successive daily maps. The only other instance in which this criterion was simultaneously met in both the Atlantic and Pacific occurred in January 1950. The marked similarity in these departures from normal of the intensity of the Atlantic and Pacific high-pressure centers in January 1937 and January 1930 increases considerably the meteorological reasonableness of combining these two storms in a hypo-sequence, since the small-scale features follow through more easily when the large-scale features are similar. As can be seen by reference to these two storms, the above-normal pressure in the Atlantic is instrumental in providing a greater-than-normal transport of moisture into the eastern United States.

A survey of cases of persistent above-normal pressures in the eastern Pacific showed that under these conditions there seems to be a much greater probability for the High cell to be oriented north-south than east-west. Of 22 instances of persistent well-above-normal pressure in the eastern Pacific, 16 cases had a definite north-south orientation while of the remaining cases three had a north-south orientation part of the time. Such north-south orientation is associated with greater meridional amplitude of the associated ridge aloft which, in turn, favors an import of cold air masses into the western portion of the country. This was obviously true in both the January 1937 and January 1930 storms when surface temperatures well below 0°F invaded the country from Canada. The similarity in the over-all controlling synoptic features thus is largely instrumental in making reasonable the hypothetical combination of these two January storms.

Transposition of January 1930 storm

The transposition of the Brownsville, Tenn., center 175 miles to the northeast is meteorologically reasonable. First, the transposition parallels the Appalachians so that no orographic complications are introduced.

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*Lower Cumberland Reservoir Project, op. cit.

**Daily Synoptic Series Historical Weather Maps, op. cit.

The transposition just brings the eastern extension of the isohyetal pattern into the 1000 to 1500-ft elevations and for this reason adjustments for barrier depletion are not considered necessary. Furthermore, isohyetal patterns associated with the quasi-stationary frontal type situation have been observed near the transposed position. A search of "Storm Rainfall in the United States*" disclosed several instances of similar isohyetal patterns centered closer to the transposed position. Actually, the 1937 storm had a secondary center close to the desired area of transposition of the 1930 storm. In addition, the storm of January 21-24, 1920 (OR 6-23) produced an isohyetal center close to the transposed 1930 position.

Although the frequency of occurrence of tropical air diminishes markedly with northward displacement in January, the 175-mile transposition northeastward in this hypo-sequence does not present any serious difficulty in this respect since tropical air is occasionally found northward to the Canadian border. The necessity of the quasi-stationary front being at a position further to the east is also meteorologically reasonable. Although the time transposition in this sequence is more than three weeks, nevertheless, it is justified since rainfall occurrences of the type in this January 1930 storm might certainly occur with equal reasonableness at least as late as the first week in February.

Conclusion

The changed transpositions and rotations in this Ohio River Hypo-Flood No. 2 from that of Hypo-Flood No. 2 of the Tennessee and Cumberland Basin Study** do not alter the meteorological reasonableness of the sequence. This hypo-sequence as set up on data sheet 9, page 52 is therefore meteorologically reasonable.

HYPO-FLOOD NO. 3

Storms in sequence

This hypo-sequence uses the heaviest rainfall period of the storm of January 1937 (OR 5-6) following the first portion of the February 1883 storm covering the period February 2-7. Data sheet 10, page 53 pertains to this sequence.The January 1937 storm is discussed on pages 4-5 and the February 1883 storm on page 9 of chapter I. For reasons presented hereinafter Hypo-Flood No. 3 is considered meteorologically reasonable.

*Corps of Engineers, Department of the Army, "Storm Rainfall in the United States". Washington, D. C. 1945.

**Lower Cumberland Reservoir Project, op. cit.

Large-scale weather similarities and hypothetic sequence of maps

In February 1883 the second period of rain occurred about 3-3/4 days following the ending of the initial period of rain which was used in this hypo-sequence. In addition, the center of rainfall was quite near to the heaviest portion of the 1937 rain used in this sequence. This is not surprising, in the light of the similarity of the prevailing weather patterns over the eastern United States in the two storms, particularly the persistent trough aloft. The rainfall burst of February 6, 1883, is comparable to that of January 17, 1937. Since a subsequent significant burst followed that of January 17 in somewhat less than three days, a three-day interval between February 7, 1883, and January 20, 1937, is not unreasonable, especially in considering the over-all synoptic similarity of the two situations. The fact that the main High following the rain of February 6, 1883, pushed somewhat further south than that of January 18-19, 1937, is allowed for by increasing the interval slightly to a full three days (as compared to an interval of less than three days in January 1937).

A tabulation of once-a-day pressure at Jacksonville, Fla., for the period of the February 1883 rain showed an average value of around 1024 mb which, like the 1937 storm, is apparently indicative of well-above-normal pressure in the Bermuda High. A seemingly distracting feature of the 1937 storm is the unusually high pressure present (with a closed isobar of 1050 mb.) northeast of the Great Lakes on January 20. However, the unusual magnitude of this barometric reading is evidently a transitory feature since prior to and following the January 20 map with the high pressure a closed 1035-mb isobar was the highest pressure indicated. The High of peak central pressure of about 1040 mb in February 1883 therefore represents rather good agreement. Sharp temperature contrast is also apparent in both storms in this sequence, with morning temperatures just after the February 2-7, 1883 period and just prior to the January 20-25, 1937 period ranging roughly from the 60's in the extreme southeast to around 20°F. below zero near the Canadian border west of the Great Lakes. These similarities all lend support to the meteorological reasonableness of this hypo-sequence.

The following modifications of the 1883 synoptic picture are deemed necessary for a sequence evolving into that of January 20, 1937. The trough which moved eastward near the Canadian border following the rain period of February 1883 used in this study should be considered modified to the extent of having an extension into the more southerly latitudes, perhaps resembling the situation of January 17, 1937. The southernmost portion of this impulse then follows through in line with January 19. A weak trough of low pressure is in evidence in western Arizona on the map for February 7, 1883. For the situation to evolve into something resembling that for January 20, 1937, it is only necessary for an impulse from the northwest to activate this disturbance, with the resulting Low moving into eastern New Mexico. This would produce a situation resembling that of January 20, 1937. With the residual front remaining near the Gulf during the evolvement of this pattern, a readily available supply of moisture for the ensuing development is assured. It is thus reasonable for the residual front in the vicinity of the Gulf to remain inactive until the necessary umpulse arrives from the west to result in cyclogenesis.

The prolonged persistence of prevailing synoptic features in January 1937 similar to those of the February 1883 storm lends additional support to the hypothetical combination of portions of the two storms.

Transposition in time

Synoptic features of the portion of the February 1883 and January 1937 storms used in this hypo-sequence are equally likely in the latter portion of January or the first part of February so that the 10- to 12-day time transpositions made in this sequence are meteorologically reasonable.

HYPO-FLOOD NO. 4

Storms in sequence

This hypo-sequence is made up of two January storms. The storm of January 1-3, 1907 (LMV 1-5) is followed after three intervening days by that of January 10-11, 1913 (LMV 1-9). Data sheet 11, page 54 pertains to this sequence. The January 1907 storm is discussed on page 9 and the January 1913 storm on pages 9-10 of chapter I.

For reasons presented hereinafter, Hypo-Flood No. 4 with its 3-day interval is considered meteorologically reasonable when allowance is made for some modification of the weather charts at the end of LMV 1-5. The sweep of drier air across the Gulf on January 4, 1907, was not as pronounced as that in 1913 prior to the rains that began on January 10. This in itself lends support to the reasonableness of this sequence, at least from the point of view of the return of a flow of moist air from the Gulf of Mexico. Following January 3, 1907 and also prior to January 10, 1913, the Atlantic subtropical anticyclone was reinforced by a large migratory high cell from the United States, making such a migratory High a common feature of both storm periods.

Justification of sequence through historical analogues and similar features

Some of the best justifications for the reasonableness of this sequence may be found, first, in what actually occurred following the heavy rain of the January 1907 storm. In addition, the similarity of synoptic features would make it a rather simple matter to follow through with a 3-day interval in this sequence except for the fact that the migratory High in the 1907 storm is primarily of Pacific origin as contrasted with modifying polar air existing on January 10, 1913. It is necessary to substitute a migratory High of primarily polar origin so that the temperature contrast displayed in the January 1910 storm might be maintained. With this basic modification of the January 1907 storm and with other slight alterations the reasonable 3-day interval can be used in setting up this hypothetical sequence. The map for January 3, 1907 might then be the one where a modification is made by giving more prominence to the polar High cell in the Northern Plains similar to what actually occurred on January 8, 1907.

A survey of the broader scale synoptic features showed that the prevailing pressure over western Canada was considerably higher in January 1907 than in January 1913. However, during the storm period that concerns us in January 1913 higher pressure did prevail over western Canada thus tempering somewhat this otherwise distracting contrast in synoptic features.

Another feature which favors the combining of the 1907 and 1913 storms is the striking similarity in the isohyetal patterns. This can easily be seen by reference to the S-2 forms of "Storm Rainfall in the United States*". The storm of January 5-24, 1937 (OR 5-6) might be mentioned as one which showed a repetition of rainfall bursts over the same region, lending support to the reasonableness of combining two storms that have similar concentrations of precipitation, thus implying the persistence or repetition of synoptic type.

Transposition precipitation experience and synoptics

The transpositions of these two storms are to the foothills of the Appalachians, a region of somewhat lesser storm potential of the type giving isohyetal patterns elongated southwest-to-northeast. However, a search of "Storm Rainfall in the United States*" for colder season storms disclosed several comparable storms with isohyetal centers closer to the transposed regions. First might be mentioned the January 1913 storm itself in which there was a center at Taylorsville, Ky., not too far west of the transposed position of the New Madrid center. The storm of January 21-24, 1920 (OR 6-23) was a longer duration storm, but 48-hour rainfall was comparable with a secondary center at Williamsburg, Ky. Other noteworthy storms in this region are those of December 4-8, 1924 (OR 4-18) with a center at Brownsville, Tenn.; Oct. 30-Nov. 1, 1919 (LMV 1-13B) with centers in Kentucky; and March 21-23, 1929 (OR 7-15) with an isohyetal center at Rock Island, Tenn.

The synoptic features conducive to rainfall in the January 1913 storm, for example, a large supply of moist unstable air, a weak depression imbedded in the moist flow, and the arrival of a cold front to provide the lifting and convergence to accentuate the rainfall, are all features that could reasonably combine so as to produce flood-producing rain in the transposed areas. Likewise, the convergence-producing, rain-intensifying characteristic of the wave action along a quasi-stationary front in the January 1907 storm is a feature that can just as readily operate at the transposed position in Ohio. The rotations of these isohyetal patterns are sufficiently minor to be considered reasonable a priori.

*"Storm Rainfall in the United States", op. cit.

Moisture depletion for barrier

Since transposition of the New Madrid center carries the rainfall pattern into the Appalachians moisture depletion for the upwind barrier is required. The method used in computing the moisture depletion for the upwind barrier is outlined in Hypo-Flood No. 21. Application of this procedure results in the following reduction values.

Zone 1 = 0.90
Zone 2 = 0.86
Zone 3 = 0.81
Zone 4 = 0.80

HYPO-FLOOD NO. 50

Storms in sequence

This sequence consists of two actual rain periods as they occurred in May 1943, but the isohyetal centers are transposed and rotated. The Lowell, Kan., center used in this sequence was close to the magnitude of the primary center in SW 2-21 at Mounds, Okla. In SW 2-20 most of the rain in the region of interest was over by 6 p.m. CST on May 10. In SW 2-21 rain prior to 6 p.m. CST on May 15 was rather insignificant. Data sheet 12, page 55 pertains to this sequence. The two storms used in this hypo-sequence are discussed jointly in chapter I, page 10.

These two storms have been used in other hypothetical flood sequences for other basins. Hypo-sequence No. 50 is essentially the same as Hypo-Flood No. 30 of the Tennessee and Cumberland Basin Study*. In this same Cumberland Report other sequences in which SW 2-20 has been used are Hypo-Flood No. 21, following the March 23-26, 1913 storm (OR 1-15) and Hypo-Flood No. 31, following the April 15-18, 1900 storm (LMV 2-5) after two rainless days. In the hypothetical late spring flood, in Hydrometeorological Report No. 35** these two May 1943 storms are used in reverse order following the storm of April 12-16, 1927 (LMV 4-8). Three intervening days are placed between SW 2-21 and SW 2-20.

For reasons presented hereinafter, the transpositions in this sequence are reasonable and therefore the sequence is reasonable. This reduction in interval means that there are then approximately 2-1/2 days between significant rains. Such a shortening of the interval does not alter the adjustment factors as given on data sheet 12.

Modification of storm features

Dew points in the high sixties were still prevalent along the Texas Gulf Coast on May 12, 1943. For the return of heavy rain it becomes necessary to postulate the reoccurrence of a significant northward motion of a

*Lower Cumberland Reservoir Project, op. cit.

**Hydrometeorological Report No. 35, op. cit.

moisture-laden layer of air so that the moisture can be transported to, and precipitated in, the desired area.

During the period May 13-15, 1943 the main surface Low in the western portion of the United States was in a disorganized state until it was picked up by a trough aloft on May 15. Subsequent deepening of the surface Low along a northeastward track followed. With the high dew points previously poised within striking distance, it is reasonable to assume that significant rain could have readily begun a full day prior to its actual occurrence on May 15. This applies to the transposed position. Such an alteration would reduce the interval between rains to 2-1/2 days. The earlier arrival of a significant trough from the west is the primary synoptic change required to reduce the interval since the moisture remains readily available. The pressure fell significantly on May 11-12 over the Southeast and must be postulated to increase again (or at least the flow directed from the South must increase) to give the necessary inflow of moisture. The changes on the surface charts for May 14-15 show how quickly it is possible for the development of a pressure gradient to bring Gulf moisture northward. An approaching trough from the West with its associated large pressure falls was the mechanism for this increase.

Recurrence data

In a study by Malkin* of recurrence intervals of significant Lows (with a central pressure of 1000 mb or less) for the months of January and April, a tabulation of 25 years' data showed four cases in April with intervals of less than five days in the vicinity of the transposed location of the May storms. There was one case of a 3-day interval in April 1937. This contrasted with a number of cases with intervals of less than 3 days in the vicinity of the actual storm occurrences of May 1943. The relative frequency of significant Lows themselves in these two regions may be the controlling factor. In any case, these figures demonstrate the greater likelihood of a shorter interval between storms at the place of occurrence of the May 1943 storms but at the same time they show that intervals at least as short as 3 days are possible at the transposed position.

In addition, a survey of the 500-mb Historical Weather Map Series for the months of April and May showed that slowly moving or nearly stationary closed Lows at 500 mb are considerably more frequent in the place of occurrence of these May storms than further east near the transposed positions. Considering, however, that many factors other than the reoccurrence of low-pressure disturbances go into the production of significant rain, support for shortening the interval in this sequence might be found in the historical occurrences of significant isohyetal patterns in the general area of transposition. A survey of 24-hour precipitation maps for April and May for ten recent years showed 3 or 4 instances of significant rain repeating within about 3 days in the Tennessee area.

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*William Malkin, "Some Methods for Estimating Minimum Time Intervals Between Successive Depressions", Hydrometeorological Section, U. S. Weather Bureau, February 1956. (Unpublished.)

Meteorological discussion of transpositions

Current opinion is that the region of transposition of the May 6-12, 1943 storm must be considered the easternmost permissible limit. The transposition to Old Hickory Dam has already been declared meteorologically reasonable in Hypo-Flood No. 30 in the Tennessee and Cumberland Basin Study*. The small rotation of 5° is reasonable a priori. The over-all shape of the isohyetal pattern in both of these May storms is the southwest-to-northeast elongated pattern commonly associated with undulating quasi-stationary fronts (usually associated with colder-season storms). Such quasi-stationary fronts giving elongated precipitation patterns can occur over most portions of the United States. The "broadening out" of the precipitation pattern, brought about by the superposition of a deep layer of winds with pronounced components from the south (most marked with closed circulations aloft), is also a feature that is not particularly limited, although persistence of such a feature would very likely have significant regional variations.

The isohyetal patterns of these storms should not be transposed substantially into the Appalachians and the portion of the pattern that is intercepted by the mountains should be adjusted for lower level moisture depleted by the intervening barrier.

A search of "Storm Rainfall in the United States**" discloses other storms which produced similar isohyetal patterns nearer the areas of transposition. Among these might be mentioned the May 9-13, 1918 storm (LMV 1-11) which was of a similar synoptic type but occurred nearer the area of transposition, the storm of April 12-15, 1911 (LMV 1-8) with a secondary center at Jackson, Tenn., and the storm of June 1-5, 1928 (LMV 2-18) in which a center greater than fifteen inches occurred south of the transposed position.

Depletion for barrier

Transposition of the May 1943 storms require barrier depletion computations for those portions of the isohyetal patterns transposed into the more mountainous portions of the Appalachians. The method for determining the depletion due to barrier is that which is outlined in Hypo-Flood No. 21. For the transposed Warner, Okla. center in the storm of May 6-12, 1943, the computed barrier reduction values are as follows for the four zones outlined on figure 2-1. The representative 12-hour dew point used in these computations was 70°.

Zone 1 = 1.00
Zone 2 = 0.93
Zone 3 = 0.85
Zone 4 = 0.80

*Lower Cumberland Reservoir Project, op. cit.

**Corps of Engineers, Department of the Army, op. cit.

A computation of the barrier depletion for the Lowell, Kans., center of SW 2-21, using the representative 12-hour dew point of 71°, gives the following barrier reduction values for the four zones.

Zone 1 = 0.98
Zone 2 = 0.96
Zone 3 = 0.91
Zone 4 = 0.86

HYPO-FLOOD NO. 40

Storms in sequence

This sequence combines the March 1913 storm (OR 1-15) with that of May 6-12, 1943 (SW 2-20) with three rainless days intervening. Except for the transpositions, this sequence of storms is the same as Hypo-Flood No. 21 in the Tennessee and Cumberland Basin Study*. Data sheet 13, page 56 pertains to this hypo-sequence. The March 1913 storm is discussed on pages 5-6 and the May 1943 storm on page 10 in chapter I.

Transposition of SW 2-20

The region near Louisville, Ky., to which the Warner, Okla., center in the May 6-12, 1943 storm is transposed is one of lesser storm potential. However, the storm type is sufficiently common to the Ohio Valley, so that the areal transposition may be considered reasonable. The transposition of the May 1943 storm in time is more than five weeks into the colder season; it can be considered reasonable to have a storm of the May 1943 type occur at this earlier date as long as the proper seasonal adjustments are made. The fact that this May 1943 storm had characteristics similar to cool season storms enhances the reasonableness of the transposition in time.

Depletion for lower-level moisture

The transposition takes a portion of the isohyetal pattern into the Appalachians. A check into the possible necessity of depletion of the rainfall for the lower-level moisture cut-off by the mountains indicated that in this case the effect was sufficiently minor to obviate any barrier-depletion adjustment.

Antecedent rainfall

It is recommended that the antecedent conditions for this storm be such that at least one full rainless day precede the beginning of OR 1-15. Using the March 1945 antecedent originally proposed for this sequence does not meet this requirement. The chief difficulty of using the March 1945 antecedent arises from the fact that a large dry air mass dominated the

*Lower Cumberland Reservoir Project, op. cit.

entire Ohio Valley region on March 22, 1913, whereas in 1945, March 29, 30 and 31 all require that the air in the region of concern be well modified in the form of substantial moisture content. Appropriate antecedents for this Hypo-Flood can be found in conditions existing prior to March 23, 1913 or March 28, 1945.

HYPO-FLOOD NO. 68

Pertinent storm data

Only one storm is used in Hypo-Flood No. 68, that of July 25-August 3, 1875 (OR 4-1). The only modification of the storm is transposition of the Kenton, Ohio, isohyetal center about 150 miles east to New Philadelphia, Ohio. Data sheet 14, page 57 pertains to Hypo-Flood No. 68. The 1875 storm is discussed in chapter I on pages 10-11.

Transposition of OR 4-1

For reasons presented hereinafter the transposition of the 1875 storm as proposed in this Hypo-Flood is reasonable, as long as proper adjustments are made for depletion of lower-level moisture. A search of "Storm Rainfall in the United States*" disclosed at least eight storms with similar isohyetal patterns centered roughly in the area of desired transposition. The designated storm periods in these examples extended from 48 hours to 132 hours. The storms giving isohyetal centers closest to the transposed position were those of August 25-30, 1903 (GL 1-9), June 15-18, 1920 (GL 1-18), June 14-18, 1912 (OR 8-16B) and August 6-7, 1935 (OR 9-11). The storm of August 25-30, 1903, was of quite similar synoptic type, having features in common with the 1875 storm, such as an east-west quasi-stationary front with waves and higher pressure and colder air to the north of the area of rainfall. In 126 hours this storm produced a 7.5-inch rainfall center at Strongsville, Ohio, quite near to the transposed site of New Philadelphia, Ohio. Such an example supports the reasonableness of the transposition of the 1875 storm some 150 miles eastward to New Philadelphia, Ohio.

Depletion for barrier

The transposition of this storm carries a portion of the isohyetal pattern into the Appalachian Mountains, thus requiring an adjustment for the lower-level moisture depleted by the mountains. Details of procedure for computing this orographic depletion may be found by reference to Hypo-Flood Study No. 21. The representative dew point used in the computations for the 1875 storm was 72°. The portion of the isohyetal pattern transposed into zone 4 is insignificant so that compilations for three zones only were required in this case and are as follows:

*"Storm Rainfall of the United States", op. cit.

Zone 1 = 0.97
Zone 2 = 0.93
Zone 3 = 0.86

HYPO-FLOOD NO. 90

Storms in sequence

This hypothetical sequence combines the October 3-6, 1910 storm (OR 4-8) and the storm of October 2-7, 1941 (UMV 3-20) with three rainless days intervening. OR 4-8, centered at Golconda, Ill., is transposed to Bellefontaine, Ohio and UMV 3-20 centered at Galesburg, Ill., to Edmonton, Ky. The 1910 storm terminated with the flow of dry Canadian air over the area, which subsequently reached to the southern Gulf of Mexico. Both the October 1910 and October 1941 storms are discussed on page 11 of chapter I. Data sheet 15, page 58 pertains to this sequence.

The limiting factor on the time interval between these two storms is the time required to reestablish a vigorous moist flow from the south. Historical analogues show that this can take place in three days (rain on the fourth). The problem therefore in this sequence is to justify a necessary deep flow of moisture northward into the Gulf States within three days after the area was dominated by a dry northern air mass. For reasons presented hereinafter, this transition is considered meteorologically reasonable.

Historical analogues to hypo-sequence

Precedent for the transition postulated has been found in historical weather maps for October. The series of October 27-31, 1920 is a reasonably good analogue considering minor adjustments such as displacement of the High cell further to the southeast allowing the moisture to come in from a more easterly point. Other examples are October 12-16, 1946 (with a weaker inflow) and October 9-12, 1925.

Transposition and precipitation experience

The transposition of these two storms are to regions of somewhat lesser storm potential than where they occurred. However, the elongated northeast-southwest isohyetal patterns of the storms have been observed in central Ohio and Kentucky numerous times. Neither of the transpositions in this sequence brings the isohyetal pattern sufficiently into the foothills of the Appalachians to require a depletion for lower level moisture.

DATA SHEETS FOR HYPO-FLOOD SEQUENCES

On pages 44-58 are data sheets for the 15 meteorologically acceptable Ohio River Hypo-Flood sequences in the order in which the sequences are discussed in the text. No data sheet is shown for the rejected sequence referred to in the text as Hypo-Flood No. 22. In addition to a portrayal of the sequences as used the data sheets show data relating to storm transposition, storm maximization adjustments and antecedent conditions.

Data Sheet 1

OHIO RIVER PROJECT FLOOD STUDY

HYPO-FLOOD NO. 1

Ohio River Above Metropolis

Hypo-Flood Date	Effective Storm Dates and Assignment Nos. OR 5-6 5-24 Jan 1937	3-16 Jan 1950
5 Jan	5 Jan 1937	
.	.	
.	.	
.	.	
24	24	
25		
26		
27		
28		
29		3 Jan 1950
30		4
31		5
1 Feb		6
.		.
.		.
.		.
11		16 Jan 1950
Transpose to:	Transpose center at McKenzie, Tenn. (240 mi. ENE) to Little Hickman, Ky. No rotation	No transposition No rotation
Adjustments		
A. Geographical relocation	100%	100%
B. Seasonal	100%	101%
C. Maximization	110%	115%
Total Adjustments		
A x B	100%	101%
A x B x C	110%	116%

Antecedent prior to Jan. 5, 1937.

Data Sheet 2

OHIO RIVER PROJECT FLOOD STUDY

HYPO-FLOOD NO. 21

Ohio River Above Wheeling to Golconda

Hypo-Flood Date	Effective Storm Dates and Assignment Nos.	
	OR 1-15 23-26 March 1913	UMV 2-4 24-26 March 1904
23 March	23 March 1913	
24	24	
25	25	
26	26	
27		
28		
29		24 March 1904
30		25
31		26
1 Apr		
Transpose to:	Transpose center at Bellefontaine, Ohio 158 mi. E and 43 mi. S. No rotation (Approved previously by Hydrometeorological Report No. 2)	Transpose center at Washington, Ind. 200 mi. ENE. No rotation
Adjustments:		
A. Geographical	102%*	94%
B. Seasonal	100%	100%
C. Maximization	117%	154%
Total Adjustments		
A x B	102%*	94%
A x B x C	119%*	145%

*A barrier depletion adjustment is made to southeast portion of transposed storm in addition to these adjustments. See text.

Antecedent prior to March 23, 1913.

Data Sheet 3

OHIO RIVER PROJECT FLOOD STUDY

HYPO-FLOOD NO. 23

Ohio River Above Louisville and Metropolis

Hypo-Flood Date	Effective Storm Dates and Assignment Nos. OR 1-15 23-26 March 1913	UMV 2-4 24-26 March 1904
23 March	23 March 1913	
24	24	
25	25	
26	26 (Use rain through	
27	6 p.m.)	
28		
29		24 March (Use rain after
30		25 6 p.m.)
31		26
Transpose to:	No transposition No rotation	Transpose Washington, Ind., center ESE to Hazard, Ky. No rotation
Adjustments:		
A. Geographical relocation	100%	104%*
B. Seasonal	100%	99%
C. Maximization	117%	154%
Total Adjustments		
A x B	100%	103%*
A x B x C	117%	158%*

*A barrier depletion adjustment is made. See text.

Antecedent prior to March 28, 1945.

Data Sheet 4

OHIO RIVER PROJECT FLOOD STUDY

HYPO-FLOOD NO. 22-A

Ohio River Above Louisville and Golconda

Hypo-Flood Date	Effective Storm Dates and Assignment Nos.	
	SA 1-27 16-18 March 1936	SA 1-27 16-18 March 1936
16 March	16 March 1936	
17	17	
18	18 (noon)	
19		
20		
21		16 March 1936 (noon)
22		17
23		18
Transpose to:	No transposition No rotation	No transposition No rotation
Adjustments:		
A. Geographical relocation	100%	100%
B. Seasonal	100%	101%
C. Maximization	151%	151%
Total Adjustments		
A x B	100%	101%
A x B x C	151%	152%

Antecedent conditions and snow cover of March 9, 1936 occurring on March 15th of Hypo-Flood date.

Data Sheet 5

OHIO RIVER PROJECT FLOOD STUDY

HYPO-FLOOD NO. 30

Ohio River Above Wheeling

Hypo-Flood Date	Effective Storm Dates and Assignment Nos.	
	SA 1-27 16-18 March 1936	SA 5-13 25-28 April 1937
30 March	16 March 1936	
31	17	
1 April	18	
2		
3		
4		
5		25 April 1937
6		26
7		27
8		28
9		29
Transpose to:	Transpose storm approx. 85 miles W-NW. No rotation	Transpose storm approx. 135 miles NW. No rotation
Adjustments:		
A. Geographical relocation	98%*	91%*
B. Seasonal	103%	104%
C. Maximization	151%	158%
Total Adjustments		
A x B	100%*	95%*
A x B x C	151%*	150%*

*A barrier depletion adjustment is made. See text.

Antecedent prior to March 16, 1936.

Data Sheet 6

OHIO RIVER PROJECT FLOOD STUDY

HYPO-FLOOD NO. 22-B

Ohio River Above Cincinnati

Hypo-Flood Date	Effective Storm Dates and Assignment Nos. SA 1-27 16-18 March 1936	SA 1-27 16-18 March 1936
16 March	16 March 1936	
17	17	
18	18 (Noon)	
19		
20		
21		16 March 1936 (Noon)
22		17
23		18
Transpose to:	No transposition No rotation	Transposed 100 miles West and 40 miles South No rotation
Adjustments		
A. Geographical relocation	100%	105%*
B. Seasonal	100%	103%
C. Maximization	151%	150%
Total Adjustments		
A x B	100%	108%*
A x B x C	151%	162%*

*A barrier depletion adjustment is made. See text.

Antecedent conditions and snow cover of March 9, 1936 occurring on March 15th of Hypo-Flood date.

Data Sheet 7

OHIO RIVER PROJECT FLOOD STUDY

HYPO-FLOOD NO. 24

Ohio River Above Metropolis

Hypo-Flood Date	Effective Storm Dates and Assignment Nos.	
	OR 1-15 23-26 March 1913	OR 1-15 23-27 March 1913
23 March	23 March 1913	
24	24	
25	25	
26	26 (Use rain through midnight)	
27		
28		
29		
30		24 March 1913 (Use all rain on 24th)
31		25
1 April		26
2		27
Transpose to:	No transposition No rotation	Transpose Bellefontaine, Ohio center to Athens, Ohio. Storm pattern rotated 7 degrees counter-clockwise
<u>Adjustments</u>:		
A. Geographical relocation	100%	105%*
B. Seasonal	100%	100%
C. Maximization	117%	117%
<u>Total Adjustments</u>		
A x B	100%	105%*
A x B x C	117%	123%*

*A barrier depletion adjustment is made. See text.

Antecedent prior to March 23, 1913.

Data Sheet 8

OHIO RIVER PROJECT FLOOD STUDY

HYPO-FLOOD NO. 20

Ohio River Above Wheeling

Effective Storm Dates and Assignment Nos.

Hypo-Flood Date	SA 1-27 16-19 March 1936	OR 1-7 12-14 March 1907
16 March	16 March 1936	
17	17	
18	18 (Do not use last six hours rainfall from 1800E to 2400E)	
19		
20		
21		12 March 1907 (Use only rainfall after 1800E of 12th)
22		13
23		14
24		15
Transpose to:	No transposition No rotation	Transpose storm center at Clarington, Ohio 150 mi NE. Rotate 6 degrees counterclockwise
Adjustments:		
A. Geographical relocation	100%	92%
B. Seasonal	100%	96%
C. Maximization	151%	136%
Total Adjustments		
A x B	100%	97%
A x B x C	151%	119%

Antecedent prior to March 16, 1936.

Data Sheet 9

OHIO RIVER PROJECT FLOOD STUDY

HYPO-FLOOD NO. 2

Ohio River Above Metropolis

Hypo-Flood Date	Effective Storm Dates and Assignment Nos. OR 5-6 5-24 Jan 1937	LMV 2-22 7-11 Jan 1930
5 Jan	5 Jan 1937	
6	6	
.	.	
.	.	
.	.	
24	24 Jan 1937	
25		
26		
27		
28		
29		7 Jan 1930
30		8
31		9
1 Feb		10
2		11
3		
Transpose to:	No transposition No rotation	Transpose center at Brownsville, Tenn., 175 mi NE. No rotation
Adjustments:		
A. Geographical relocation	100%	91%
B. Seasonal	100%	102%
C. Maximization	107%	158%
Total Adjustments		
A x B	100%	93%
A x B x C	107%	145%

Antecedent prior to Jan. 5, 1937.

Data Sheet 10

OHIO RIVER PROJECT FLOOD STUDY

HYPO-FLOOD NO. 3

Ohio River Above Cincinnati and Louisville

Hypo-Flood Date	Effective Storm Dates and Assignment Nos. OR 5-11 2-9 Feb 1883	OR 5-6 20-25 Jan 1937
20 Jan	2 Feb 1883	
21	3	
22	4	
23	5	
24	6	
25	7	
26		
27		
28		
29		20 Jan 1937
30		21
31		22
1 Feb		23
2		24
3		25
Transpose to:	No transposition No rotation	No transposition No rotation
Adjustments:		
A. Geographical relocation	100%	100%
B. Seasonal	100%	99%
C. Maximization	130%	107%
Total Adjustments		
A x B	100%	99%
A x B x C	130%	106%

Use antecedent flow prior to Jan. 5, 1937 with Jan. 5, 1937 occurring Jan. 19th in Hypo-Flood date.

Data Sheet 11

OHIO RIVER PROJECT FLOOD STUDY

HYPO-FLOOD NO. 4

Ohio River Above Metropolis

Hypo-Flood Date	Effective Storm Dates and Assignment Nos. LMV 1-5 1-3 Jan 1907	LMV 1-9 10-11 Jan 1913
1 Jan	1 Jan 1907	
2	2	
3	3	
4		
5		
6		
7		10 Jan 1913
8		11
Transpose to:	Transpose Marion, Ky. center to Columbus, Ohio and rotate 10 degrees clockwise	Transpose New Madrid, Mo. center to Saylersville, Ky., and rotate 4 degrees clockwise
Adjustments:		
A. Geographical relocation	80%	93%*
B. Seasonal	100%	99%
C. Maximization	113%	129%
Total Adjustments		
A x B	80%	92%*
A x B x C	91%	119%*

*A barrier depletion adjustment is made for portion of isohyetal pattern transposed into mountains. See text.

Antecedent conditions prior to January 1, 1907.

Data Sheet 12

OHIO RIVER PROJECT FLOOD STUDY

HYPO-FLOOD NO. 50

Ohio River Above Metropolis

Hypo-Flood Date	Effective Storm Dates and Assignment Nos. SW 2-20 6-12 May 1943	SW 2-21 15-20 May 1943
6 May	6 May 1943	
7	7	
8	8	
9	9	
10	10	
11	11	
12		
13		
14		
15		15 May 1943
16		16
17		17
18		18
19		19
20		20
Transpose to:	Transpose Warner, Okla. center to Old Hickory Dam, Tenn. Rotate 5 degrees clockwise	Transpose Lowell, Kan. center to Nashville, Tenn. Rotate 5 degrees counterclockwise
Adjustments:		
A. Geographical relocation	95%*	101%*
B. Seasonal	100%	100%
C. Maximization	132%	121%
Total Adjustments		
A x B	95%*	101%*
A x B x C	125%*	121%*

Antecedent prior to May 5, 1943

*A barrier depletion adjustment is made. See text.

Data Sheet 13

OHIO RIVER PROJECT FLOOD STUDY

HYPO-FLOOD NO. 40

Ohio River Above Louisville and Golconda

Hypo-Flood Date	Effective Storm Dates and Assignment Nos. OR 1-15 23-26 March 1913	SW 2-20 6-12 May 1943
23 March	23 March 1913	
24	24	
25	25	
26	26	
27		
28		
29		
30		6 May 1943
31		7
1 April		8
2		9
3		10
4		11
5		12
Transpose to:	No transposition No rotation	Transpose Warner, Okla. center to vicinity of Louisville, Ky. No rotation
Adjustments:		
A. Geographical relocation	100%	90%
B. Seasonal	100%	121%
C. Maximization	117%	132%
Total Adjustments		
A x B	100%	109%
A x B x C	117%	144%

For antecedent conditions, see text.

Data Sheet 14

OHIO RIVER PROJECT FLOOD STUDY

HYPO-FLOOD NO. 68

Ohio River Above Louisville

Hypo-Flood Date	Effective Storm Dates and Assignment No. OR 4-1 25 July-3 August 1875
25 July	25 July 1875
26	26
27	27
28	28
29	29
30	30
31	31
1 Aug	1 Aug
2	2
3	3

Transpose to: Transpose center at Kenton, Ohio, Approx. 150 miles eastward to New Philadelphia, Ohio. No rotation

Adjustments:

A. Geographical relocation	98%*
B. Seasonal	100%
C. Maximization	129%

Total Adjustments

A x B	98%*
A x B x C	127%*

*A barrier depletion adjustment is made. See text.

Data Sheet 15

OHIO RIVER PROJECT FLOOD STUDY

HYPO-FLOOD NO. 90

Ohio River Above Metropolis

Hypo-Flood Date	Effective Storm Dates and Assignment Nos. OR 4-8 3-6 Oct 1910	UMV 3-20 2-7 Oct 1941
3 Oct	3 Oct 1910	
4	4	
5	5	
6	6	
7		
8		
9		
10		2 Oct 1941
11		3
12		4
13		5
14		6
15		7
Transpose to:	Transpose Golconda, Ill. center to Bellefontaine, Ohio, and rotate 10 degrees clockwise	Transpose Galesburg, Ill. center to Edmonton, Ky. No rotation
Adjustments:		
A. Geographical relocation	90%	105%
B. Seasonal	100%	105%
C. Maximization	113%	124%
Total Adjustments		
A x B	90%	110%
A x B x C	102%	137%

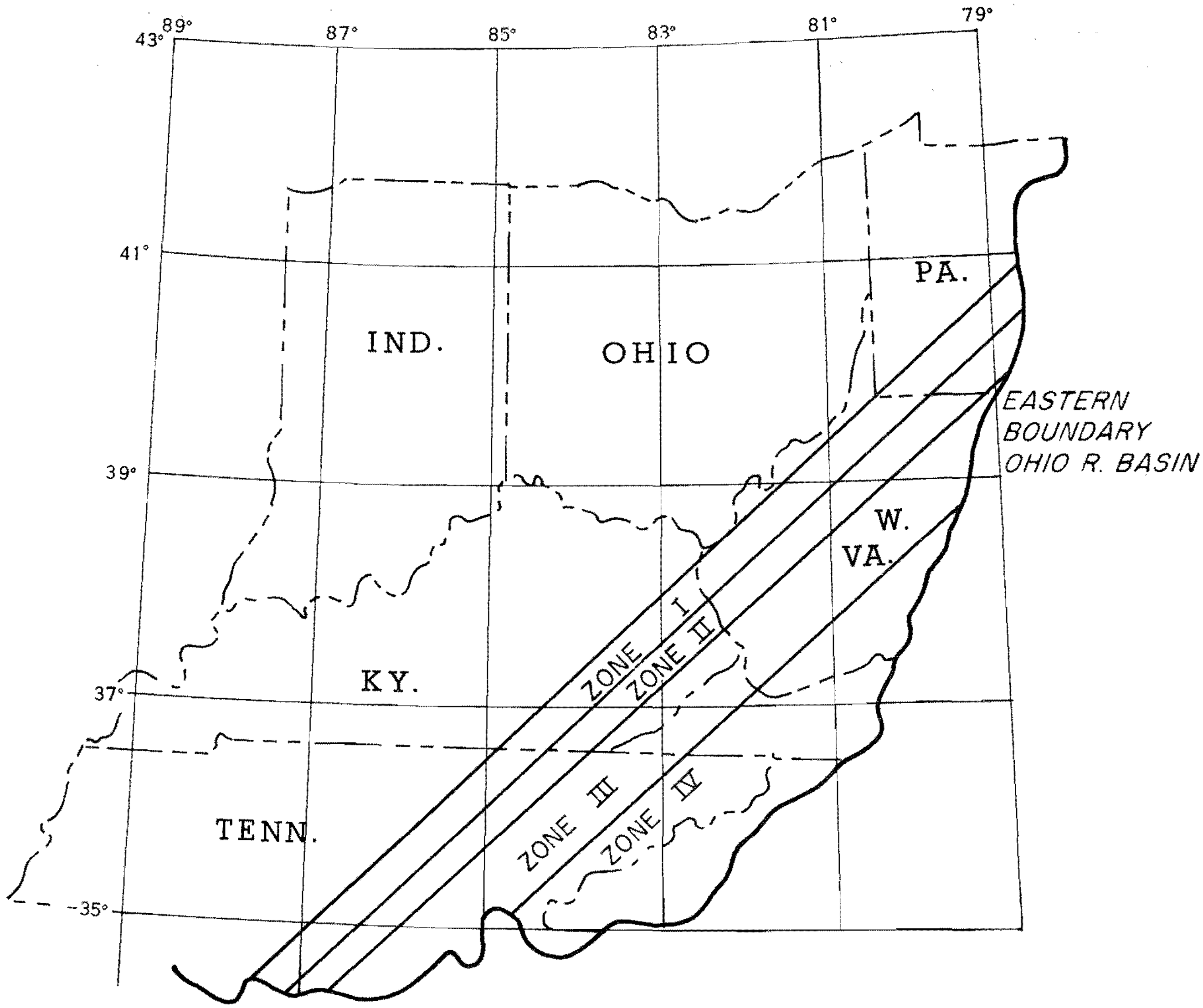
Antecedent flow 18 September- 3 October 1950

ACKNOWLEDGMENTS

Much credit is due Mr. Dwight E. Nunn of the Office of Chief of Engineers in the development of hydrologically significant hypothetical sequences.

The author appreciates the guidance offered by Vance A. Myers, Chief of the Hydrometeorological Section. Recognition is also made of Roger R. Watkins for taking part in the construction of the hypothetical sequences, of George A. Lott and John T. Riedel for helpful suggestions and advice.

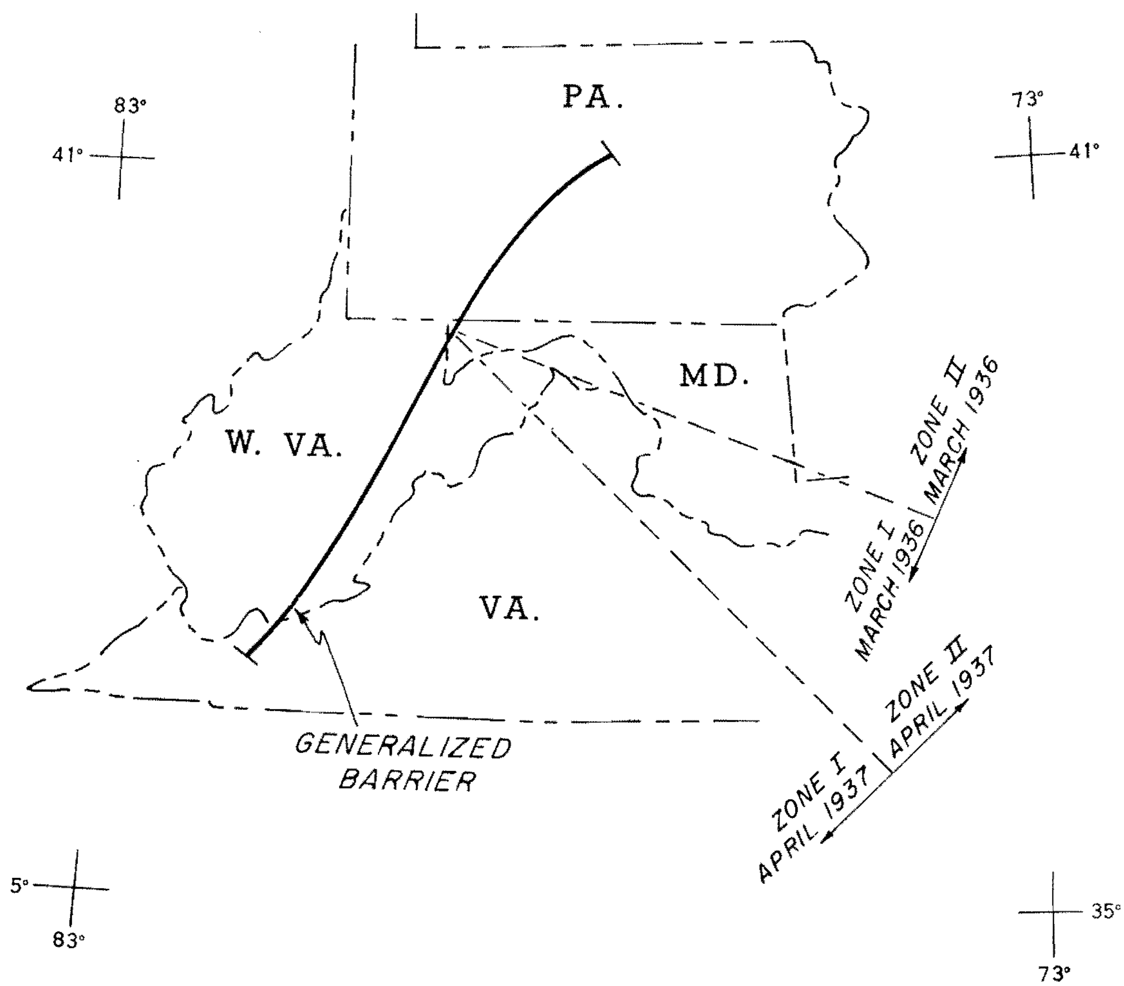
BARRIER DEPLETION CHART
FOR SOUTHWEST FLOW



POLYCONIC PROJECTION
SCALE - 1: 7,000, 000

FIG. 2-1

BARRIER DEPLETION CHART
FOR SOUTH THROUGH EAST FLOW



POLYCONIC PROJECTION
SCALE - 1:7,000,000

FIG. 2-2

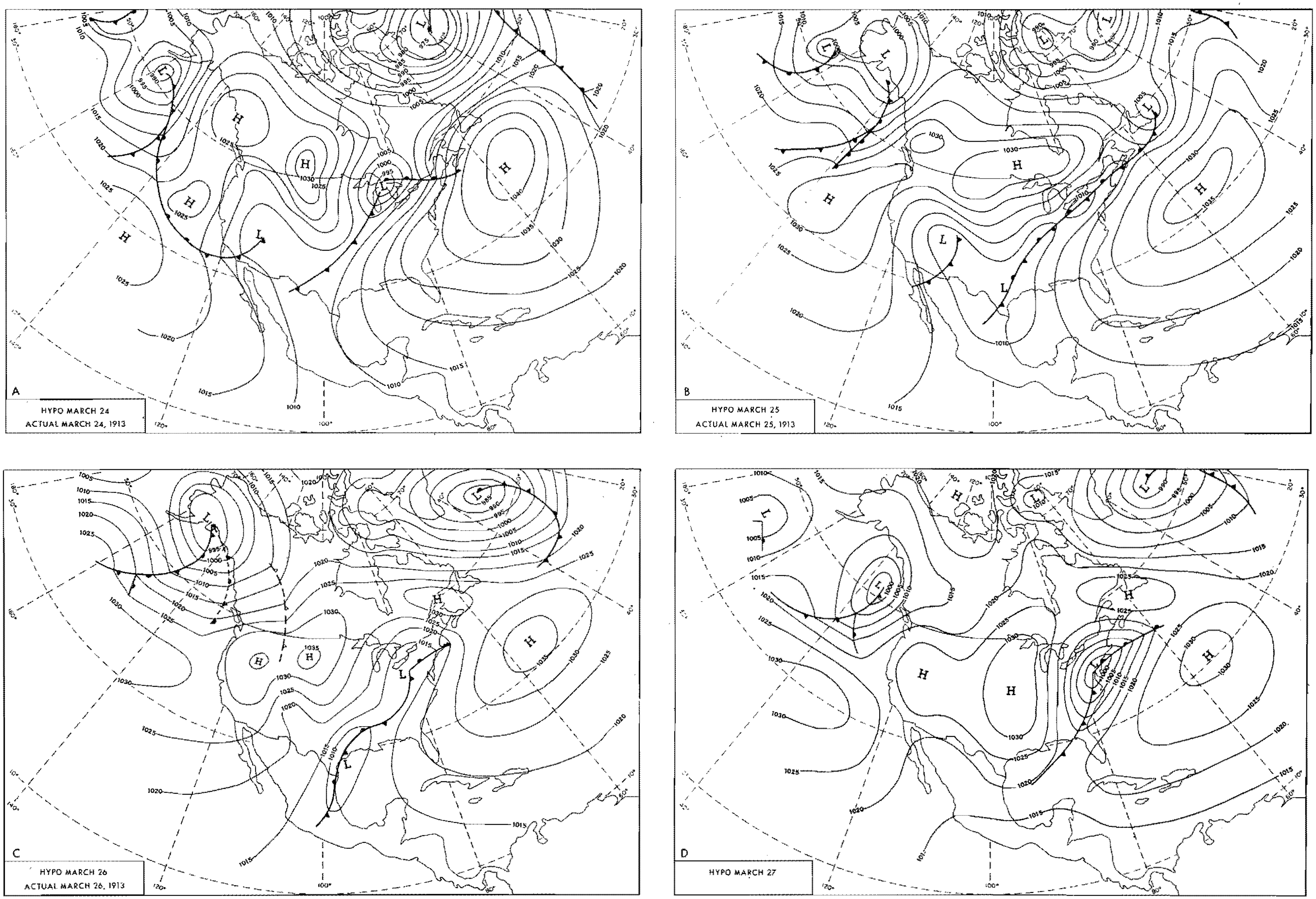


Figure 2-3 HYPO FLOOD NO. 21

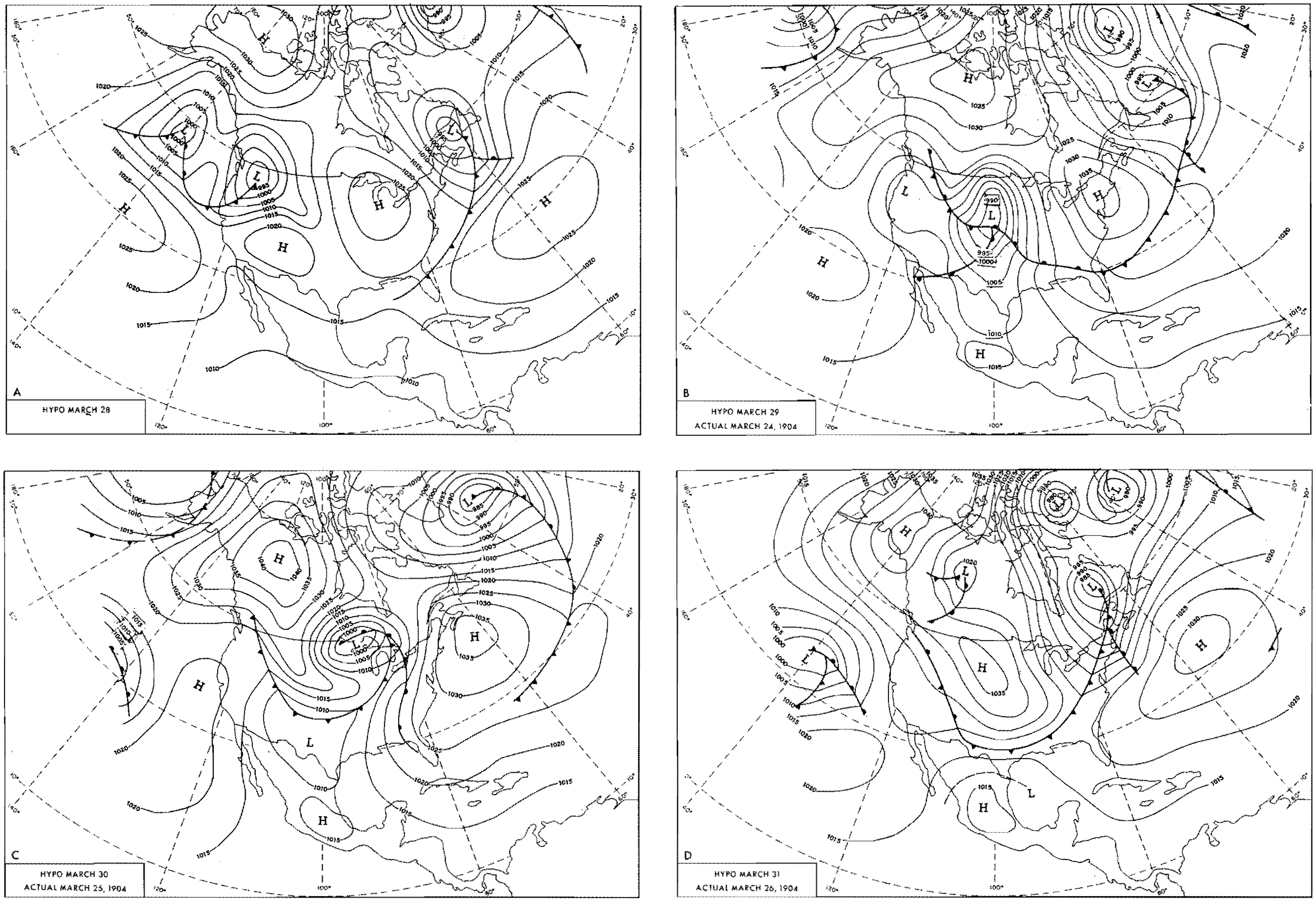


Figure 2 - 4 HYPO FLOOD NO. 21

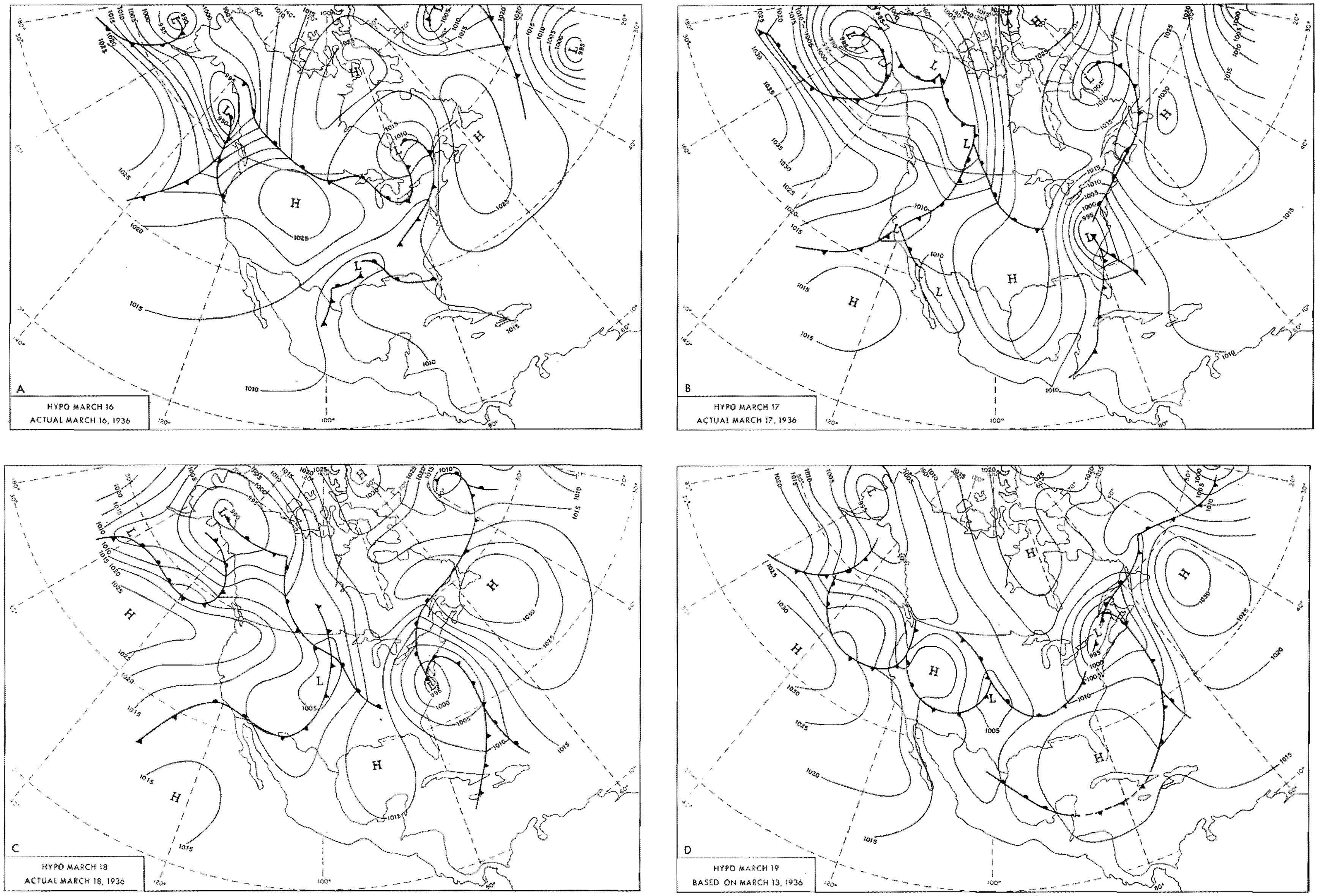


Figure 2-5 HYPO FLOOD NO. 22A

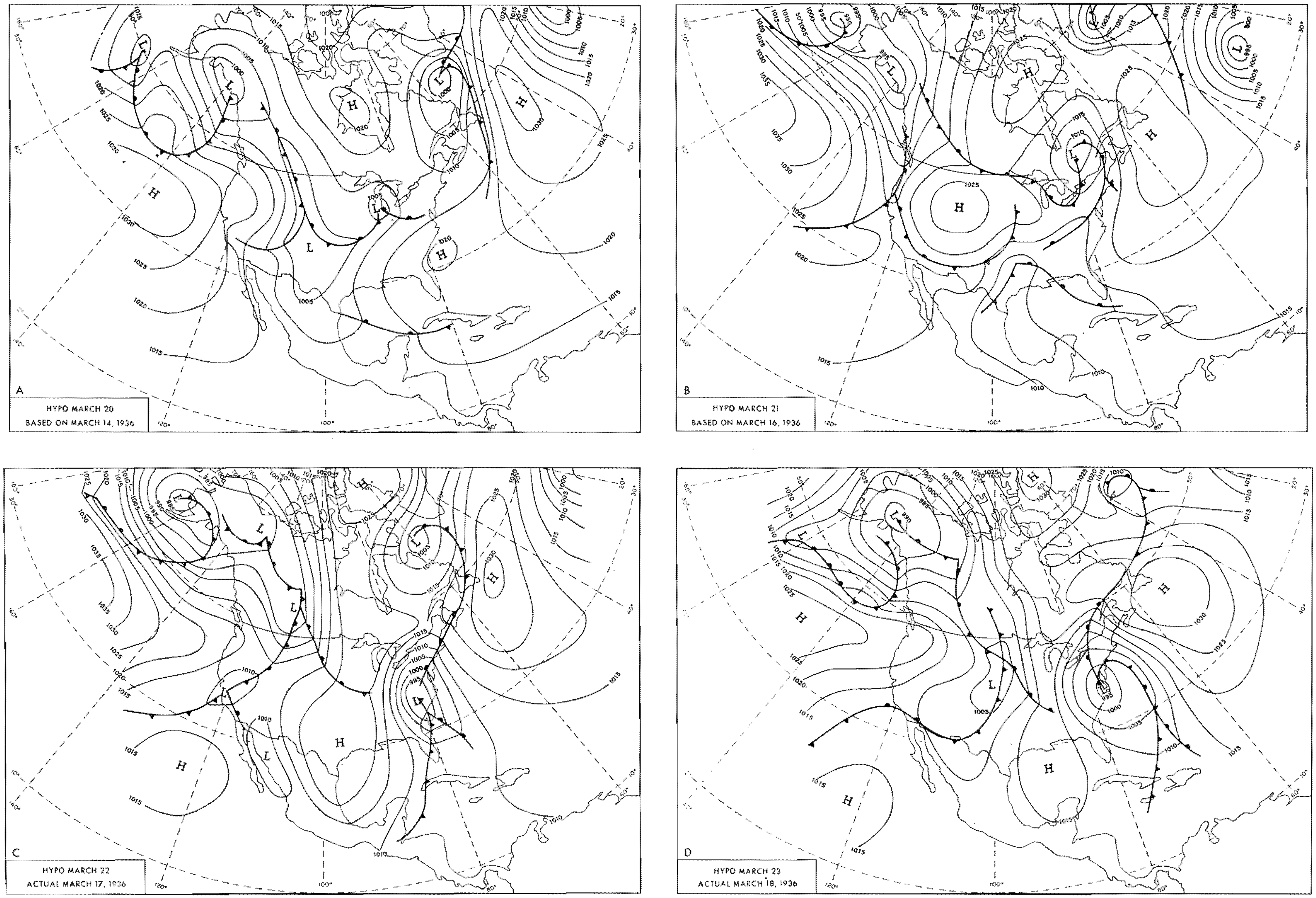


Figure 2-6 HYPO FLOOD NO. 22A

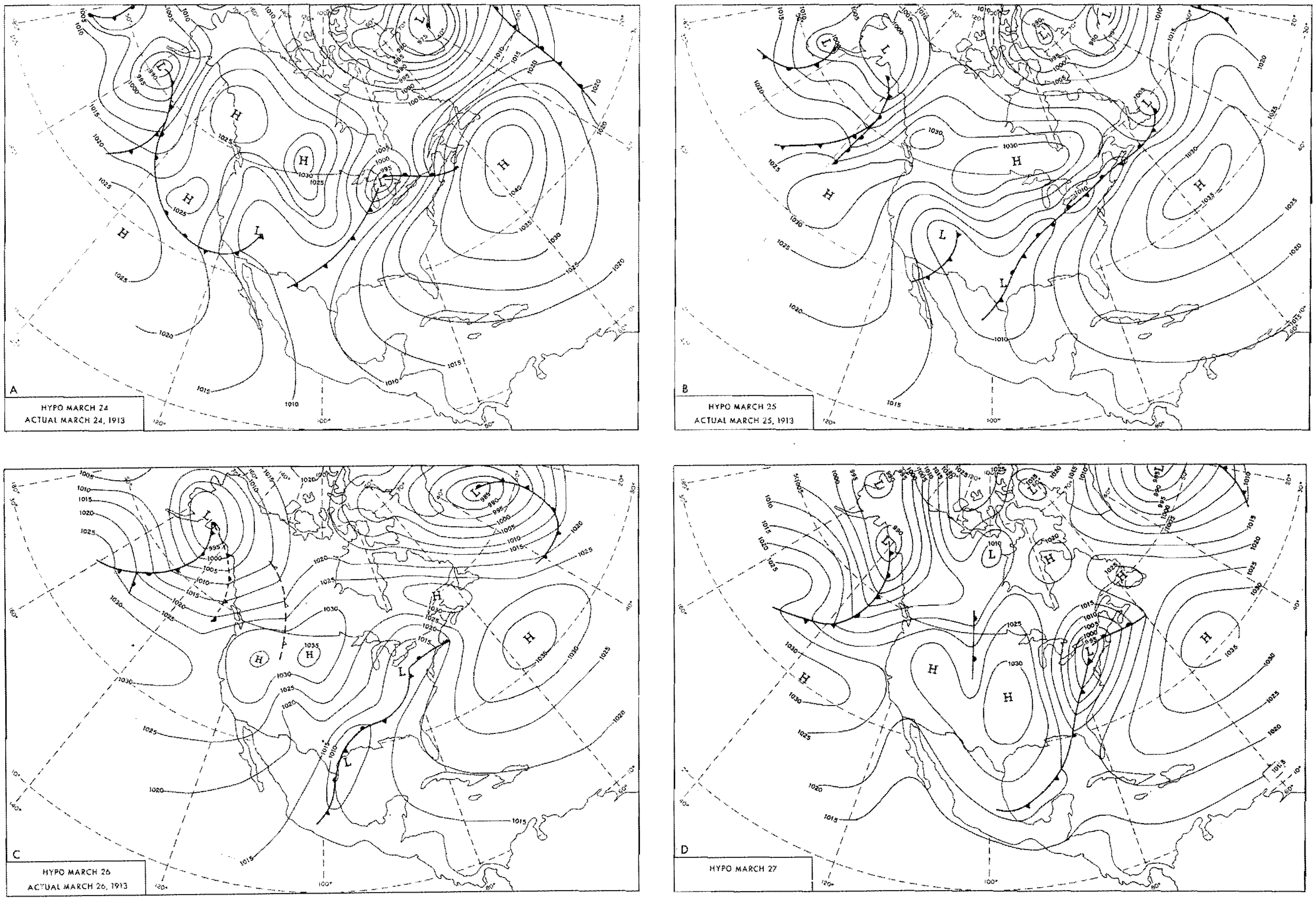


Figure 2 - 7 HYPO FLOOD NO. 24

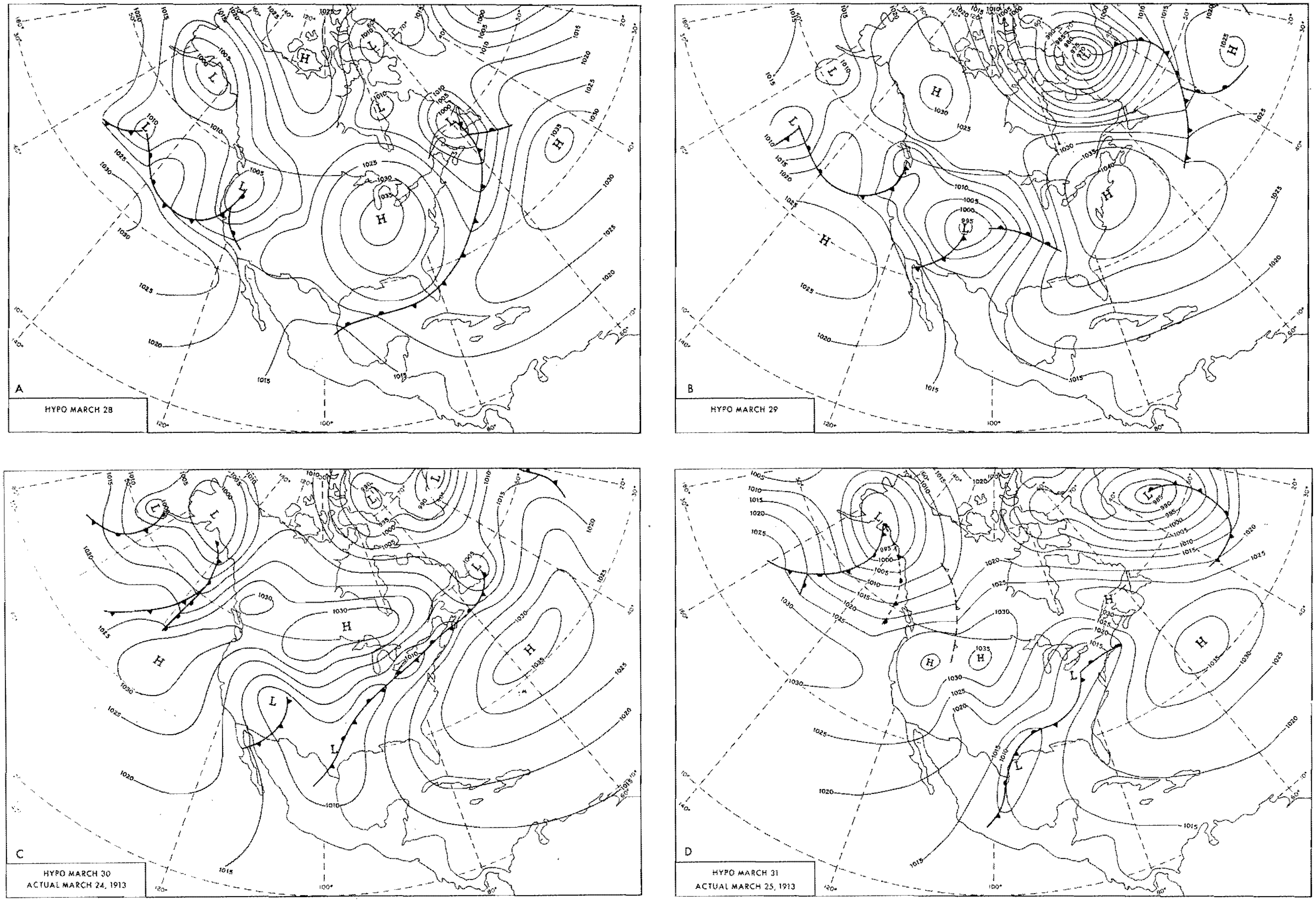


Figure 2-8 HYPO FLOOD NO. 24

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