1940

Hydrology study for the Buffalo Bayou, Texas flood control project.

Wilbur E. Kelley 1908-1989
University of Louisville

UNIVERSITY OF LOUISVILLE

HYDROLOGY STUDY
FOR THE
BUFFALO BAYOU, TEXAS
FLOOD CONTROL PROJECT

A Dissertation

Submitted to the Faculty

Of the Speed Scientific School of the

University of Louisville

In Partial Fulfillment of the

Requirements for the

Professional Degree of Civil Engineer

By

Wilbur E. Kelley, Jr.
B.S. in C.E., June, 1931

June, 1940

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PROFESSIONAL HISTORY

June, 1931	Graduation from Speed Scientific School with degree of B.S. in C.E.
June 1931-Oct. 1933	U.S. Engineer Office, Rock Island, Illinois. Mr. J. W. Dixon
Duties:	Assistant to head of Hydraulic Department. Had charge of all office hydraulic computations and field work. Supervised backwater computations, power studies, seepage studies, discharge measurements and hydraulic reports of various kinds.
Oct. 1933-Jan. 1935	U.S. Engineer Office, Rock Island, Illinois. Mr. J. B. Alexander
Duties:	Chief of layout and inspection party on construction of Mississippi River lock at Quincy, Illinois. Made form layout, baseline measurement, triangulation, miter gate and operating machinery layout, estimate surveys, pile bearing tests, pile driving inspection.
Jan. 1935-Sept. 1935	U.S. Engineer Office, Rock Island, Illinois. Mr. J. E. Reeves

Duties: In charge of construction and operation of all hydraulic models operated at the University of Iowa for the Rock Island District. This included investigation of two new movable dam gates, a hundred foot submergible roller and a sixty foot submergible tainter gate, also sill and apron designs, scouring effects, gate loading pressures. The test results were the basis for design of Dams 11, 12, 13, 17, 18, 21 and 22 in the Rock Island District.

Sept. 1935-Sept. 1936 U. S. Engineer Office, Rock Island, Illinois.
Mr. J. H. Peil

Duties: Chief of layout on Dam 18 at Burlington, Iowa. Made first installations of new type roller and tainter gates. Suggested changes that were used in later designs.

Sept. 1936-March 1938 U.S. Engineer Office, Rock Island, Illinois.
Mr. J. H. Peil

Duties: Assistant Resident Engineer on Lock and Dam 14 at Pleasant Valley, Iowa. Had complete charge of field work on construction of $5,000,000 structure. Supervised all layout and inspection, foundation studies, bridge construction, concrete placement and steel work.

March 1938-Feb. 1940 U.S. Engineer Office, Galveston, Texas.
Mr. H. R. Norman

Duties: Project engineer and assistant project engineer on Houston, Texas, flood control project. Made hydraulic and hydrology studies for design of the project, outlined the various plans of control, made cost estimates, special reports and directed the operations of the survey sub-offices as well as the mapping and other drafting work in the district office. Supervised the adoption of the Lambert grid to the survey work of the district.

Feb. 1940-June, 1940 The Panama Canal, Canal Zone. Col. T. B. Larkin

Duties: Inspector of Special Item Projects (anti-sabotage construction) for the Special Construction Division. Also planning work in connection with the construction of the Third set of Locks for the Panama Canal.

Wilbur E. Kelley

Wilbur E. Kelley, Associate Engineer.

LIST OF ILLUSTRATIONS

Acknowledgment. The study described in this thesis was a part of the writer's work as assistant to the project engineer in charge of the flood protection work for Houston, Texas. The study was carried out in the U. S. Engineer Office at Galveston, Texas. The work of compiling storm data and computing the curves was performed by Mr. K. M. Smith, Junior Engineer, and Mr. Fred Belcher, Assistant Engineer, under the writer's direction. It is through the courtesy of Mr. H. R. Norman, Engineer, and Captain M. J. Asensio, C. E., U. S. A., that the data contained herein can be used.

Object of Study. The purpose of the study was to determine the rate and amount of rainfall and run-off to use in the design of a system of flood protection for Houston, Texas, and the Houston Ship Channel. The value of the areas subject to overflow made the study of vital interest to the Corps of Engineers in its design of the project. Directions from the Chief of Engineers instructed the Galveston District Office to make a complete study of the possible rainfall in the area, the maximum rate at which that quantity might fall, and the probable run-off produced by such a storm. The general method of approach to the problem is one developed largely within the Corps of Engineers. The particular method used was outlined by the writer and consisted of the following steps:

1. A comprehensive study of all the large storms of record in Texas. (This includes the most intense storms in the United States.)

2. Particular study of the largest storm (1899), the most intense storm (1921), the largest of record on the basin (1935), the largest isolated storm on the basin with complete rainfall and run-off records (1938).

3. Study of the possibility of a large storm visiting the area.

4. Derivation of a distribution graph from the 1938 rainfall and run-off data.

5. Check of the distribution graph against known storms.

6. Extrapolation of the observed data to predict the run-off from a storm with the volume of the one of 1899 and the rate of the one of 1921.

7. Conclusions as to the peak flows to be handled by a flood control system.

Note: Not included here is the further study carried out by the writer of a plan of flood control submitted by local interests and the study of a plan of flood control proposed by the writer and favorably accepted by the Chief of Engineers, U. S. Army.

HYDROLOGY STUDY - BUFFALO BAYOU BASIN, TEXAS

A. GENERAL.

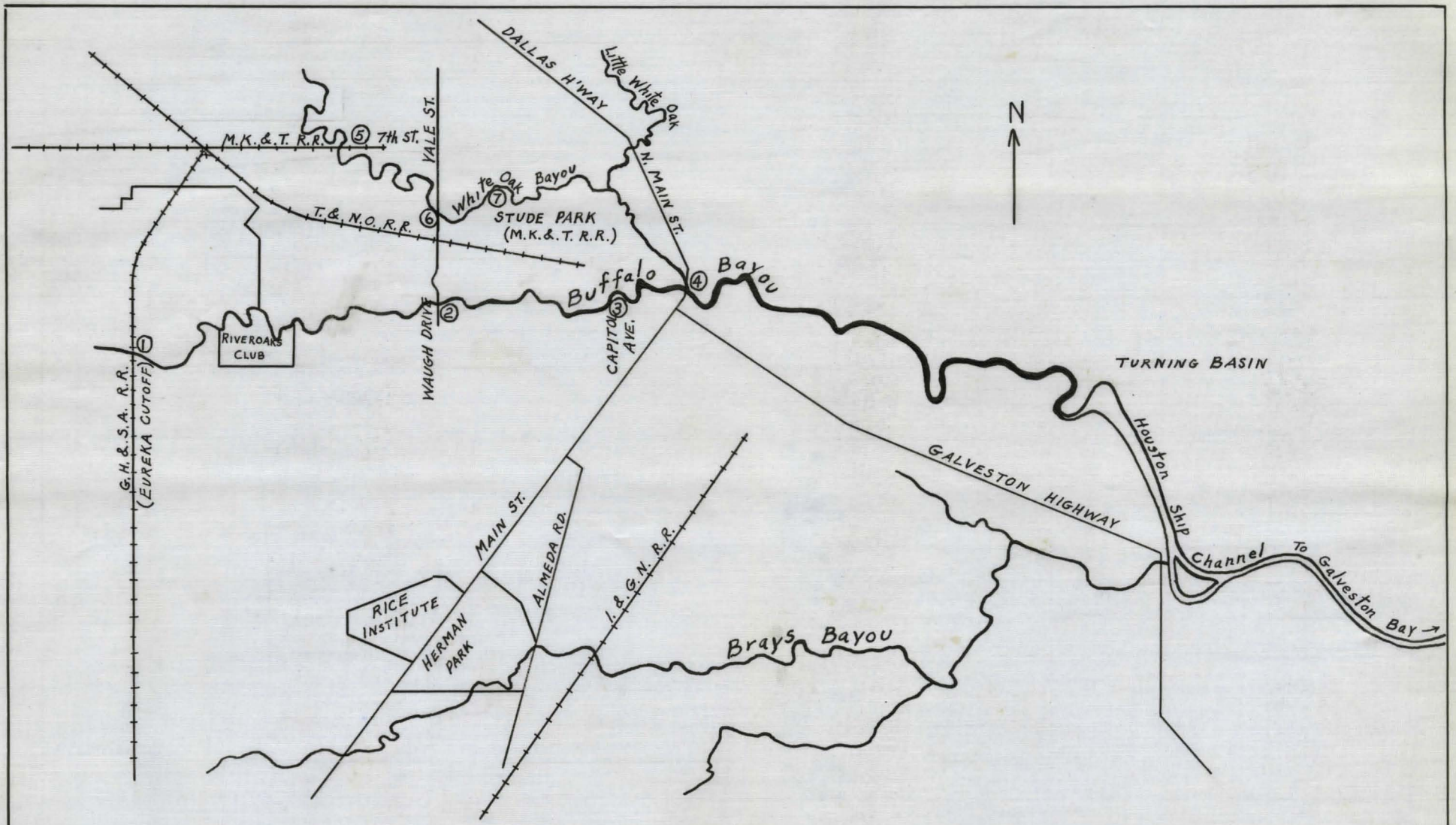
1. Topography.

a. The principle stream draining through Houston is Buffalo Bayou. Buffalo Bayou has its source in the gently sloping prairie bordering the coast of Texas. The stream flows eastward 75 miles in a narrow and tortuous channel, and enters the San Jacinto River 9 miles above the mouth of the latter at the head of Galveston Bay. The city of Houston occupies an area of 70 square miles on both sides of the channel. Its upper and lower limits are 31 and 12 miles, respectively, above the mouth. The Houston Ship Channel, with an authorized depth of 34 feet, extends from deep water at the entrance to Galveston Bay, northward 25 miles across the open shallow waters of the bay to Morgan Point, thence northwest and west an additional 25 miles up San Jacinto Bay and River and Buffalo Bayou to a turning basin in the city of Houston; whence a light draft channel continues up the bayou an additional distance of 6½ miles to the mouth of White Oak Bayou at Main Street. The city, the Houston Ship Channel Navigation District and numerous private interests have constructed extensive terminal facilities along the upper reaches of the deep-draft channel and along the

shallow-draft channel. The mean range of tide decreases from 1.3 feet in lower Galveston Bay to less than 0.5 foot in San Jacinto River and Buffalo Bayou. The drainage basin, shown on Fig. 1, is roughly 50 miles long and up to 30 miles in width. It rises gently toward the northwest at a rate of less than 3 feet per mile. The water courses are usually heavily wooded, but elsewhere the vegetal covering is limited chiefly to coarse native grasses. The relative impermeability of the surface soils facilitates the rapid run-off of flood waters. Buffalo Bayou traverses the business section of the city. As shown on the sketch map of Houston, Fig. 2, and aerial photograph, Fig. 3, the increasing value of lands in this commercial area has resulted in encroachment upon the flood plain of Buffalo Bayou by buildings adjacent to the channel and even over it. There are no bridges over the Houston Ship Channel below the turning basin. Numerous bridges cross Buffalo Bayou above the turning basin and present serious obstructions to the flow of floodwaters, particularly those bridges above the confluence of White Oak and Buffalo Bayou. (See accompanying photographs Figs. 4 to 6.)

DRAINAGE BASIN MAP

Fig. 1



NOTE:
Numbers show locations of discharge measurements.

SKETCH MAP OF HOUSTON

Fig. 2

Fig. 3. Aerial view of downtown Houston showing intersection of Buffalo and White Oak Bayous at Main Street. A large portion of the area shown was flooded in 1935.

Fig. 4. Franklin Ave. Bridge; note the restricted channel and the buildings destroyed by the 1935 flood, view looking upstream.

Fig. 5. The Milam Street Bridge, seriously damaged by the 1935 flood, looking downstream.

Fig. 6. The restricted channel at the Preston Avenue Bridge, looking upstream toward Farmer's Market.

b. Mound Creek, a gully draining some 70 square miles of comparatively steep land about equally in Waller and Harris Counties, debouches into fairly level land at the head of Big Cypress Creek. A small depression leading to Big Cypress Creek is an inadequate channel for the rapid run-off from Mound Creek. As a result, it is estimated that a considerable portion of the peak run-off, due to a heavy rain, flows from the Mound Creek area into Buffalo Bayou watershed. The area contributing a part of its flow is outlined by the short dashed line on the locality map accompanying this paper as Fig. No. 1. The portion of the area in Waller County has not been mapped adequately as yet and the sketched outline was obtained by a careful study of aerial photographs. Surveys now underway will determine the land actually contributing. The Buffalo Bayou drainage area above White Oak Bayou, as recently revised by surveys and studies of aerial maps, is 362 square miles. The area contributing during storms large enough to cause overflow at Cypress Creek, is 432 square miles. (See Fig. 1, the discussion in Part D, par. 2 and profile along Mound Creek, Cypress Creek and the Buffalo Bayou divide, shown on Fig. 29.)

c. White Oak Bayou, with its tributary, Little White Oak Bayou, is the principal tributary of Buffalo Bayou above the turning basin of the Houston Ship Channel. The drainage basin lies entirely in Harris County north of Houston and contains about 114 square miles. The basin is 21 miles long and 7 miles wide at the widest part. The upper portion of the stream traverses a Houston residential district

and the lower portion traverses a portion of the business district before joining Buffalo Bayou at Main Street. Numerous bridges cross the stream and restrict its high water flow. During the 1935 flood there was noticeable flow from White Oak Bayou to Buffalo Bayou across low ground on the right bank of White Oak Bayou in the vicinity of Shepherd Drive (See Fig. 1). The channel is tortuous, and overgrown with brush above the low water line, with consequent poor stream discharge characteristics at high stages. The stages at the lower portion are raised by backwater from Buffalo Bayou and it is difficult, if not impossible, to determine flood flows from stage relations with the limited data available.

2. Soils.

a. The soils of the Buffalo Bayou region represent the outcrops of the Lissie and Beaumont formations and consist, respectively, of Katy fine sandy loam and Lake Charles clay. In their natural state these soils support only a scattering growth of timber and are covered by coarse native grasses such as carpet grass, sedge grass, bear grass, and saw grass. The Katy fine sandy loam is generally poorly drained and this poor drainage is accentuated by the fact that it is underlain at depths of 2 to 3 feet by a tight fine sandy clay. The Lake Charles clay is also poorly drained and, due to its texture, does not in the natural state, allow much percolation of water. Both soils are much improved by drainage, to provide which several drainage districts have been organized.

3. Climatic Conditions.

a. Climatic conditions surrounding Houston are typical of the Gulf plains areas. The normal annual rainfall is about 47 inches, with a minimum annual rainfall of 17.66 inches and a maximum annual rainfall of 72.86 inches. The normal annual temperature is 69 degrees, with a minimum annual temperature of 67.5 and a maximum annual temperature of 71.5 degrees.

4. Available Data on Rainfall.

a. In the 265,896 square miles in Texas some 490 official and cooperative rainfall stations have been in operation during the history of the U. S. Weather Bureau. Many of the stations have been operated intermittently and the records are of varying value. In the 476 square miles of the Buffalo Bayou drainage area above Main Street (this area includes White Oak and Little White Oak Bayous drainage basins) there are no official stations. However, the Houston station and nine others are in the immediate vicinity. To aid in obtaining information in the basin, the city of Houston installed several stick gages after the 1929 flood. Unfortunately, the value of the observations has been decreased by the poor record keeping. Very small allotments of municipal funds were made for the purpose. There was a noticeable lack of system of recording. Many of the records in the files were lost. During the December storm of 1935, which caused the largest flood of record, valuable unofficial records were obtained by interested residents of the locality. Five of the city gages measured the rainfall, but the best information on the rate of rainfall came from

a farmer at Westfield who recorded the time of filling of a can in his yard. (See discussion of the 1935 storm in Part B, par. 4.) Records obtained from the unofficial sources are of great value in studying the storm, as the U. S. Weather Bureau Houston station was outside the area of heaviest rainfall.

b. In 1936 and 1937 the city of Houston established five strategically located recording gages in the basin. The operation of those gages was of great value in May of 1938 during the occurrence of a one-day storm over the watershed. Mass curves, prepared from the records and shown on Fig. 19, were used in the derivation of distribution graphs for both Buffalo Bayou and White Oak Bayou which are included as Figs. 27 and 28.

c. U. S. Weather Bureau records are available for the Houston station since 1889, but the station can serve as a guide only since the heaviest rainfall in all the important storms with which we are concerned was observed in areas away from Houston.

5. Available Data on Run-off.

a. No information pertaining to stream discharge is available before 1929 for Buffalo Bayou. During the 1929 flood the city of Houston obtained several observations at the Capitol Avenue bridge. The observations were made by current meter at a depth of one foot and the mean discharge computed by multiplying the observed value by a constant. The peak discharge at this location was computed as 18,500 c.f.s. A reliable discharge hydrograph, was prepared from the information obtained by the city, is included as Fig. 31.

b. It is unfortunate that in the December 1935 storm the city was unable to obtain, with its own personnel, reliable discharge measurements on Buffalo and White Oak Bayous. Due to the numerous rescue and salvage activities of the city engineering force during the flood, it was impossible to delegate experienced men to the task of obtaining discharge measurements. For that reason, the city was able to make only one reliable observation. At the San Jacinto Street bridge at a stage 1.6 feet below the crest of the flood, the measured discharge was 49,000 c.f.s. and the crest flow, as computed by the U. S. Geological Survey, was 56,600 c.f.s. The latter value is a reliable figure for the maximum combined flow of Buffalo Bayou and White Oak Bayou during the 1935 flood.

c. Several measurements of discharge were obtained by a local consulting engineer and numerous discharge hydrographs derived therefrom. These hydrographs, without the supporting data, were furnished to the city but are not considered reliable and, therefore, are not included in this report. The peak discharges are probably accurate, but the slopes of the hydrographs below the peaks are apparently incorrect. In one instance the base width of the discharge hydrograph is shorter than the duration of the rain on the basin. As a result, it is extremely difficult to estimate the duration of the flow or to determine the total run-off from the various streams during the 1935 flood.

d. In May 1936, the U. S. Geological Survey established a recording gage at Yale Street bridge over White Oak Bayou and at Waugh

Drive bridge over Buffalo Bayou. (For locations, see Fig. 2. That same month a storm over the basin produced a flow measured of 9,650 c.f.s. on Buffalo Bayou. Information obtained by U.S.G.S. and U. S. Engineer forces during May and June in 1936 has been used in the construction of a reliable rating curve for low flows. By combining the low flow data obtained in 1936 with the 1929 flow obtained by the city, a rating curve can be constructed for flows up to 25,000 c.f.s. No accurate extension to higher flows is obtainable.

e. On May 16, 1938, a 12-hour storm occurred that produced flows equal to those of May 1936. Measurements were obtained by U. S. Engineer forces that verified the U.S.G.S. rating curve for Buffalo Bayou at Waugh Drive.

f. No reliable information is available for White Oak Bayou flow during the 1929 flood. The only information pertaining to the 1935 flood is a hydrograph submitted by the local consulting engineer mentioned above Par. 5, b, preceding. In May 1936 the U. S. Geological Survey obtained measurements at Yale Street after the peak had passed. However, their estimate of the peak flow is 4,000 c.f.s. In May 1938 sufficient discharge measurements were obtained by U. S. Engineer forces to verify the U.S.G.S. rating curve and increase its range slightly. All the information concerning run-off from White Oak Bayou has been derived from measurements made above the mouth of Little White Oak Bayou, in order to avoid the backwater effects from Buffalo Bayou.

g. No reliable measurements have been obtained of the flow from the 20 square mile Little White Oak Bayou drainage basin.

6. Meteorology and Rainfall.

a. The Buffalo Bayou basin is in an area fulfilling all the requirements for extreme precipitation in both rate and quantity. The basin is near the Gulf of Mexico, the source of the warm moisture laden tropical air masses that make possible protracted intense storms. Althought the basin is somewhat south of the region of most active frontal formation it has been subject to conditions causing precipitation almost as rapid as any along the Balcones Fault zone. (In 1935, 20.6 inches fell in 35 hours at Westfield.) There are no topographic features to prevent the continual ingress of large quantities of moist air, nor are there any features to prevent the invasion of the area by a dense cold air mass wedge that by its lifting effect, might supply the "trigger" action necessary to start precipitation. The area also is directly in the path of tropical hurricanes and subject to the heavy precipitation usually accompanying such storms. However, the storms producing the maximum rainfall in Texas have not been of the hurricane type. A flood control system for Houston may at any time, be subjected to storms equal to any of record in Texas, and greatly in excess of any so far experienced over the basin. Some 52 Central Texas and coastal storms of the past have been studied in order to determine the worst storm of record and to study the area-rainfall and rate-of-rainfall characteristics of the various storms.

b. Because of the comparatively small size of the Buffalo Bayou basin, the storms of most value are those showing the most rapid rainfall over areas equal to that of Buffalo Bayou. Five storms were

studied in detail and many others were studied sufficiently to allow their reasonable elimination from further detailed study. Special emphasis was placed on the June 27 - July 1, 1899, storm at Hearne and Turnersville, Texas, and the September 6-10, 1921, storm centered near Taylor, Texas. Both storms are important indications of what might occur over the Buffalo Bayou Basin. Liberal use was made of the work of Mr. Gail B. Hathaway ("Special Report on Hydrological Studies, Possum Hingdom Project") in the study of these storms. (See discussion of 1899 storm under Part B, SPECIFIC STORMS).

c. The December 6-8, 1935, storm, centered at Westfield, Texas, caused the worst flood of record on Buffalo and White Oak Bayous at Houston. Special studies were made of that rainfall. The May 24-30, 1929, storm caused the second highest flood of recent history in Houston. This also has been studied extensively. The work of the Houston City Engineering Department has been of value on conditions subsequent to 1929.

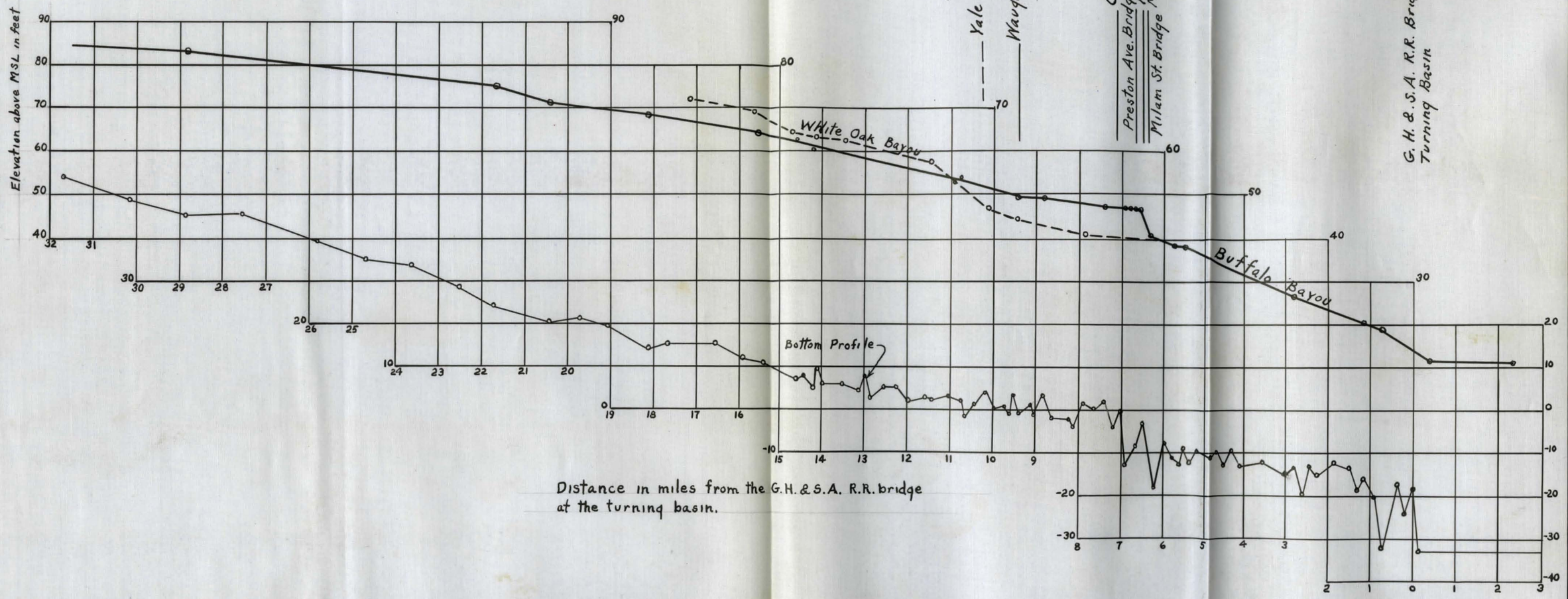
d. A one-day storm centered over the Buffalo Bayou basin on May 16, 1938, has been studied as a means of deriving a distribution graph for the basin. No other short storms of appreciable size have occurred over the area since the basin was equipped with recording rain and stream gages.

e. The data used in the storm studies were taken from published and unpublished U. S. Weather Bureau information, supplemented by reliable unofficial records where such were available.

7. Past Floods.

a. The city of Houston was founded in 1835. The first flood of consequence thereafter was in 1854. One major flood has occurred in each of the years 1875, 1879, 1907, 1929, and 1935. The most destructive of these floods was that of December 1935. Records of stages and photographs, made by old residents, indicate that the flood discharges in order of increasing magnitude were about as follows: 1854, 1907, 1875, 1879, 1929, 1935. No discharge measurements were made of any floods prior to 1929 and all conclusions as to the relative sizes of earlier floods are based on statements contained in the newspapers published at the time and photographs of a foundation wall on Buffalo Bayou at the foot of Fannin Street, one block downstream from Main Street. The 1935 flood crest exceeded previous flood crests by about six feet at Fannin Street and exceeded the 1929 flood crest by eight feet. (See profile included as Fig. 7).

b. The 1935 flood caused the loss of eight lives and property damage of $2,500,000 in the city of Houston. Commerce within the city was disrupted. A serious fire and health hazard existed. Utilities were interrupted. The Port of Houston was idle for a period of three days because of excessive currents in the ship channel and further delays were caused by silt deposits. The 1929 flood resulted in no loss of life and damages were estimated at about $1,400,000. (See photograph of the 1935 floods, Fig. 8).



BUFFALO BAYOU PROFILE
1935 FLOOD

Fig. 7

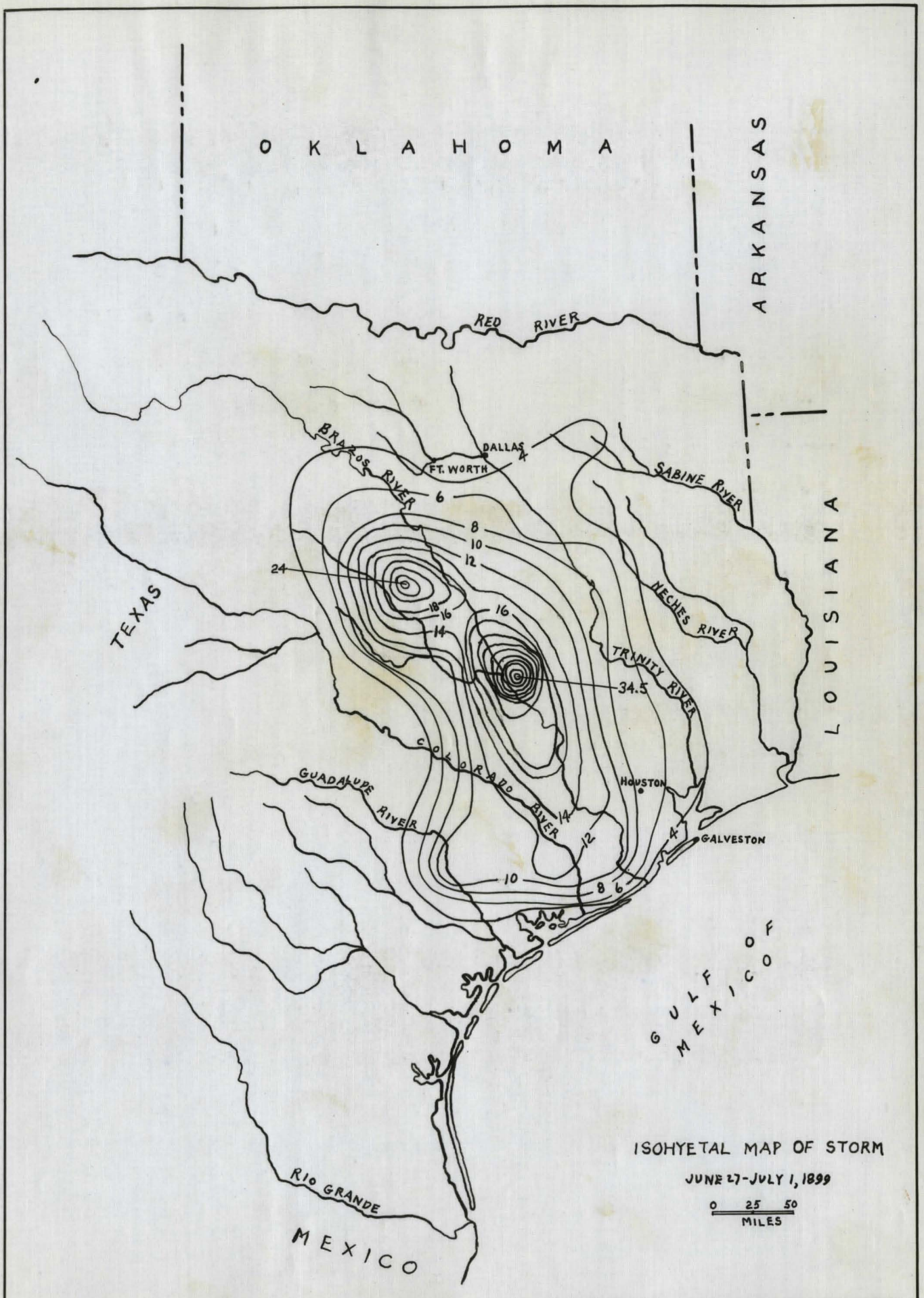
Fig. 8. View of the Farmer's Market area during the 1935 flood at a stage approximately six feet below the crest.

B. SPECIFIC STORMS.

1. 1899, June 27 - July 1, at Hearne, Texas.

a. Several reports have been written on the 1899 storm in Central Texas. The Monthly Weather Review for July 1899 published by the U. S. Weather Bureau contains an account of the storm and the extensive damage caused by floods resulting from the storm. Estimated damages amounted to $9,000,000. Between 30 and 35 lives were lost. The State of Texas Reclamation Department Bulletin No. 18 and No. 25, dealing with excessive rainfall in Texas, and the Miami Conservancy District Technical Report, Part V, 1936, give brief accounts of the storm. The most complete analysis and study of the 1899 storm, based on a thorough study of meteorological conditions and a careful search of all sources for rainfall data, is that of Mr. Gail Hathaway in "Hydrological Studies for Possum Kingdom Project", made for the U. S. District Engineer, Mineral Wells District at Mineral Wells, Texas, in June 1937.

b. A major point brought out by Mr. Hathaway was that the rainfall figure of 24 inches at Hearne, published in the Texas Reclamation Department Bulletin No. 25 and accepted by most authorities, was an incomplete reading and should have been more nearly 34.5 inches. As a result of combining all the information obtained and making such changes in previously published data as were indicated, the storm probably occurred as shown on Figure 9. It should be noted that two definite storm centers showed excessive rainfall, probably over the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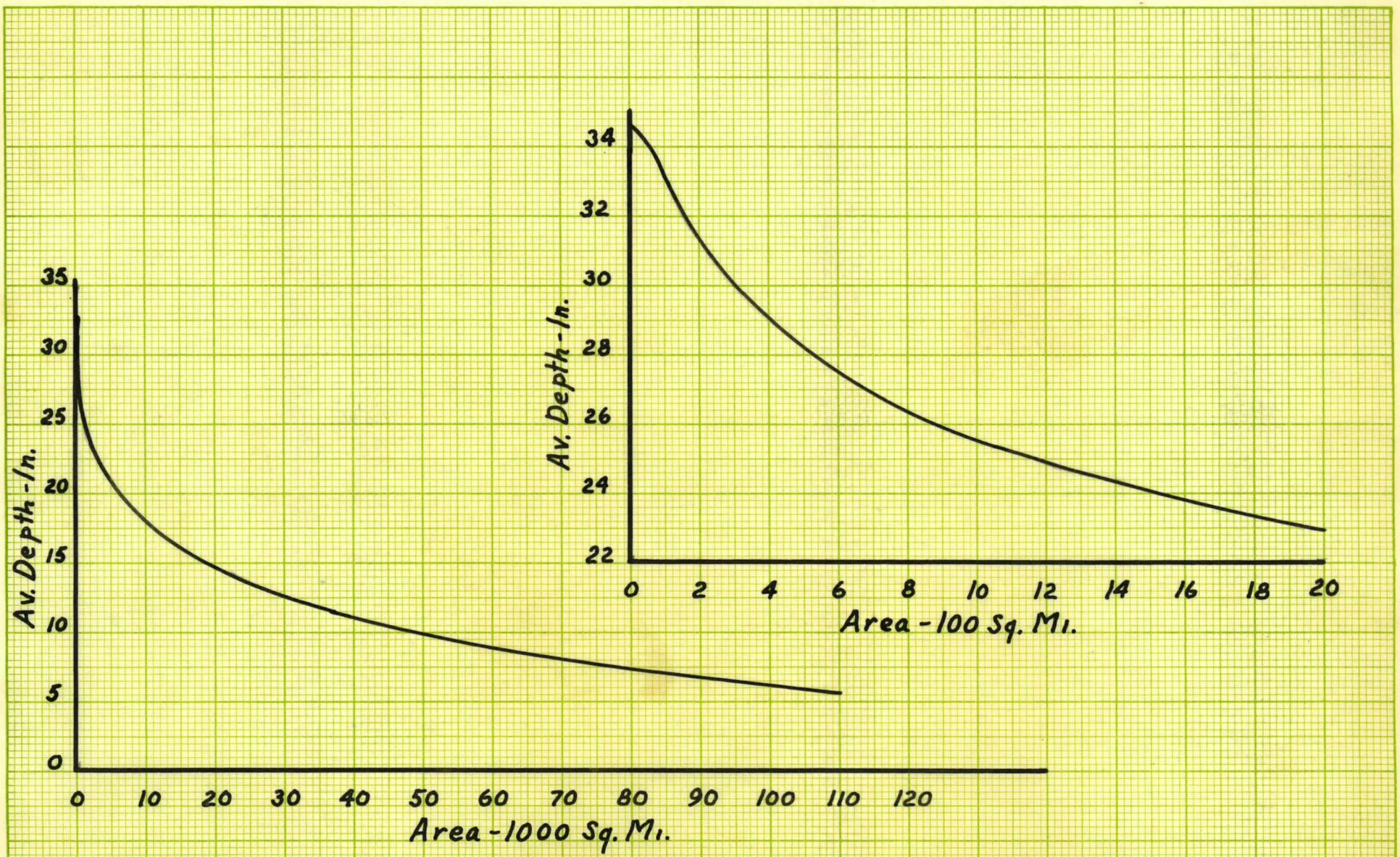
RED RIVER
BRAZOS RIVER
DALLAS
FT. WORTH
SABINE RIVER
LOUISIANA
TEXAS
NECHES RIVER
TRINITY RIVER
COLORADO RIVER
GUADALUPE RIVER
HOUSTON
GALVESTON
GULF OF MEXICO
RIO GRANDE
MEXICO
6
8
10
12
24
18
16
14
16
34.5
14
12
10
8
6
4
ISOHYETAL MAP OF STORM
JUNE 27-JULY 1, 1899
0 25 50
MILES

Fig. 9



AREA-RAINFALL CURVE
JUNE 27 - JULY 1, 1899

Fig. 10

largest area of record in the United States. By computing the areas inside the lines of equal rainfall on Figure 9 a curve of area plotted against average intensity of rainfall was prepared. This curve, included as Figure 10, indicates the large size of the storm by the fact that 400 square miles of area were covered by 29 inches of rainfall, and that 10 inches fell over 50,000 square miles. One inch or more of rain fell over an area 500 miles long and 300 miles wide, or 150,000 square miles.

c. The rate of rainfall at various points was studied by Mr. Hathaway. Information on rate of rainfall is more difficult to obtain than information on the total rain. The rate of fall requires periodic readings during the storm, while the total rainfall can be obtained by one reading after the rainfall has ceased. In the 1899 storm, rates of rainfall were not observed as completely as they would be today with recording gages, but it is thought that, the rate at Hearne during the storm has been exceeded by only one or two other Texas storms. A recording gage record of the 1921 storm at Taylor indicates maximum rates of 10.5 inches of rain in 3 hours, 19.0 inches in 15 hours, 23.11 inches in 24 hours, and 23.98 inches in 35 hours. Maximum rates for the 1899 Hearne storm were 17.7 inches in 15 hours, and 24 inches in 24 hours. Estimates of rates during the 1921 storm ran as high as 30 inches in 15 hours. (See Monthly Weather Review September 1921). Had more complete readings been obtained on the 1899 storm they might have indicated rates for the shorter intervals equal to those of the 1921 storm.

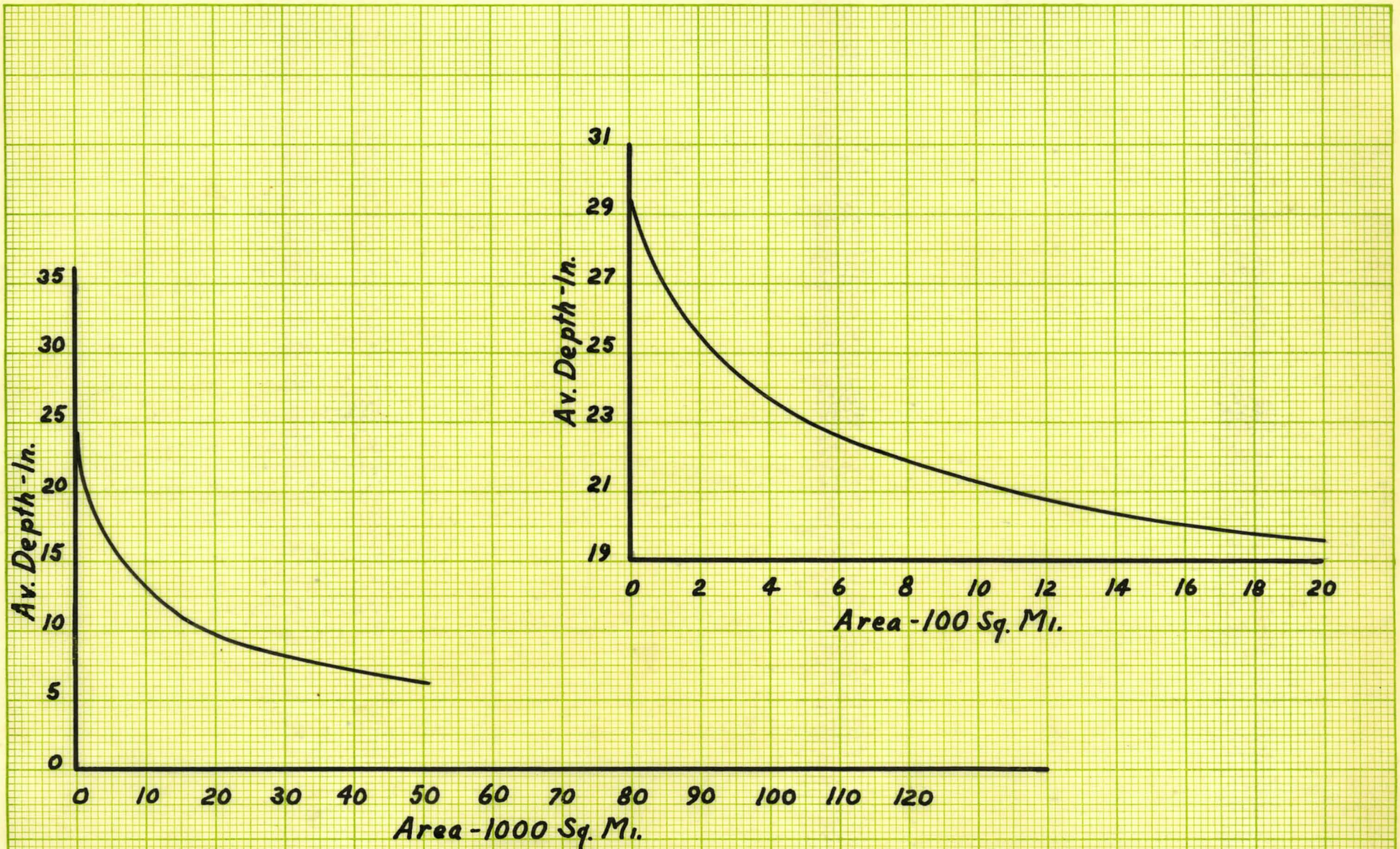
d. From an extensive study of meteorological conditions existing at the time, Mr. Hathaway has deduced the cause of the 1899 storm to have been the squeezing of a warm, moisture-laden Gulf air mass by the convergence of partially encompassing cooler air masses, resulting in the forced ascension of the Gulf air, with the consequent intense rainfall. There seems to be ample possibility of such a condition arising over the Buffalo Bayou basin, with results approaching the 1899 storm.

2. 1921, September 6-10 at Taylor, Texas.

a. The 1899 storm record of 34.5 inches at Hearne indicates one of the maximum measured rainfalls, while the rainfall near Taylor in 1921 probably fell at a greater rate and reached almost the same measured total, according to reliable but unofficial observations. The U. S. Weather Bureau recording gage at Taylor measured 23.11 inches in a 24-hour period during the storm, the maximum 24-hour rainfall of record for the United States. On September 9, 1921, the recording gage at Taylor registered 10.5 inches in three hours from 6:45 p.m. to 9:42 p.m. The steep slope of the mass curve on Fig. 24 indicates the extremely rapid rate of rainfall during the storm, as compared to the 1899 Hearne storm and the 1935 Westfield storm. The flood caused by the rapid run-off from the storm resulted in estimated damages of $10,000,000 and the loss of 224 lives.

b. The cause of the 1921 storm, as pointed out by Mr. Hathaway, was the squeezing of a warm sector of Tropical Gulf air by modified Polar air masses on either side. There is evidence that the primary cause of the heavy precipitation was not the lifting by the Balcones fault region, but was a "squeeze" condition.

c. In addition to the measurement on the U. S. Weather Bureau gage at Taylor, several persons made reliable measurements of the rainfall near the center of the storm. Mr. J. P. McAuliffe states in the Monthly Review for September 1921 that "Allowing for all errors, it seems assured that in the area northeast of Taylor some 30 inches of rain fell at many places in about 15 hours." The total rainfall in



AREA-RAINFALL CURVE
SEPT. 6-10, 1921

Fig. 11

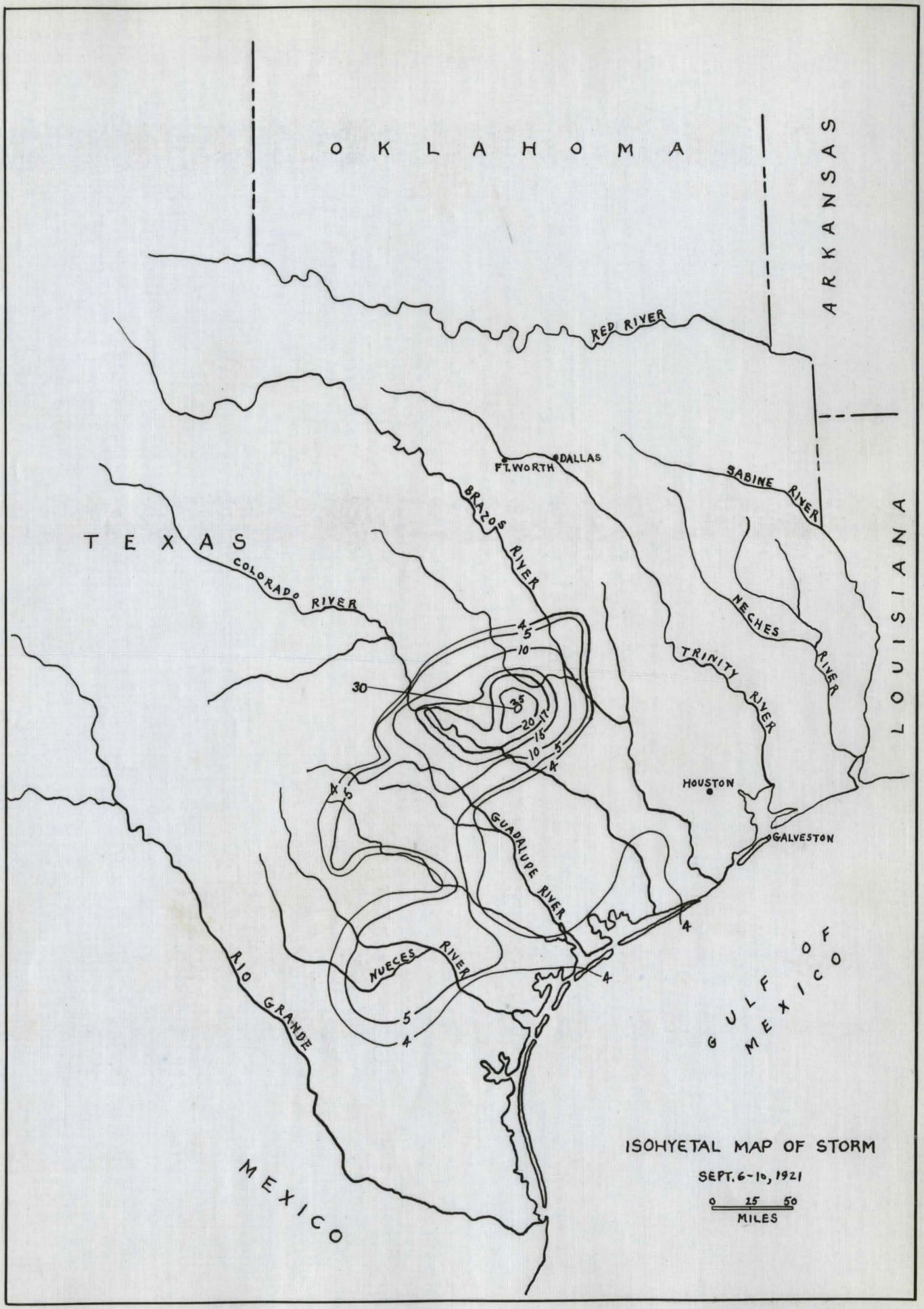

OKLAHOMA
ARKANSAS
RED RIVER
FT. WORTH
DALLAS
SABINE RIVER
BRAZOS RIVER
TEXAS
COLORADO RIVER
LOUISIANA
NECHES RIVER
TRINITY RIVER
HOUSTON
GALVESTON
GUADALUPE RIVER
NUECES RIVER
RIO GRANDE
GULF OF MEXICO
MEXICO
4
5
10
30
35
20
17
15
ISOHYETAL MAP OF STORM
SEPT. 6-10, 1921
0 25 50
MILES

Fig. 12

The total rainfall in these locations probably exceeded 36 inches for the storm.

d. The area covered by heavy rainfall in the 1921 storm was not as large as that in the 1899 storm. Were the storm centered over the comparatively small area of the Buffalo Bayou basin, the resulting damage would be enormous. Such intense rainfall would load the main streams beyond their capacity in a few hours and then the storm would continue to add to the already excessive load for hours more.

e. The area-rainfall curve for the 1921 storm, included as Fig. 11, indicates the area covered by the storm. This chart was prepared from the isohyetal map of the storm included as Fig. 12. The isohyetal chart includes all of the rain falling from September 6 to September 10, but the major portion fell in a shorter period as shown on the mass curve diagram, Fig. 24. The isohyetal map of the storm, Fig. 12, was delineated by using official Weather Bureau data and is a reasonably accurate general picture of the storm, except for the small area where the unofficial readings indicated 36 inches of rain. For that area a rainfall of 30 inches was used, as a compromise between the official reading of 25.2 inches at Taylor and the unofficial reading of 36 inches north and east of Taylor.

f. It is realized that a great many of the largest storms of record in Texas have occurred along the Balcones Fault zone, the first important topographic change met with by Tropical air in moving inland. However, it is believed that a storm as intense as the one of 1921 may occur in the vicinity of Houston, without the aid of upward

deflection of saturated air masses caused by rising topography. The Buffalo Bayou region is nearer the source of the moisture than the fault zone. The moisture content of the warm Tropical air is greater over Buffalo Bayou before the air masses move farther inland. The fact that the cooler Continental air masses will have been warmed in their movement 100 miles farther south from the fault zone tends to compensate for the nearness of Buffalo Bayou to the moisture source. It is conceded also that the Tropical air will be more stable nearer the source and more able to resist the squeezing aloft by Continental masses. However, for simplification in this study and for purposes of erring on the side of safety, it will be assumed that no reduction of either rate or amount of rainfall need be made in superimposing past Central and East Texas storms over the Buffalo Bayou Basin. Accordingly, the storm recommended later in the paper for design purposes is based on both the 1899 and 1921 storms. Because of the added safety, such an assumption does not seem unreasonable in the light of recent experiences on the west coast during the storm of February 1938, or on the east coast in September 1938. In the California storm stream discharge at some points was 186% of design figures.

3. 1929, May 24-31, Maximum at Rockland, Texas.

a. The major portion of Texas experienced heavy rainfall in the period May 24 to 31, 1929. Prior to that time intermittent rains had saturated the ground and filled the streams. As a result, the heavy rains over the heads of the drainage basins of Buffalo Bayou and White Oak Bayou caused the highest flood since 1879 on these streams. One life was lost and damages in Houston amounted to about $1,400,000, inclusive of damage to the port of Houston.

b. The U. S. Weather Bureau records for the vicinity of Houston have been supplemented by information from local sources to produce the detailed isohyetal map of the storm for the period of May 24 to 30, inclusive. (See Fig. 13). The records upon which the detailed map is based have been misplaced in the city of Houston files and are not available for checking. However, the work was done by competent engineers and is probably reliable. The isohyetal map showing the statewide distribution of the rainfall for the period of May 24 to 31, inclusive, is derived from information published in the "Climatological Data" of the U. S. Weather Bureau. Over 100,000 square miles of area in Texas received over 5 inches of rain, as shown on the Area-Railfall curve included herein as Fig. 14.

c. Hourly rainfall readings are available for the Houston station of the U. S. Weather Bureau. The city of Houston furnished the U. S. Engineer Office with daily isohyetal maps of the storm in the vicinity of Houston. A breakdown of the rainfall for 12-hour periods was derived using the Houston station-record as a guide. (Included as Fig. 30).

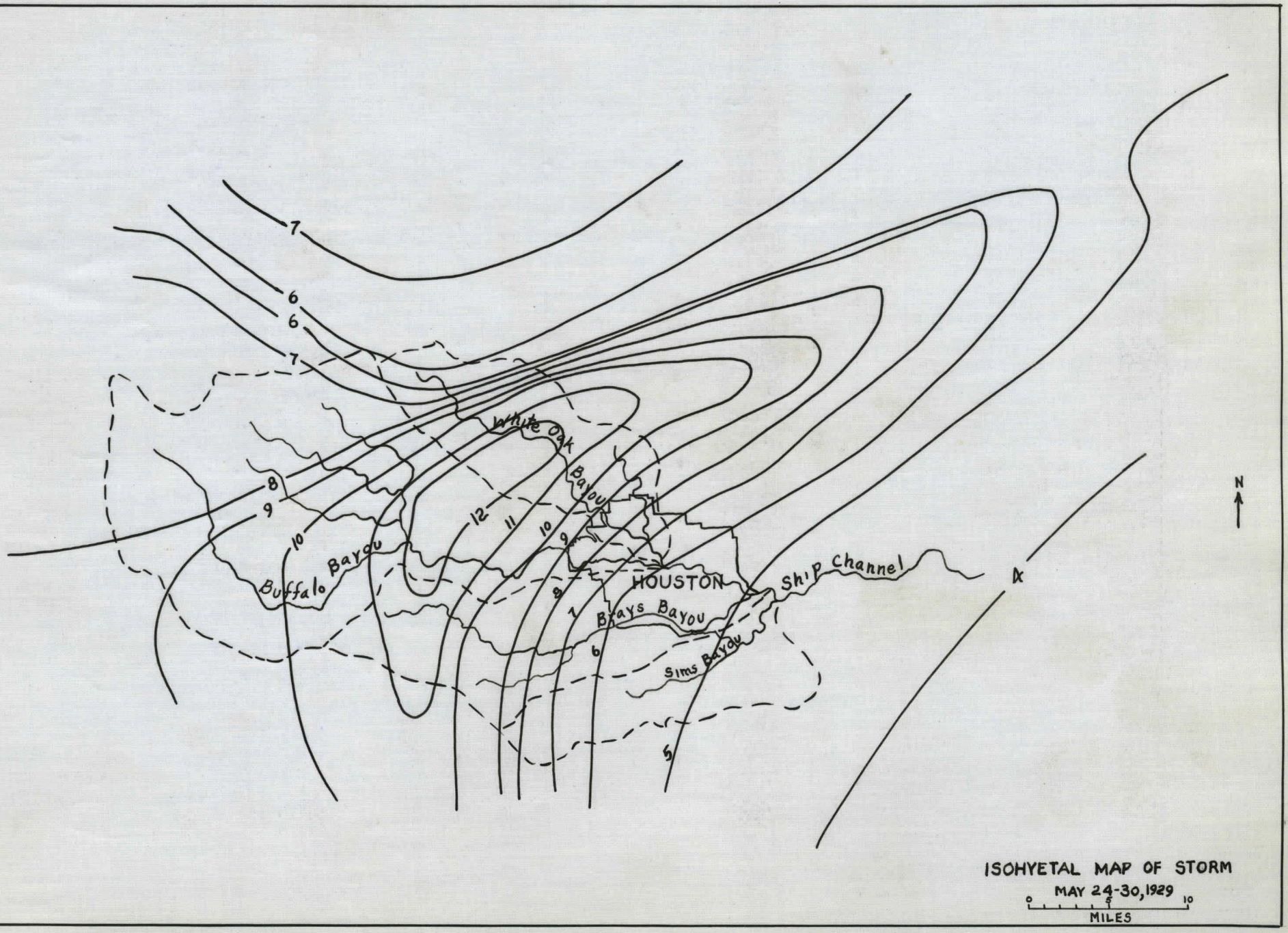
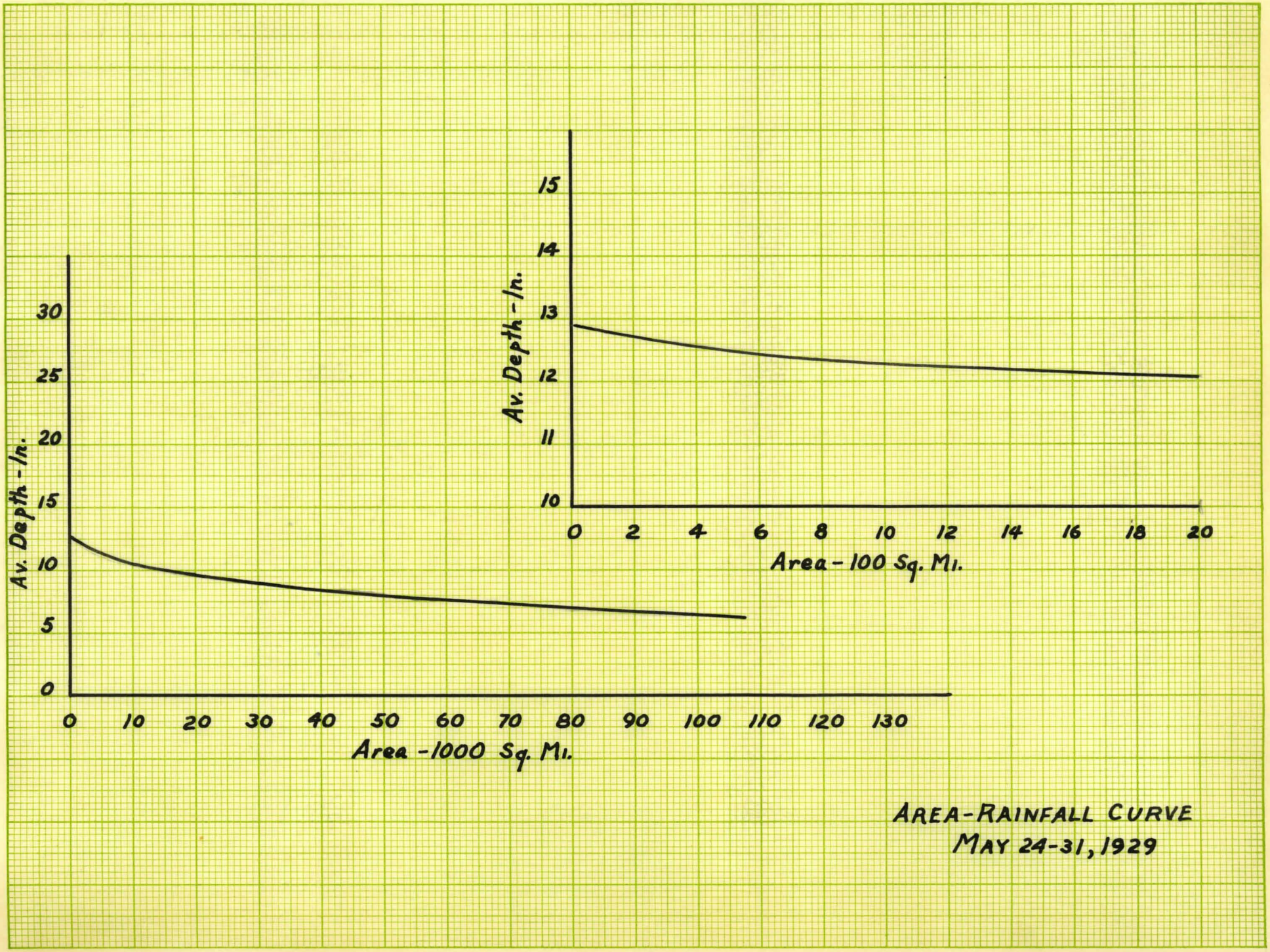

7
6
6
7
8
9
10
12
11
10
9
8
7
6
5
White Oak
Bayou
Buffalo Bayou
HOUSTON
Ship Channel
Brays Bayou
Sims Bayou
N
ISOHYETAL MAP OF STORM
MAY 24-30, 1929
0
5
10
MILES

Fig. 13



AREA-RAINFALL CURVE
MAY 24-31, 1929

Fig. 14

4. 1935, December 6-8 at Westfield, Texas.

a. The disastrous flood of December 1935 in Houston was caused by general rains which fell over the entire eastern part of Texas for the three days of December 6, 7, and 8, 1935. The heaviest rain fell north of Houston, and caused the worst flood in the history of the city. Buffalo and White Oak Bayous overflowed their banks and inundated a large part of the business district in the city, resulting in much damage to property. The city's principal pumping station was unable to supply water, and for days the city had no protection against fire. Immediately after the flood, city officials estimated the damage at $2,500,000 in direct physical loss, and $5,000,000 in intangible losses.

b. The storm causing this damage has been studied extensively in the Galveston Engineer Office in connection with proposed flood control plans. The detailed information pertaining to the rainfall during the storm was obtained largely from observations made by the city of Houston Engineering Department and various unofficial observers. The city at the time of the 1935 storm was establishing rainfall gages throughout the Buffalo Bayou and White Oak drainage basins and readings were obtained on those gages already established. Mr. W. E. White, Assistant City Engineer of Houston, made trips into the surrounding territory after the storm and obtained several readings made by various persons living in the areas of heavy rainfall.

c. One important fact about the 1935 storm is that its area of high precipitation was between U. S. Weather Bureau gages. A

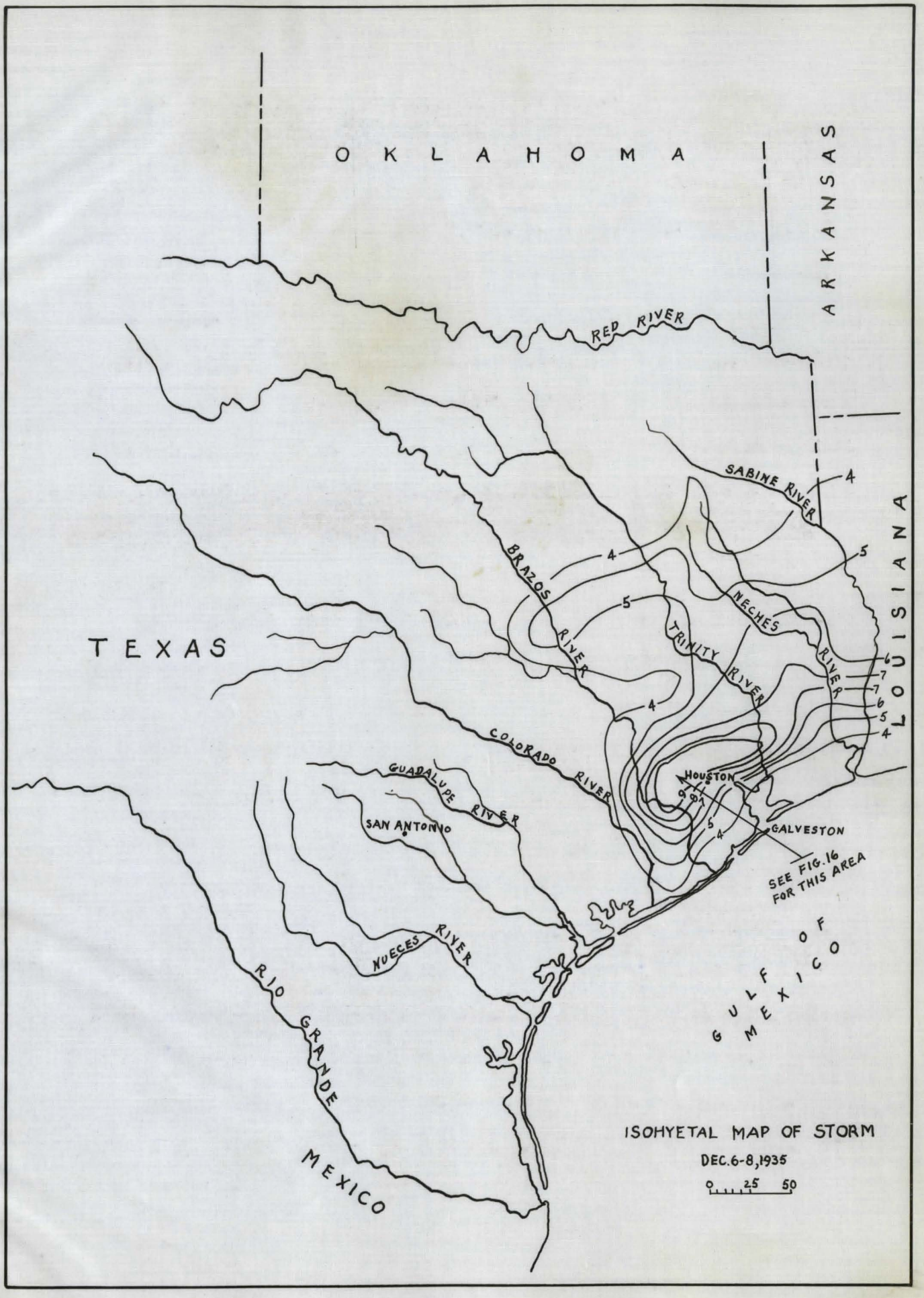

OKLAHOMA
ARKANSAS
RED RIVER
SABINE RIVER
LOUISIANA
TEXAS
BRAZOS RIVER
NECHES RIVER
TRINITY RIVER
COLORADO RIVER
GUADALUPE RIVER
SAN ANTONIO
HOUSTON
GALVESTON
SEE FIG. 16 FOR THIS AREA
NUECES RIVER
RIO GRANDE
MEXICO
GULF OF MEXICO
4
5
6
7
ISOHYETAL MAP OF STORM
DEC. 6-8, 1935
0 25 50

Fig. 15

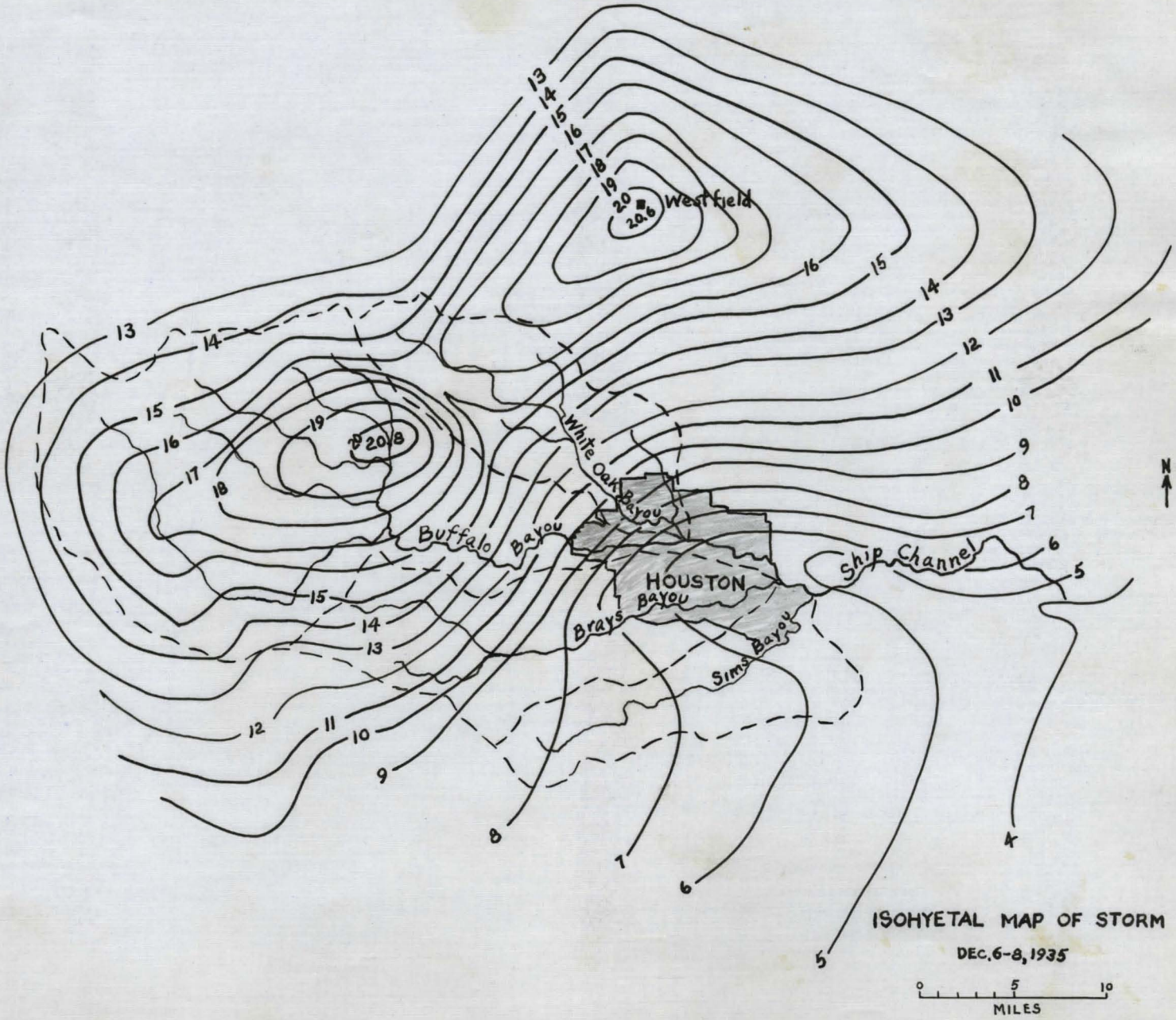
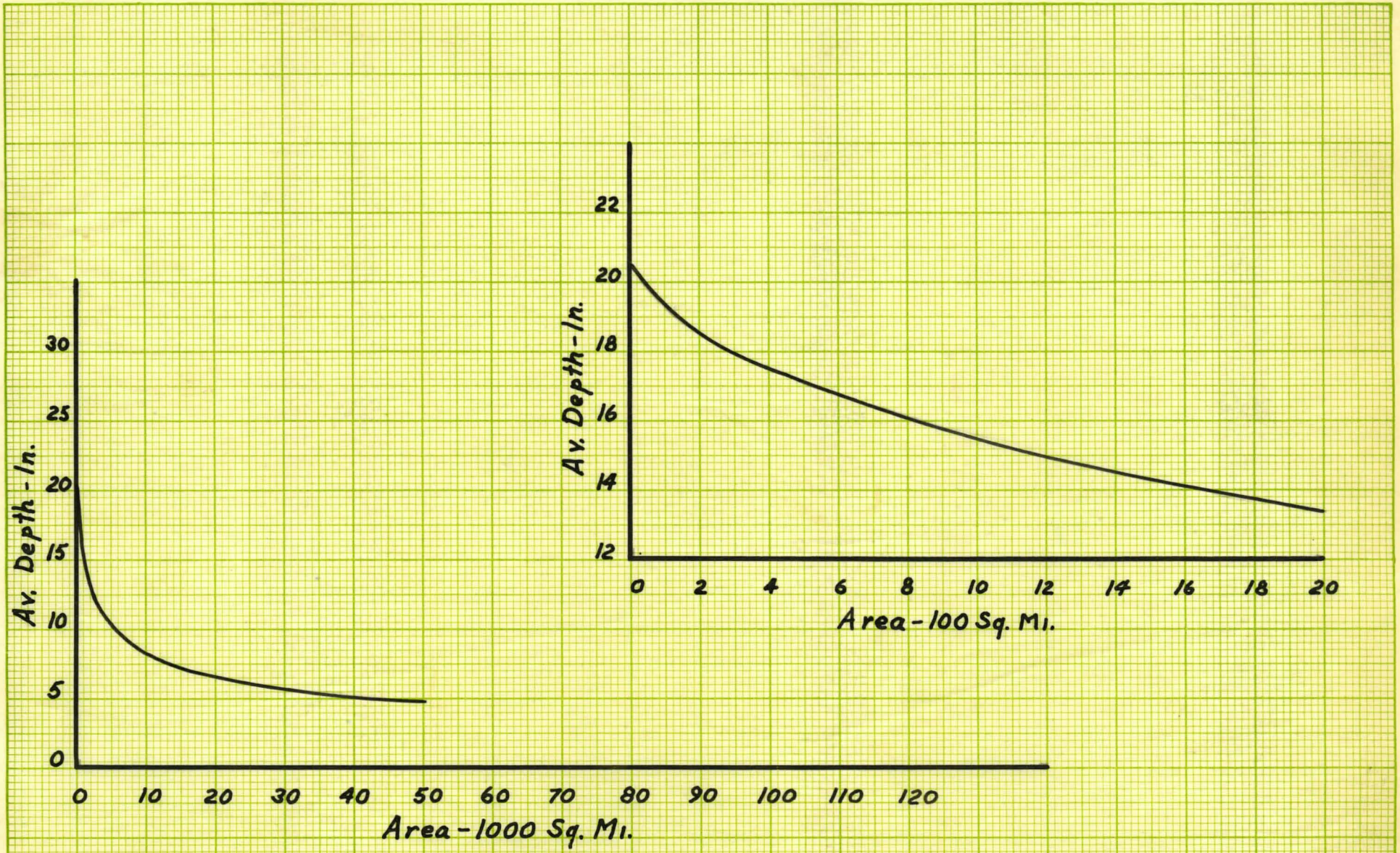

Westfield
20.6
White Oak Bayou
Buffalo Bayou
HOUSTON
Brays Bayou
Sims Bayou
Ship Channel
N
ISOHYETAL MAP OF STORM
DEC. 6-8, 1935
0 5 10
MILES

Fig. 16

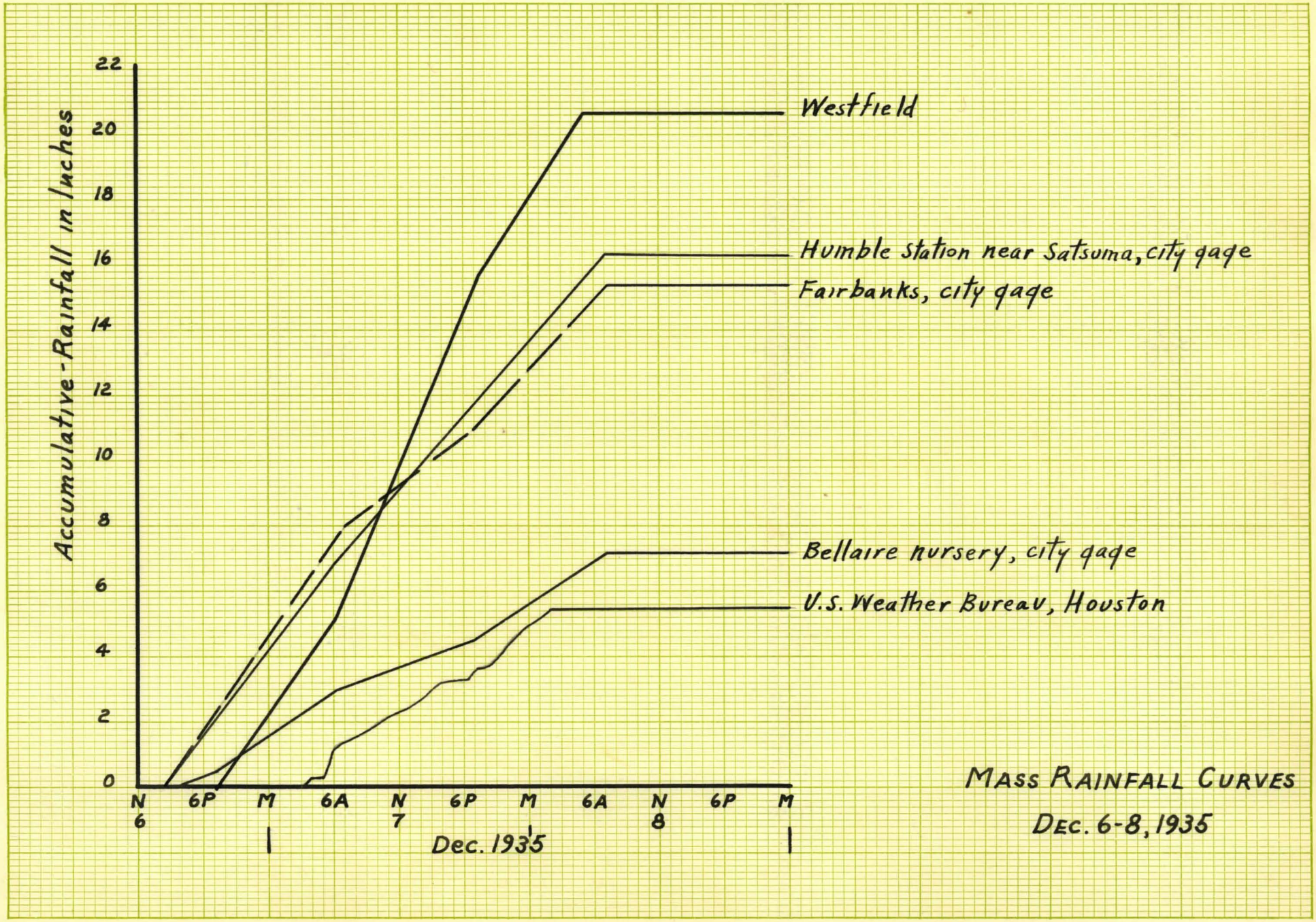
map of the storm made from Weather Bureau official readings, therefore, does not show the true conditions of the storm. It fails to indicate the heavy rains that actually fell. An isohyetal map, prepared from the Weather Bureau readings published in the December 1935 "Climatological Data", is included as Fig. 15. It should be noted that the rainfall on the area to the north of Houston, if interpolated from that map, would be about 9 inches. However, the records furnished by the city give a reading of 20.6 inches at Westfield which is only about 20 miles north of downtown Houston. With such an obvious discrepancy between the Weather Bureau's published data and the actual rainfall, it was necessary to make a detailed study of the high rate area. Therefore, a detailed map of the storm center, based on information furnished by the city of Houston, was prepared and is included herewith as Fig. 16. The area covered by heavy rainfall is small compared to some storms that have occurred in Texas, yet the drainage areas surrounding Houston received sufficient rain to exceed the run-off capacity of the streams draining through town.

d. By combining the information shown on Fig. 15, with that on Fig. 16, a curve was prepared showing the area covered by various intensities of rainfall. This curve is included as Fig. 17. From this curve it is seen that the average rainfall over 800 square miles was 16.0 inches and the maximum observed at any point was 20.8 inches. The curve is a reliable indication of the area-intensity relation for the storm, as it is derived from all the Weather Bureau readings in Texas, plus acceptable information from other observers in the Houston area.



AREA-RAINFALL CURVE
DEC. 6-8, 1935

Fig. 17



MASS RAINFALL CURVES
DEC. 6-8, 1935

Fig. 18

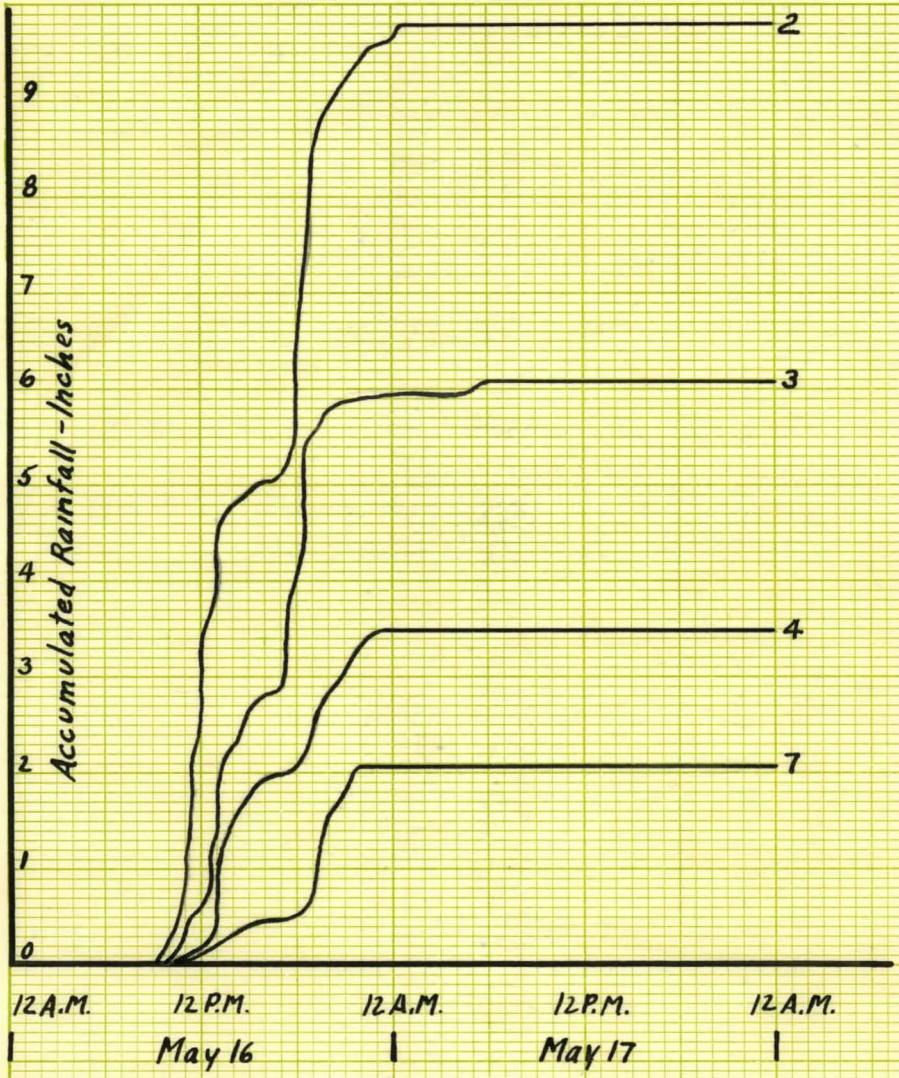
c. The rate at which the rain fell influenced the extent of the damages a great deal. The same rain falling at much slower rate probably would have passed off without appreciable damage. The data, shown in curve form on Fig. 18, presents a picture of the rate of rainfall for this storm. These curves were prepared from the information furnished by the city of Houston. The Westfield station recorded 20.6 inches of rain in 36 hours and 17.5 inches in the first 24 hours of the storm.

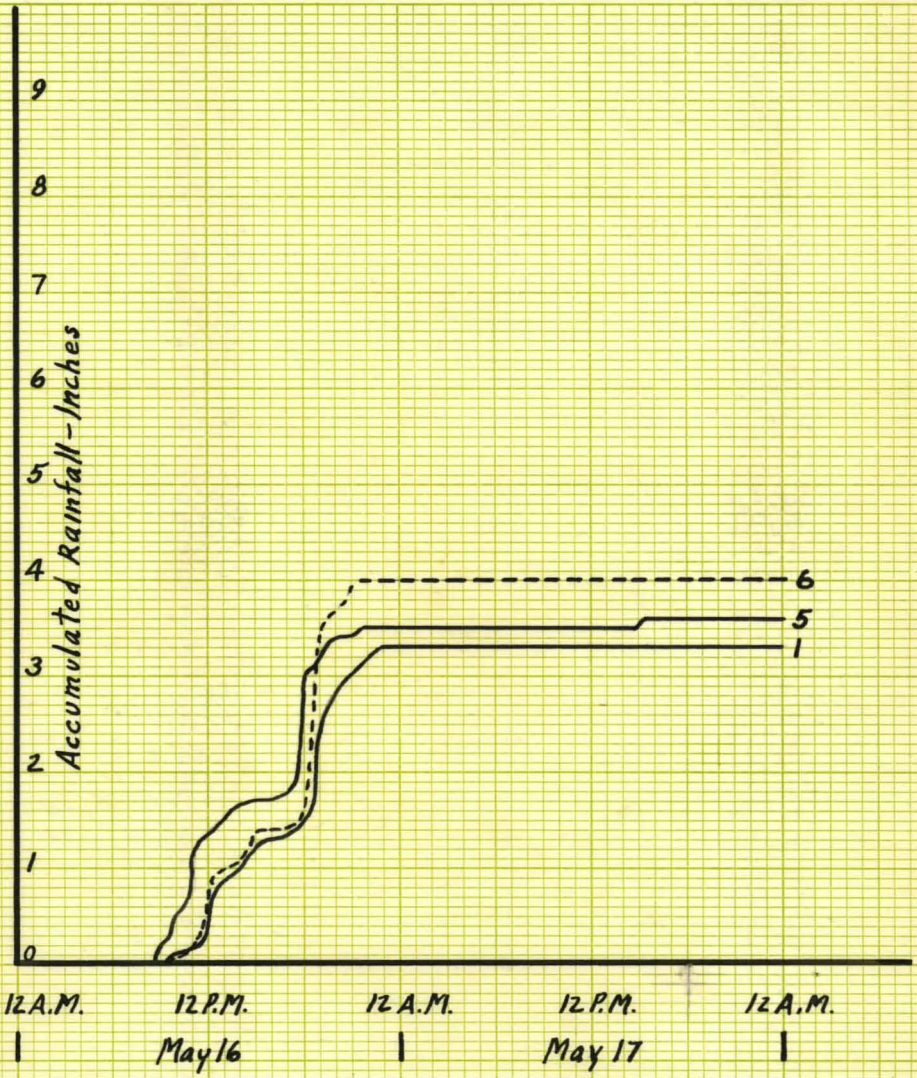
5. 1938, May 16 at Katy, Texas.

a. On May 16th, 1938 there occurred a storm centered over the upper end of the Buffalo Bayou watershed. Almost all of the rain fell within a period of 12 hours as shown by the recording gage records obtained on six gages in the basin, (See Fig. 19 and map, Fig. 20). The storm was not as extensive as usual Texas storms, but the rainfall was sufficient to produce appreciable flows on both Buffalo Bayou and White Oak Bayou.

b. The isohyetal map of the storm, included as Fig. 21, is the result of combining the data obtained from the city of Houston gages with the U. S. Weather Bureau readings for all the surrounding stations inside the area covered by the storm. It is believed that the information secured concerning this storm is sufficient to permit accurate computation of the rainfall.

c. For use in deriving a distribution graph for a small drainage basin, this storm is ideal in every feature except in its lack of uniformity over the watershed. (See Fig. 21). For the small basin the short duration of the storm is an aid to analysis, but it is unfortunate that the rainfall was not more evenly distributed. However, the storm is perhaps the best example of a short storm that has occurred over the basin since the establishment of the stream gaging stations and rainfall stations. Accordingly, the storm has been used for the derivation of a distribution graph for both White Oak and Buffalo Bayous, as shown by Figs. 27 and 28.





Note: All gages City of Houston except U.S. Weather Bureau gage, No. 7.

MASS RAINFALL CURVES
STORM OF MAY 16, 1938

Fig. 19

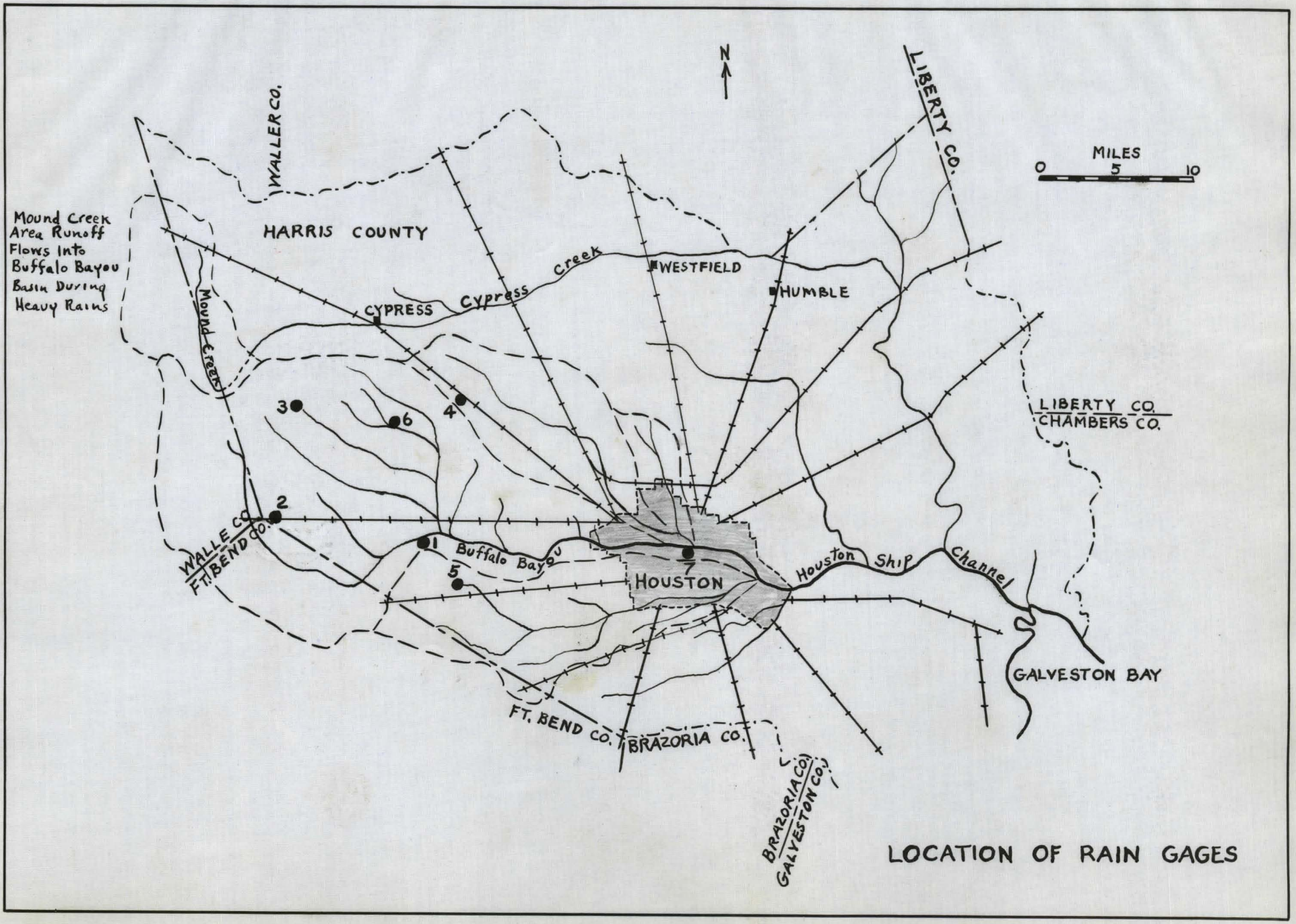
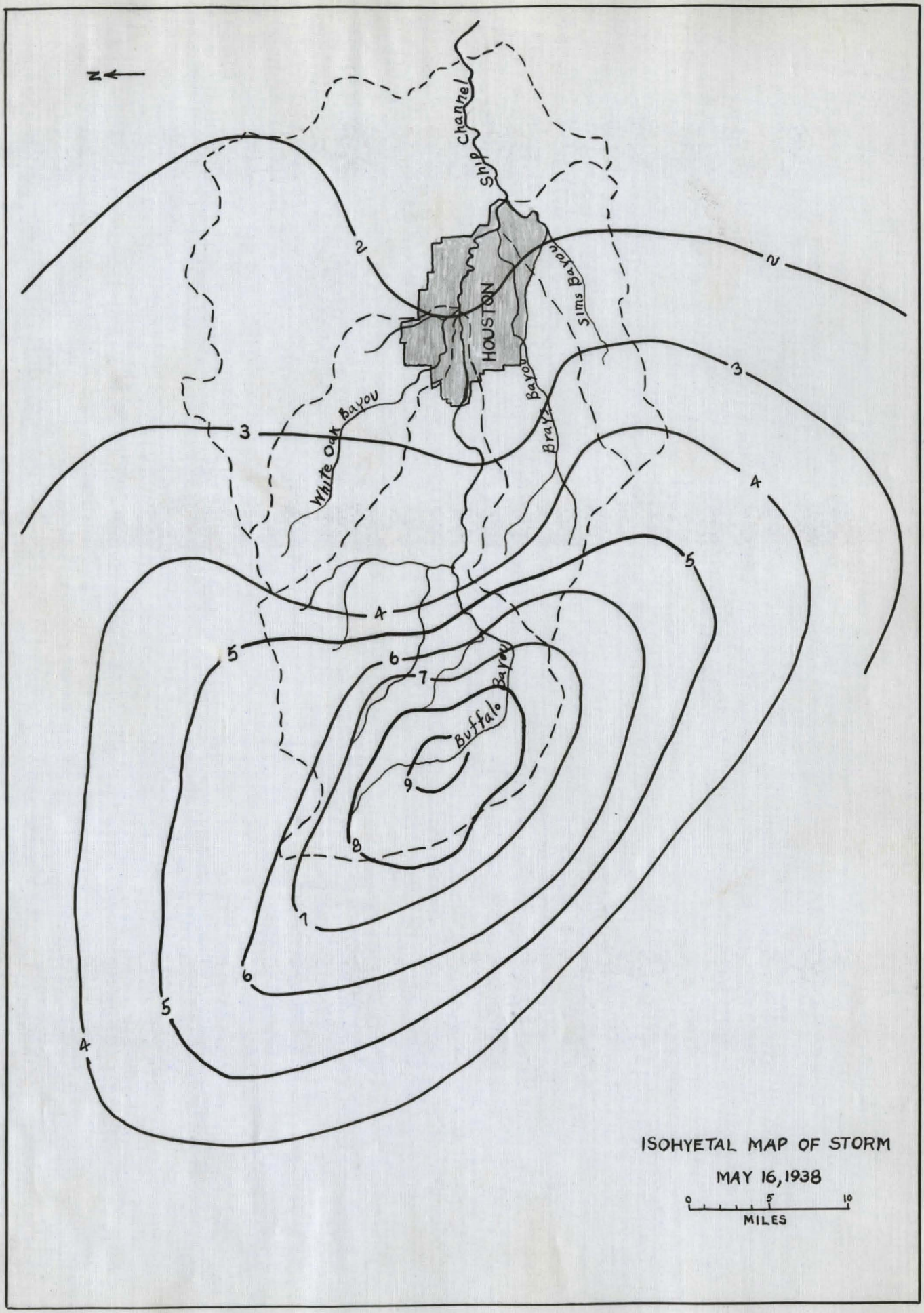

N
WALLER CO.
LIBERTY CO.
MILES
0 5 10
Mound Creek Area Runoff Flows Into Buffalo Bayou Basin During Heavy Rains
HARRIS COUNTY
Mound Creek
Cypress Creek
CYPRESS
WESTFIELD
HUMBLE
LIBERTY CO.
CHAMBERS CO.
3
6
4
2
1
5
WALLER CO.
FT. BEND CO.
Buffalo Bayou
HOUSTON
Houston Ship Channel
GALVESTON BAY
FT. BEND CO.
BRAZORIA CO.
BRAZORIA CO.
GALVESTON CO.
LOCATION OF RAIN GAGES

Fig. 20



ISOHYETAL MAP OF STORM

MAY 16, 1938

Fig. 21

6. Additional Storms Studied.

a. The following storms were plotted from the published "Climatological Data" of the U. S. Weather Bureau.

1. 1902, June 26-28, Max. rainfall 14.22 inches, at Nacogdoches, Texas.
2. 1902, July 20-30, Max. rainfall 16.90 inches, at Temple, Texas.
3. 1903, July 1-5, Max. rainfall 12.45 inches, at Beeville, Texas.
4. 1907, May 28-31, Max. rainfall 12.71 inches, at Sugarland, Texas.
5. 1913, Oct. 1-4, Max. rainfall 14.79 inches, at Boerne, Texas.
6. 1913, Dec. 1-5, Max. rainfall 15.50 inches, at San Marcos, Texas.
7. 1914, May 26-30, Max. rainfall 11.92 inches, at Beaumont, Texas.
8. 1914, Aug. 5-9, Max. rainfall 12.77 inches, at Beeville, Texas.
9. 1915, April 21-26, Max. rainfall 16.34 inches, at Austin, Texas
10. 1915, Aug. 16-20, Max. rainfall 19.83 inches, at San Augustine, Texas.
11. 1918, Nov. 5-9, Max. rainfall 16.21 inches, at Stephenville, Texas.
12. 1919, July 21-25, Max. rainfall 12.86 inches, at Cuero, Texas.
13. 1919, Sept. 14-17, Max. rainfall 12.00 inches, at George West, Texas.
14. 1921, June 21-25, Max. rainfall 14.07 inches, at Austwell, Texas.
15. 1922, April 23-28, Max. rainfall 11.14 inches, at Fort Worth, Texas.
16. 1924, May 29-30, Max. rainfall 13.85 inches, at Conroe, Texas.
17. 1932, June 30-July 2, Max. rainfall 20.28 inches, at Uvalde, Texas.
18. 1932, Aug. 29-Sept. 7, Max. rainfall 20.08 inches, near Fairfield, Texas.
19. 1933, July 22-27, Max. rainfall 21.30 inches, near Logansport, La.
20. 1936, May 22-29, Max. rainfall 15.27 inches, at Lagrange, Texas.
21. 1936, Sept. 14-17, Max. rainfall 25.19 inches, at San Angelo, Texas.
22. 1936, Sept. 25-27, Max. rainfall 15.45 inches, at Hillsboro, Texas.

With the exception of the June 30-July 3, 1932 storm and that of September 14-17, 1936, no data other than that published in "Climatological Data" were used. In those two instances peak readings were obtained from U. S. Geological Survey Water-Supply Paper No. 816.

b. The following storms were also investigated.

23. 1900, April 5-8.
24. 1900, July 12-17.
25. 1900, Sept. 20-24.
26. 1901, Oct. 7-8.
27. 1903, Oct. 10.
28. 1908, May 22-25.
29. 1911, April 30,--May 3.
30. 1913, June 27-30.
31. 1913, Sept. 24-28.
32. 1914, April 25-28.

33. 1915, Nov. 16-20.
34. 1915, May 26-28.
35. 1919, July 17-20.
36. 1920, May 12.
37. 1921, April 25-26.
38. 1923, May 18-20.
39. 1923, June 7-11.
40. 1924, June 20-22.
41. 1929, March 12-15.
42. 1930, April 28.
43. 1930, Oct. 3-7.
44. 1933, Sept. 4-5.
45. 1935, May 30-31.
46. 1938, May 4-7.
47. 1938, July 19-24.

C. THE DESIGN STORM

1. Quantity.

a. It was mentioned in Part A, Par. 6, in the discussion of Meteorology and Rainfall, that the Buffalo Bayou basin is in an area subject to all of the circumstances making possible large storms. Judging by the magnitude of the flood that was produced on Buffalo Bayou, the Westfield storm of December 1935 was the most intense storm to visit the basin in the period 1835 to 1938. However, had the 1935 Westfield storm been centered over the basin, it would have produced a more severe flood than the one that actually occurred. There is no meteorological reason evident why the storm could not have been centered squarely over the basin.

b. A careful study of the isohyetal maps of past storms gives weight to the belief that only chance has prevented the occurrence of a storm over the basin much larger than that of 1935 at Westfield. The storm showing the largest depth of rainfall over a large area of any observed in the United States (1899 at Hearne) occurred 90 miles from Houston under meteorological conditions that probably could be closely approximated over Buffalo Bayou. Should such a storm visit the area, the average rainfall over the basin would be in excess of 29 inches, almost twice the average of 15 inches that produced the disaster of 1935.

c. The Balcones Escarpment is a fault zone crossing the state of Texas in a northeast-southwest direction, roughly parallel to the coast and 150 to 200 miles inland. The zone in the southern

portion marks a sharp increase in elevation and appears to influence precipitation. The isohyetal maps of the largest past storms show that, although there is without doubt some effect from the Balcones Escarpment, there are many storm centers that seem to show very little effect of the escarpment at all. A comprehensive study of air mass and frontal conditions would explain their occurrence both inland from the escarpment (Sept. 1936, etc.) or coastward from the escarpment (Aug. 1932, July 1933, Dec. 1935, etc.). However, the fact that major storms have occurred on all sides of the Buffalo Bayou basin, is evidence that they might occur directly over the basin. There are no topographic features or atmospheric conditions peculiar to the Buffalo Bayou locality that would warrant ignoring the possibility.

d. For design purposes, it appears reasonable to assume that the June 27 - July 1, 1899 storm centered at Hearne of 34.5 inches may be transposed and superimposed over the Buffalo Bayou basin as shown on Fig. 22. For comparative purposes Fig. 23 has been prepared as a summary sheet of the area-rainfall curves of 10 major Texas storms. Note that the 1899 curve is above those of 1921 and 1932, and far enough above the maximum storm of 103 years of flood record for the basin (Dec. 1935) to warrant its use with a feeling of safety.

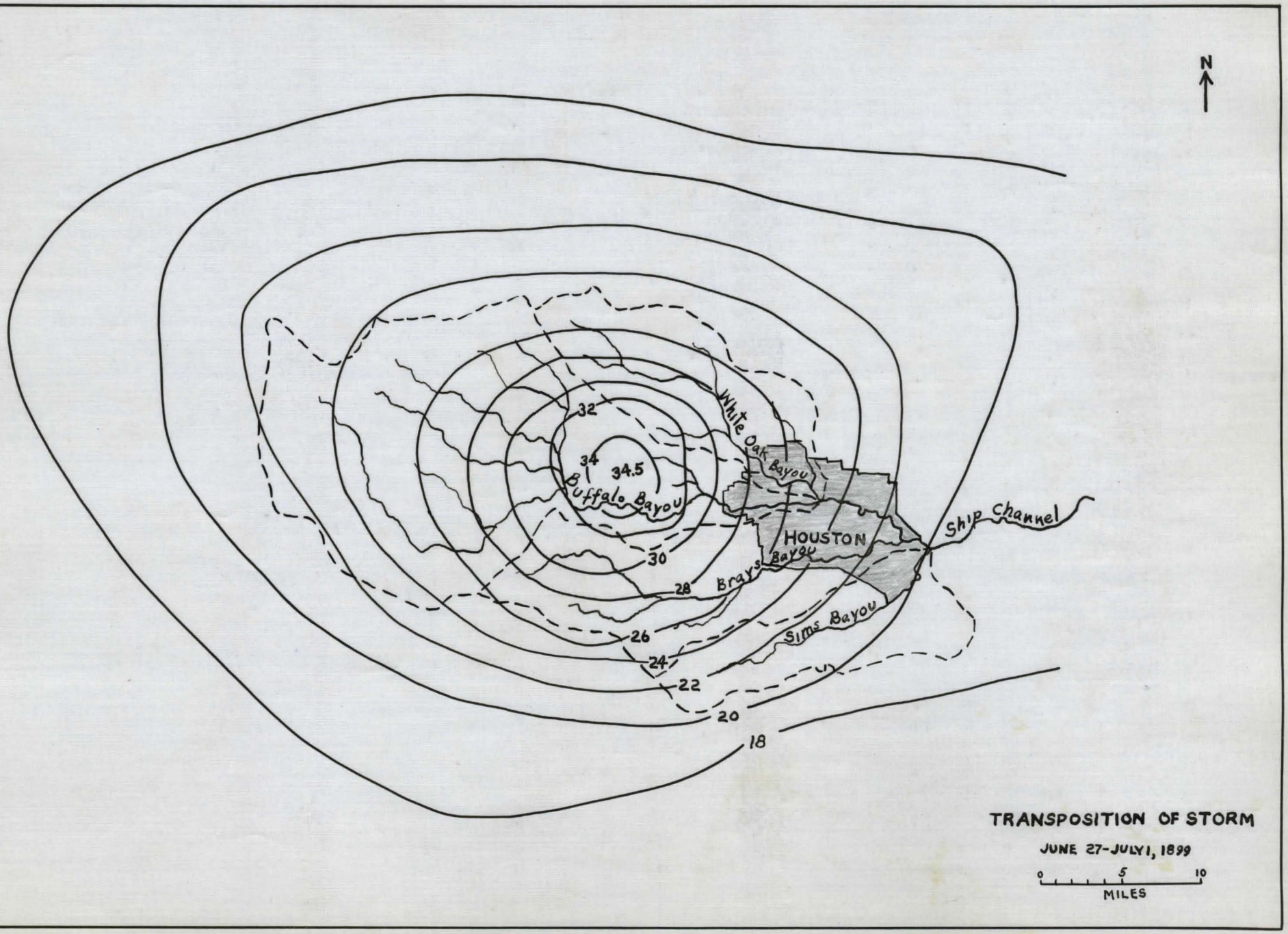
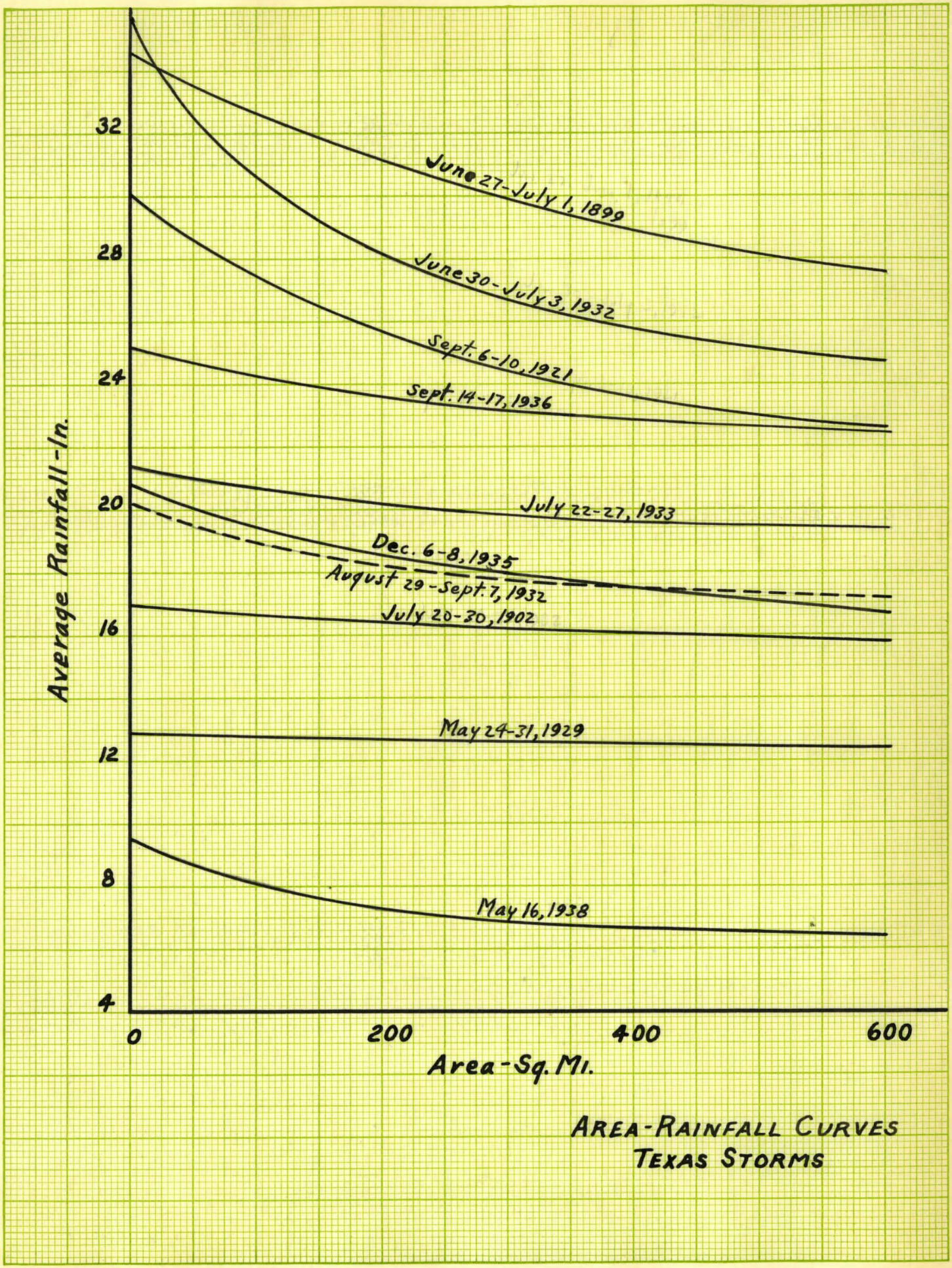

N
32
34
34.5
30
28
26
24
22
20
18
White Oak Bayou
Buffalo Bayou
HOUSTON
Ship Channel
Brays Bayou
Sims Bayou
TRANSPOSITION OF STORM
JUNE 27-JULY 1, 1899
0
5
10
MILES

Fig. 22



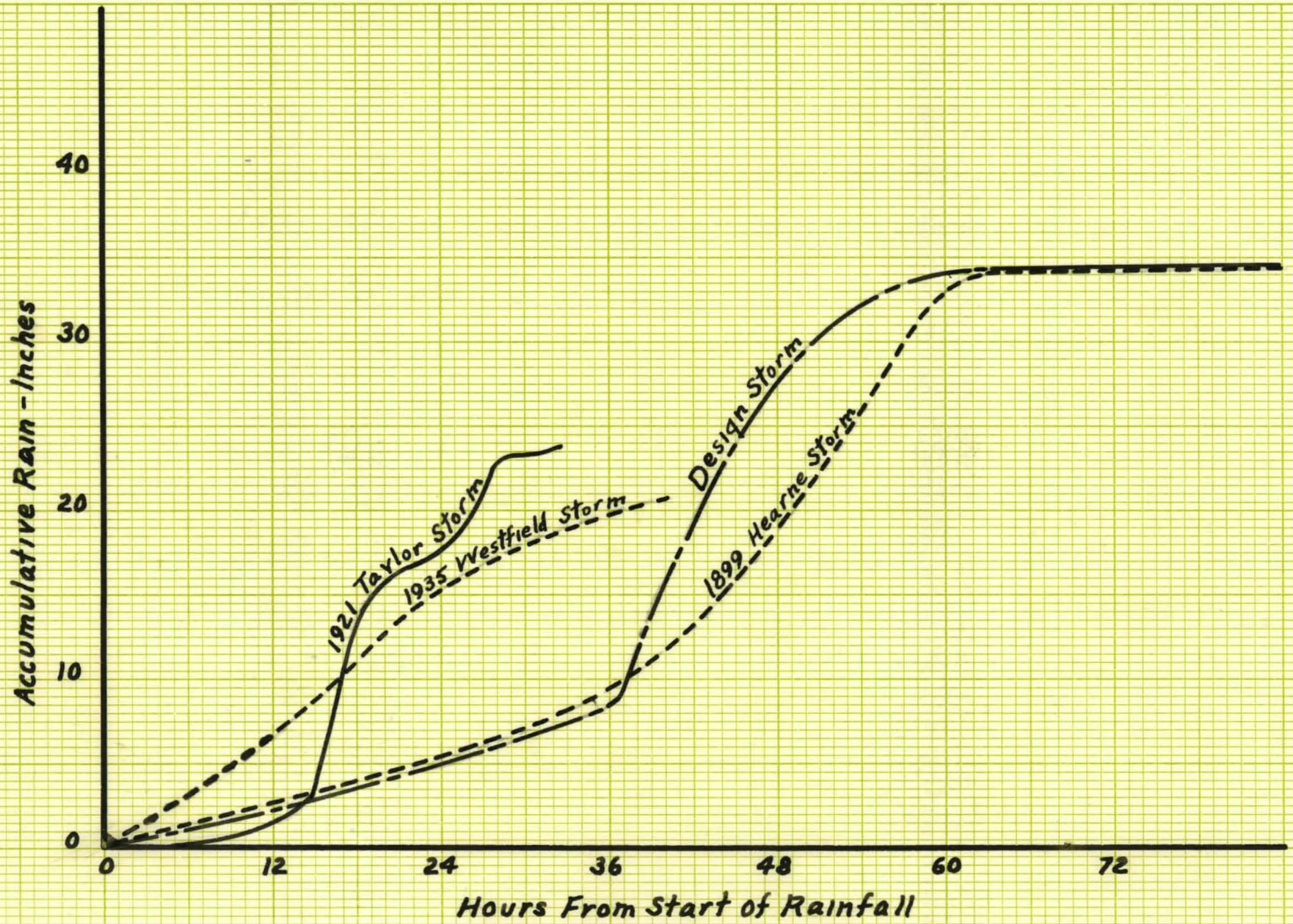
AREA-RAINFALL CURVES
TEXAS STORMS

Fig. 23

2. Rate of Rainfall.

a. The plan for flood-control, recommended by the Division Engineer in H. D. 456, 75th Congress, 2nd Session, consists of storage with a detention dam in the vicinity of Addicks and channel rectification on Buffalo Bayou below this dam. Although various plans of diversion have been proposed and studied, none of them has been found economical in the studies made to date. It follows that if detention of part of the flow is included in the plan, the greatest rainfall that can occur within the time of concentration of the uncontrolled area below the detention dam, after sufficient rain has fallen to build up the controlled flow, will produce the peak discharge to be taken through Houston.

b. Studies based on the characteristics of streams in the vicinity imply that the uncontrolled area below the Addicks damsite would have a time of concentration equal to about one day. As brought out in Part B, paragraphs 1 c, 2 a, and 4 e, in the studies of the 1899, 1921, and 1935 storms, a major portion of the rainfall occurred in 24 hours or less. (See Fig. 24). The rain falling in the earlier part of the storms whose mass curves are shown on Fig. 24 would have been sufficient to build up the regulated flow from the detention reservoir at Addicks, leaving the high rate at the end of the storm to produce a severe flood from the uncontrolled area below the reservoir. The storm producing the most rain in 24 hours was the 1921 Taylor storm, as shown on the mass curve, Fig. 24, and as indicated by the statement in U.S.G.S. Water Supply Paper No. 488 that, "it seems assured that some 30 inches



MASS RAINFALL CURVES

COMPARISON

Fig. 24

of rain fell in 15 hours." Although the maximum rainfall actually recorded for the storm in a 24-hour period was about 23.11 inches, Taylor was not at the center of the storm and the extreme rate, unfortunately, was not observed officially.

c. Guided by the rates observed in the past in Texas storms, it seems logical to expect corresponding rates in the storm that would produce the maximum rainfall of 34.5 inches over the Buffalo Bayou basin. The Hearne rate of 24.0 inches for 24 hours, from Fig. 24, is not as high as the officially observed Taylor rate, and if credence is given to the unofficial readings at Taylor, the Taylor rate was far in excess of that at Hearne. Accordingly, it appears reasonable to assume that the 34.5 inches of rain accepted as the maximum probable for the basin may be distributed in the manner shown on the mass curve sheet, Fig. 24 and marked "Design Storm". This distribution will probably produce a maximum flow on Buffalo Bayou above Main Street and indicates a reasonable manner in which the rain could fall.

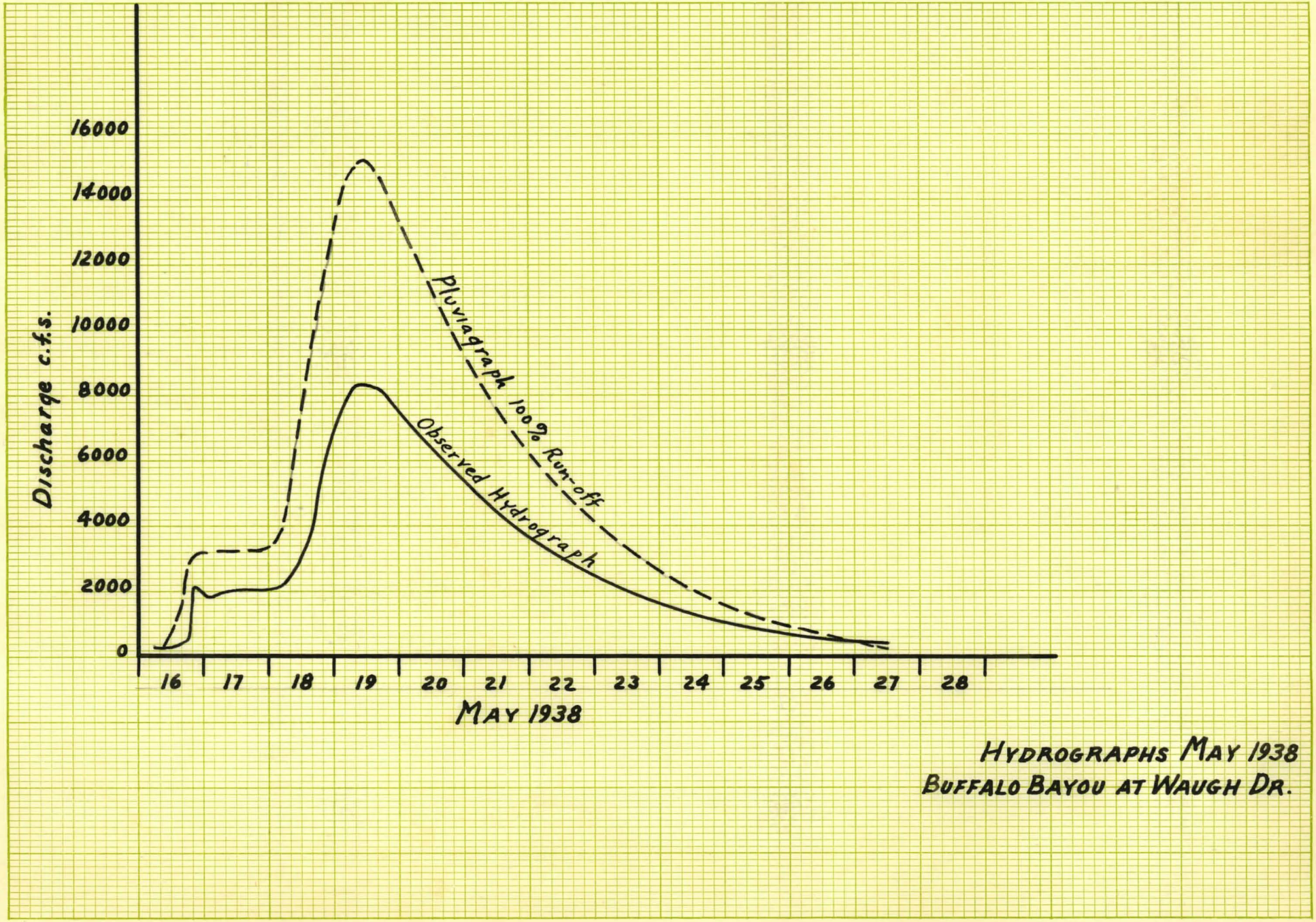
d. If 34.5 inches of rain distributed in the manner of the "Design Storm" on Fig. 24 be used, it is believed that no further allowances need be made for an added factor of safety. It did not appear reasonable to jeopardize the safety of the project by reducing either the amount or the intensity below the "Design Storm" shown on Figs. 23 and 24.

D. DEVELOPMENT OF THE DISTRIBUTION GRAPH

1. The Storm of May 16, 1938.

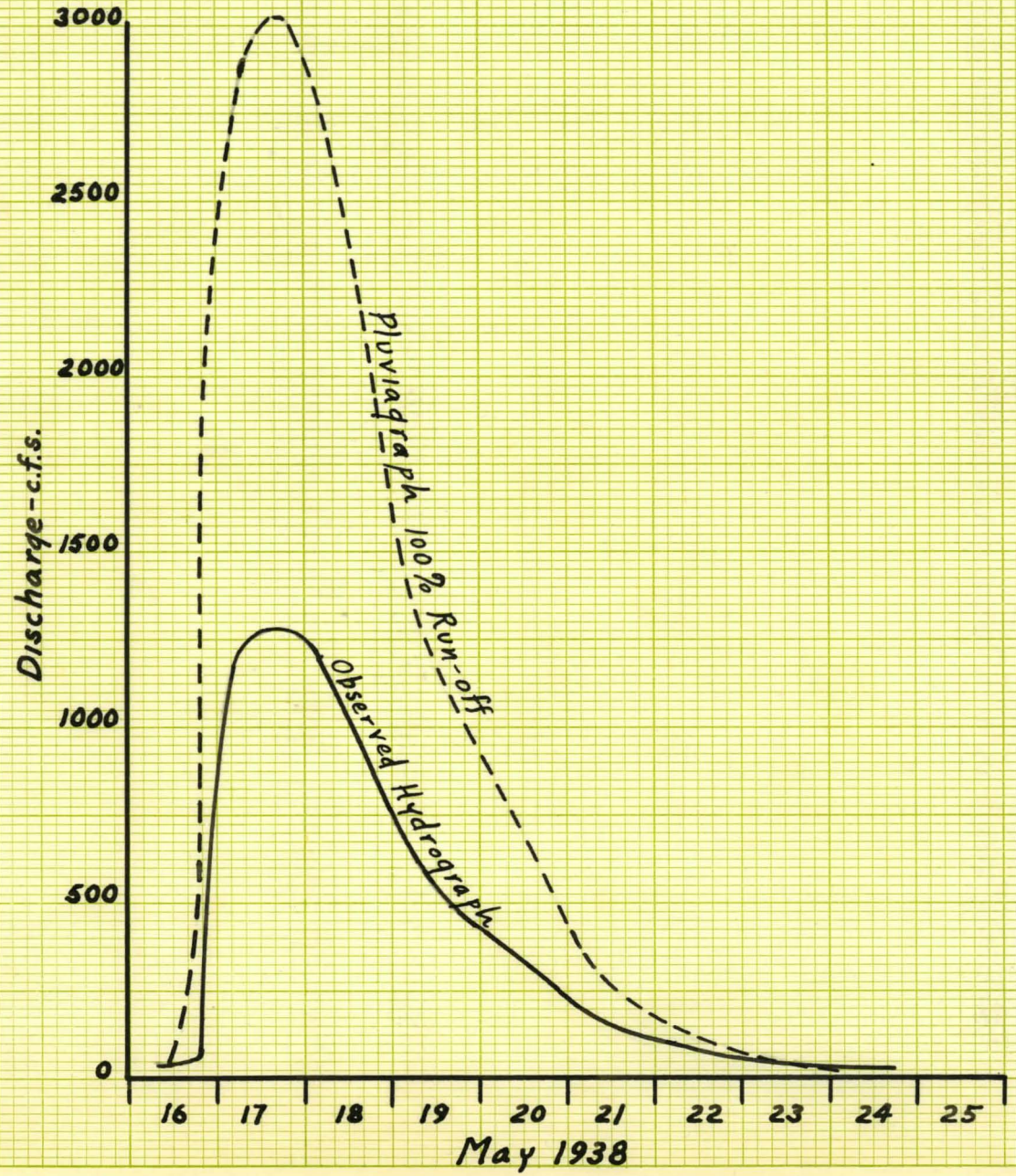
a. As outlined in the discussion of the May 16, 1938, storm in Part B, par. 5 a, practically the entire rainfall occurred within 12 hours. Excellent coverage of the area in the Buffalo Bayou basin had been obtained with the installation of six recording gages by the city of Houston. To supplement the city data, the records of 10 nearby U. S. Weather Bureau stations were used also. The average rainfall over the Buffalo Bayou basin was computed to be 5.53 inches. Over White Oak Bayou the average was computed to be 3.12 inches. The average value was obtained by planimetering the isohyetal map, shown as Fig. 21 and making the proper computations.

b. The run-off from the Buffalo Bayou basin was obtained from two sources. The Galveston office made observations of stage and discharge at the Eureka Cutoff bridge over Buffalo Bayou and checked favorably with the U. S. Geological Surveys' rating curve at Waugh Drive bridge. (For location see Fig. 2). A complete discharge hydrograph of the rise has been constructed and is included herewith as Fig. 25. Rains in the earlier part of the month produced a base flow estimated at 350 c.f.s. in Buffalo Bayou, and that amount was deducted in the computation of the distribution graph. For White Oak Bayou the base flow was estimated at 60 c.f.s. On that stream the U. S. Geological Survey records at Yale Street (See Fig. 2) were used. A complete hydrograph was obtained for that station and is included as Fig. 26.



HYDROGRAPHS MAY 1938
BUFFALO BAYOU AT WAUGH DR.

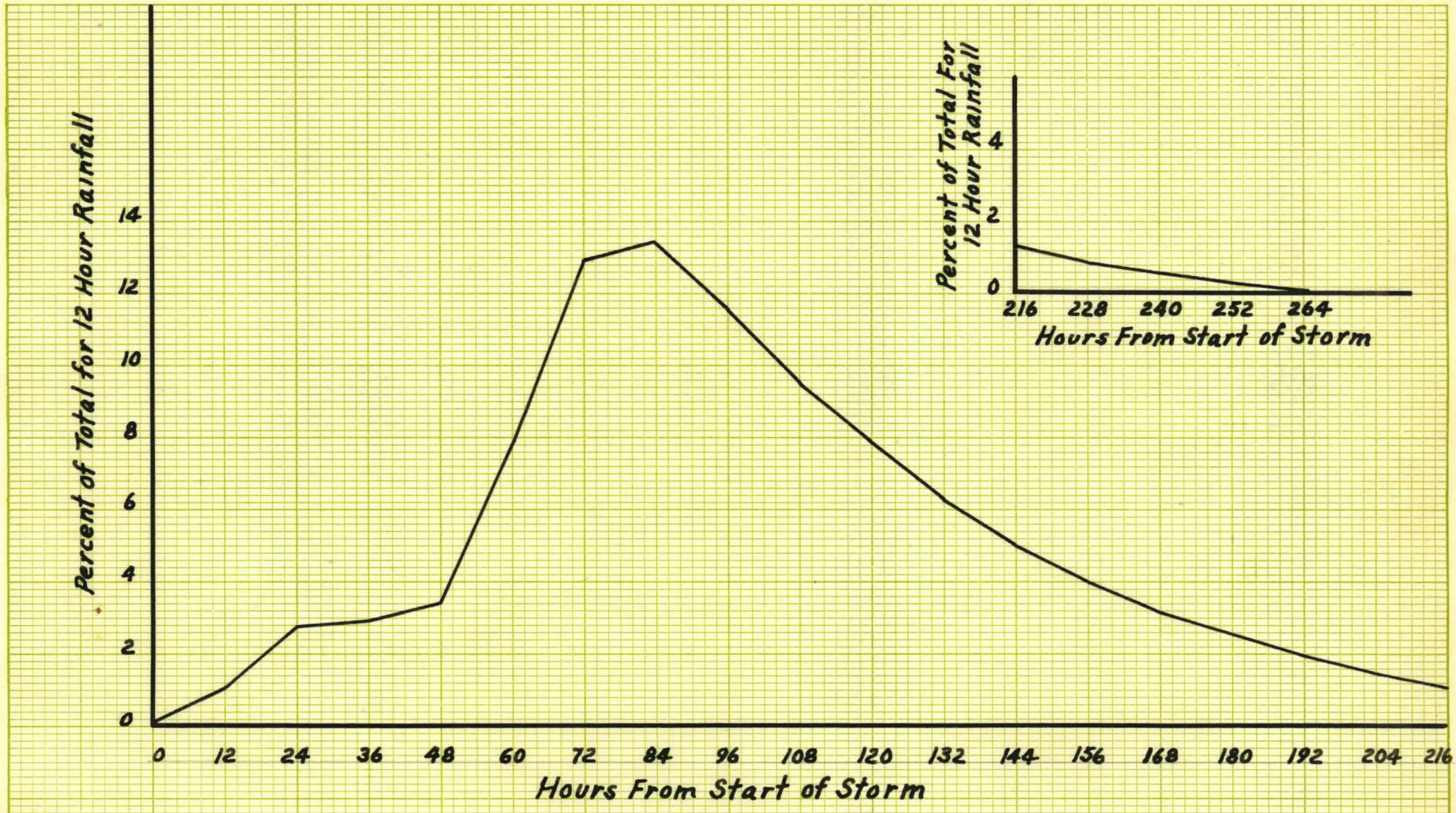
Fig. 25



HYDROGRAPHS MAY 1938

WHITE OAK BAYOU AT MAIN STREET

Fig. 26

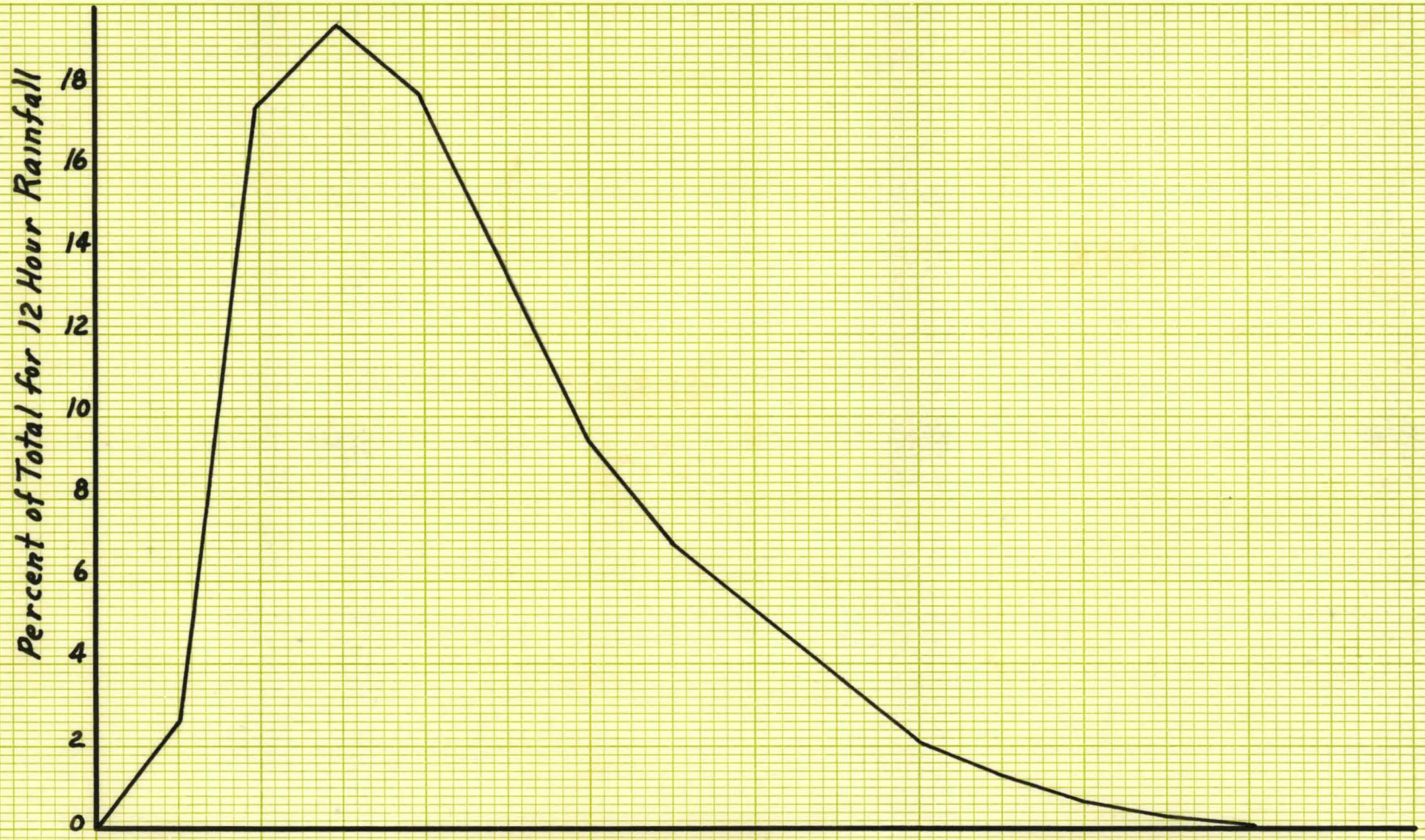


Note: 1. Distribution graph for 12 hour storm May 16, 1938 from U.S.G.S. hydrograph at Waugh Drive bridge.

2. Plotted points are means for preceding 12 hr. periods.

DISTRIBUTION GRAPH
BUFFALO BAYOU AT WAUGH DRIVE
MAY 16-27, 1938

Fig. 27



Note: 1. Distribution graph for 12 hr. storm May 16, 1938 from U.S.G.S. hydrograph at Yale St. bridge.

2. Plotted points are means for preceding 12 hr. periods.

DISTRIBUTION GRAPH
WHITE OAK BAYOU AT YALE ST.
MAY 16-24, 1938

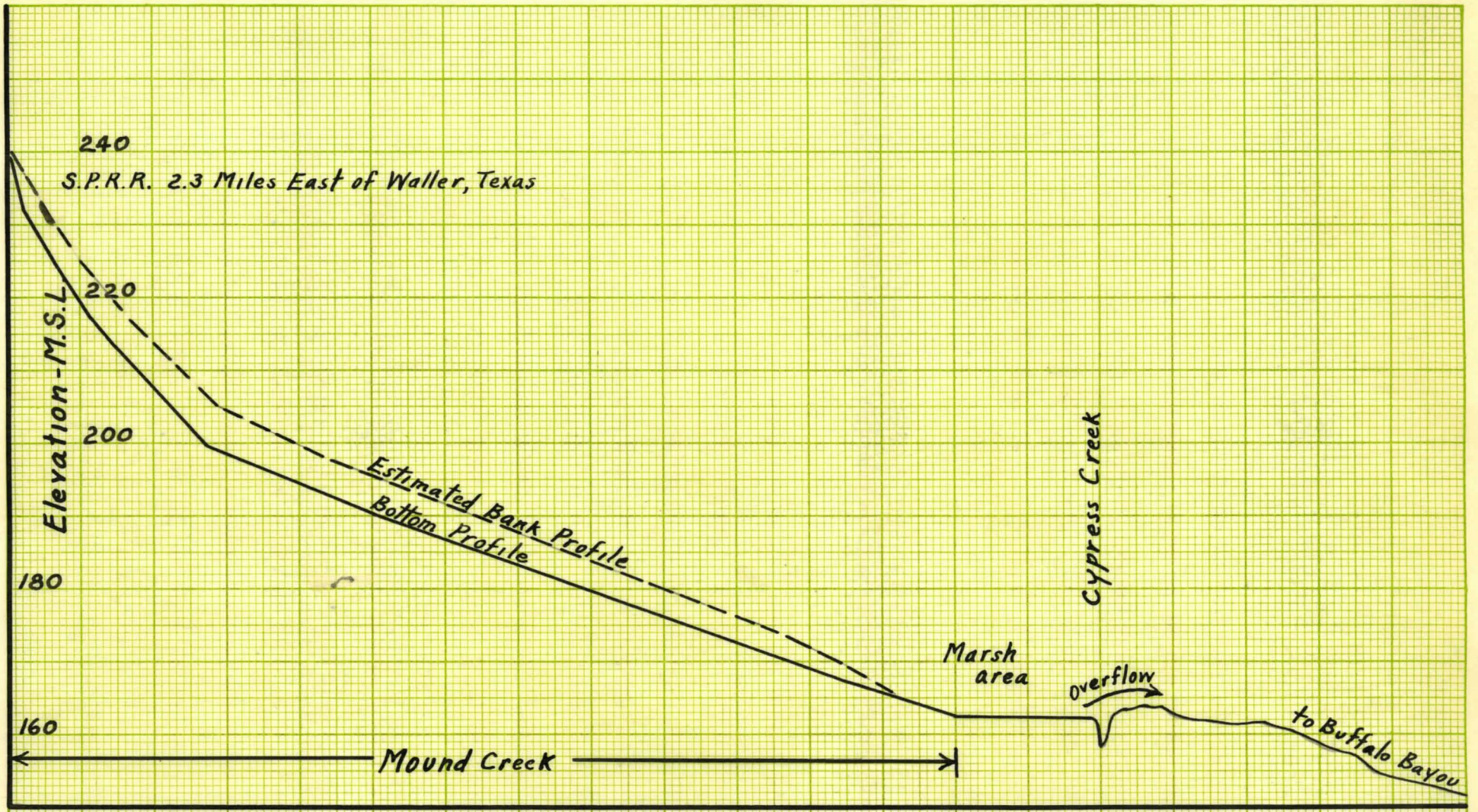
Fig. 28

c. The distribution graph for Buffalo Bayou as shown on Fig. 27 was prepared by deducting the base flow, determining the net discharge, and computing the ratio of the observed 12-hour mean discharges to the net discharge. The method used was the same for both Buffalo and White Oak Bayous. The computed distribution curves are included herewith as Figs. 27 and 28. As a check on the results, the pluviagraphs, or curves of 100 per cent run-off, were computed and are shown on the same sheets as the observed hydrographs, Figs 25 and 26. As shown, the curves peak at the same time and appear to be in accord. Even though the May 1938 storm was concentrated in the upper end of the watershed and was a comparatively small storm, it is believed that the derived distribution graphs can be used safely for predicting flood flow for larger storms, within certain limits which are considered in the following discussions.

2. Check application of distribution graphs.

a. There are numerous sources of error in applying the distribution graph from the May storm to storms considerably larger. Predicting the high water flow from Buffalo Bayou is complicated by several circumstances. The exceeding flatness of the basin permits overflow out of the basin as well as flow from other streams into the basin. Probably the most important inflow is that from Mound Creek. As shown by the included profile, Fig. 29, the creek empties into a flat marsh whose elevation is about two feet below the crest of the Cypress Creek - Buffalo Bayou divide. Rains producing flows from Mound Creek that exceed the channel capacity of the upper portion Cypress Creek, cause overflows across the low divide into the Buffalo Bayou Basin. Such flow occurred during the May 1938 storm and is included in the observed hydrograph. For flows equal to the 1929 flood, there is inflow from Mound Creek, but no outflow from Buffalo Bayou to other basins. For flows as large as that of 1935, there is inflow from Mound Creek, inflow from White Oak Bayou, and outflow to Brays Bayou. All of these inflows and outflows are highly variable and almost indeterminate with the data at hand.

b. The flow from White Oak Bayou is as complicated as that from Buffalo Bayou, with less observed data upon which to base reasonable estimates. In the May 1938 rise there was no inflow to the White Oak basin from other basins, nor was there outflow to other basins. However, in 1935 there was overflow into Buffalo Bayou, as shown in blue on Fig. 1, and reports of inflow from Cypress Creek to White Oak Bayou and from Halls Bayou to Little White Oak Bayou, as shown in red on Fig. 1. The amounts of overflow are practically indeterminate.

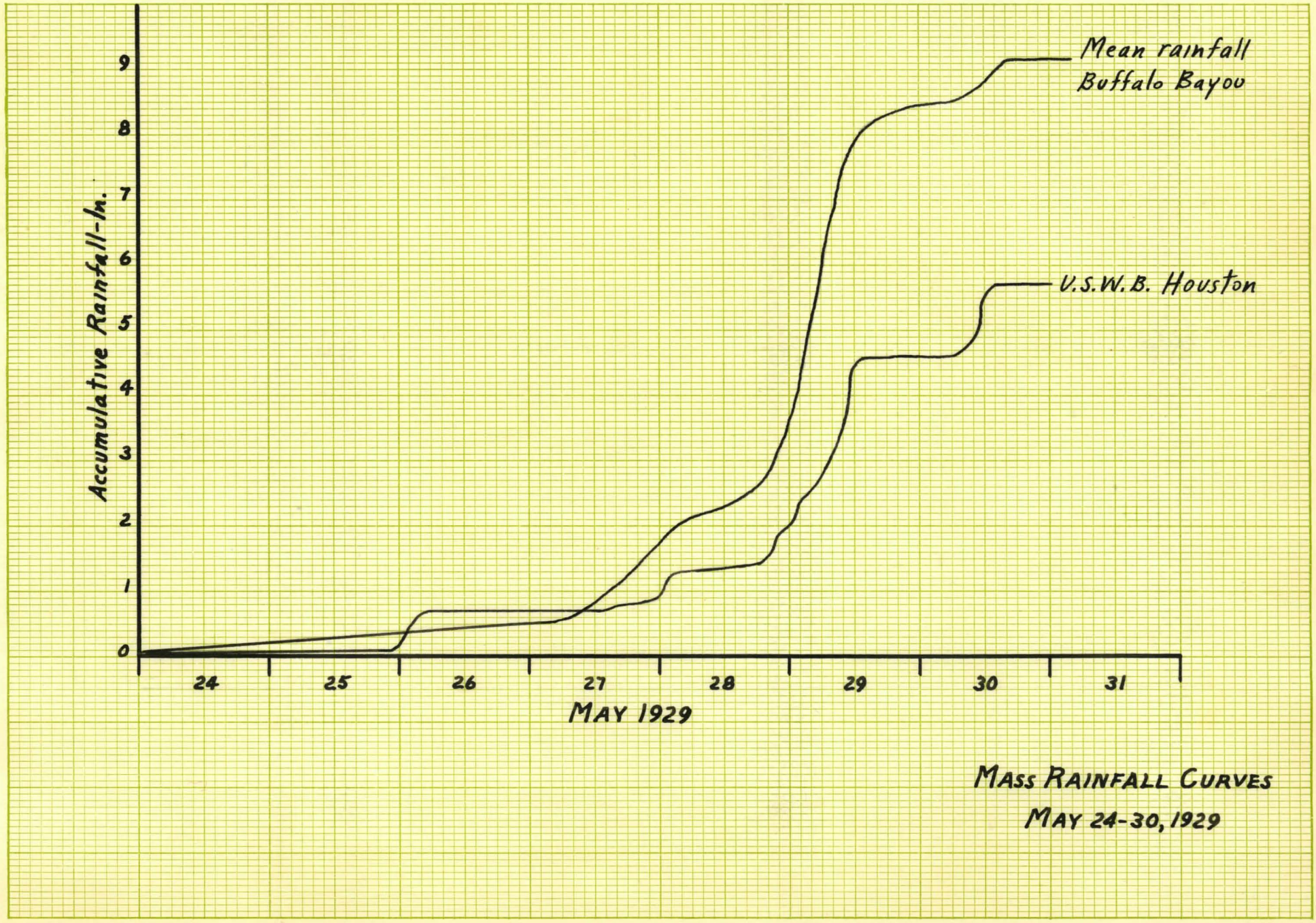


PROFILE OF
CYPRESS CREEK -
BUFFALO BAYOU DIVIDE

Fig. 29

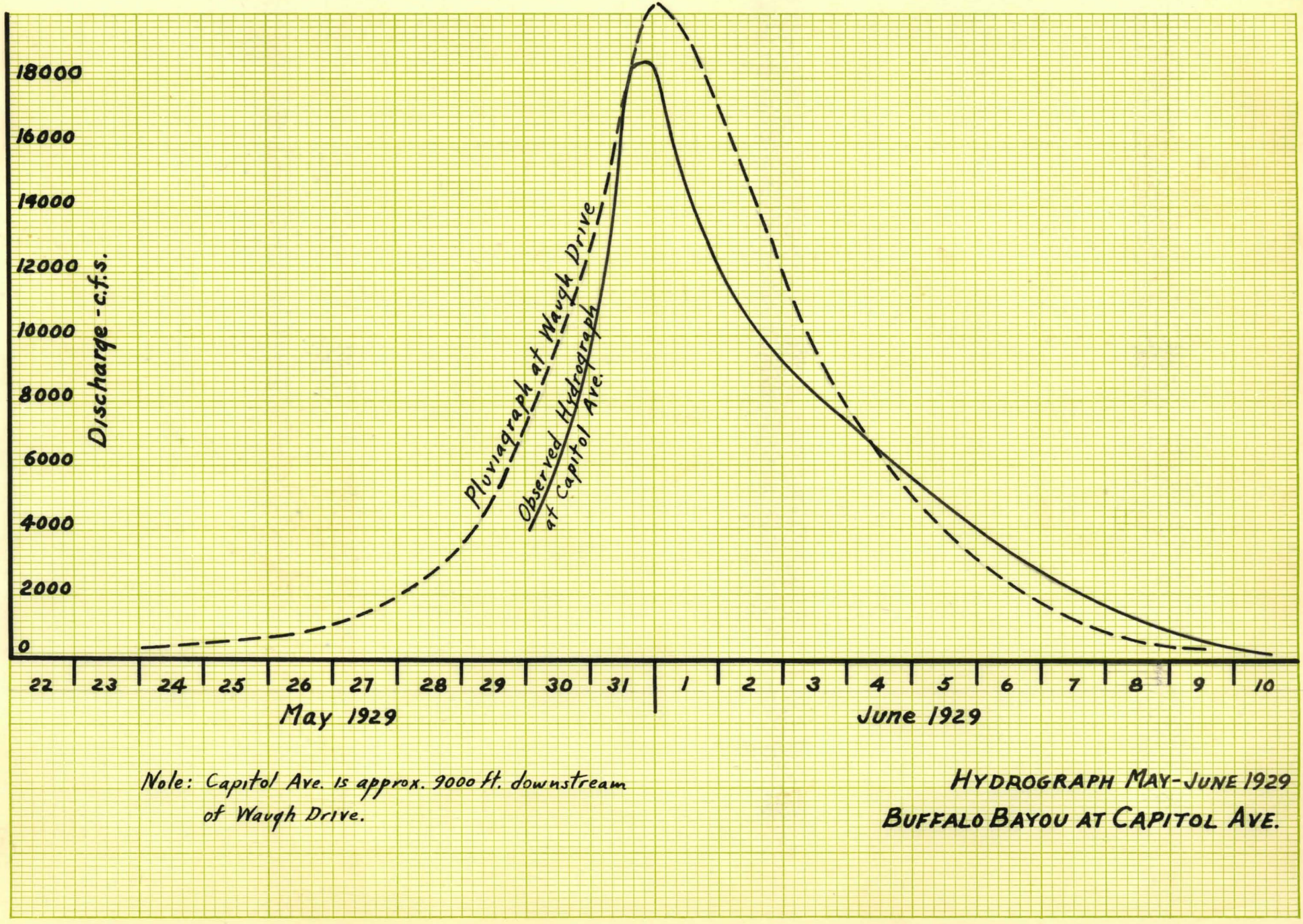
c. Notwithstanding the aforementioned sources of error in the application of the May 1938 distribution graph to larger storms, reasonable answers can be obtained. The inflow from Mound Creek was included in the May hydrograph, and as that inflow is roughly proportional to the rainfall, the inflow as a result of larger storms will effect hydrographs produced by those storms in a proportional manner. By obtaining the relation between observed hydrographs and computed hydrographs for the same flood, it is possible to predict the flow for the design storm with a reasonable degree of accuracy.

d. The 1929 storm produced a flood large enough to test the accuracy of application of the distribution graph, and reliable information is available on the rainfall and run-off. Daily isohyetal maps of the basin were furnished by the city of Houston. Those maps were planimetered and mean daily rainfall figures computed. With the hourly rainfall record of the U. S. Weather Bureau station at Houston as a guide, the mean accumulative rainfall for the basin was plotted and is included as Fig. 30. By applying the distribution graph values to the average 12-hour rainfall values, a pluviagraph was obtained for the 1929 flood. The computed pluviagraph and the observed hydrograph were plotted on the same sheet and included herewith as Fig. 31. Because of previous rains a base flow of 350 c.f.s. was added to the computed values. Assuming that all the run-off was produced by Buffalo Bayou, the ratio of run-off to rainfall is 0.8. The flood coefficient, or ratio of peak run-off to the computed 100% peak is 0.92. It is not known definitely what effect inflow from or outflow to adjacent basins had on the 1929 hydrograph, but it is known that there was inflow from Mound Creek.



MASS RAINFALL CURVES
MAY 24-30, 1929

Fig. 30



Note: Capitol Ave. is approx. 9000 ft. downstream of Waugh Drive.

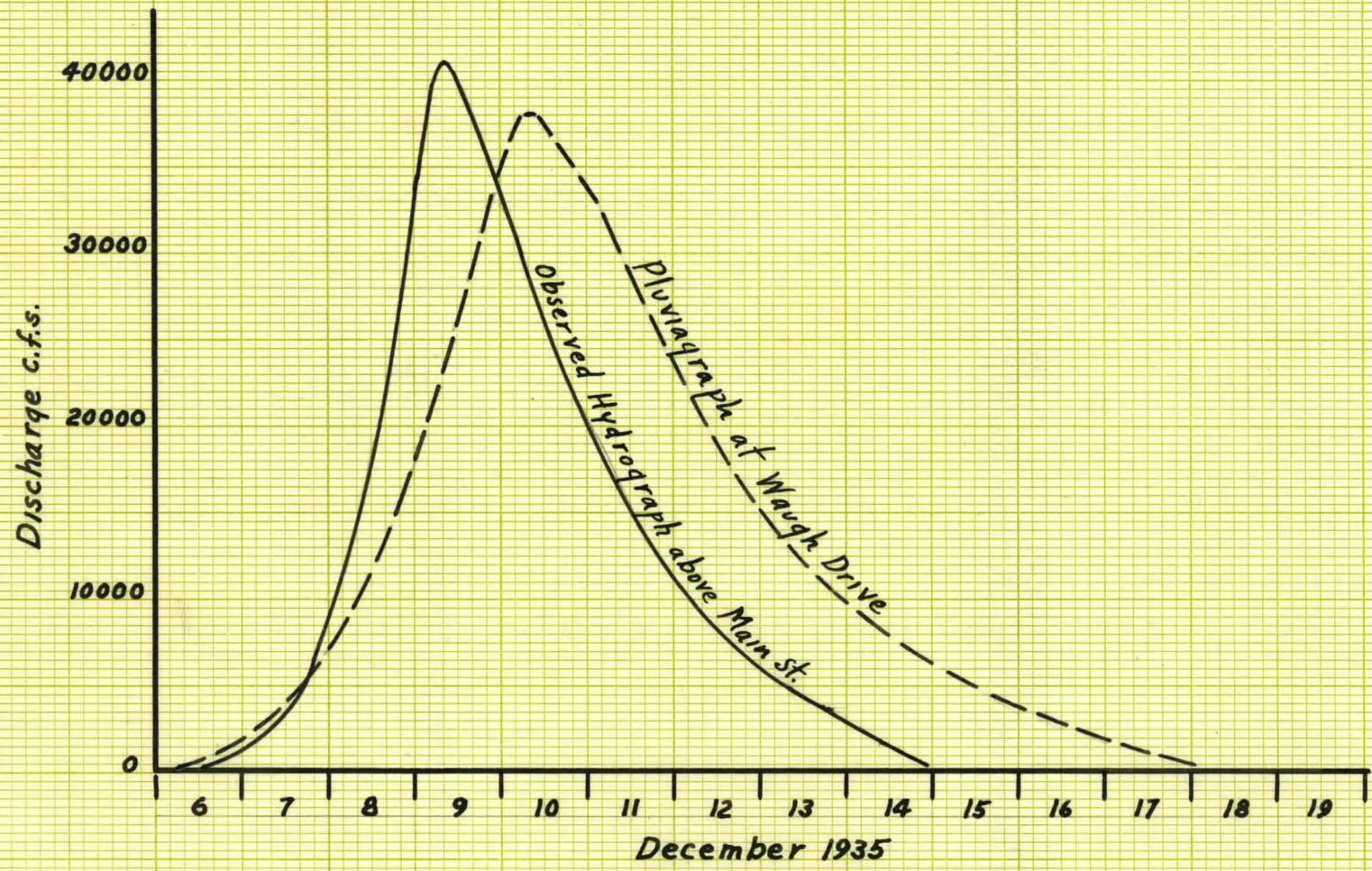
HYDROGRAPH MAY-JUNE 1929
BUFFALO BAYOU AT CAPITOL AVE.

Fig. 31

e. No data are available showing the run-off from White Oak Bayou in 1929, so no comparison can be made.

f. A more valuable check on the application of the distribution graph is the computation of the hydrograph for the 1935 flood on Buffalo Bayou. Rainfall records, as outlined in Part B, pars. 4 b and c, were available. With the station mass rainfall curves shown on Fig. 18, accumulative 12-hour isohyetal maps (not included) were constructed and the mean rainfall over the basin for 12-hour intervals was obtained. By applying the 12-hour distribution percentages of the 1938 storm to the 12-hour mean rainfall of the 1935 storm, the pluviagraphs for Buffalo and White Oak Bayous were computed for the 1935 storm and are shown on Figs. 32 and 33, respectively.

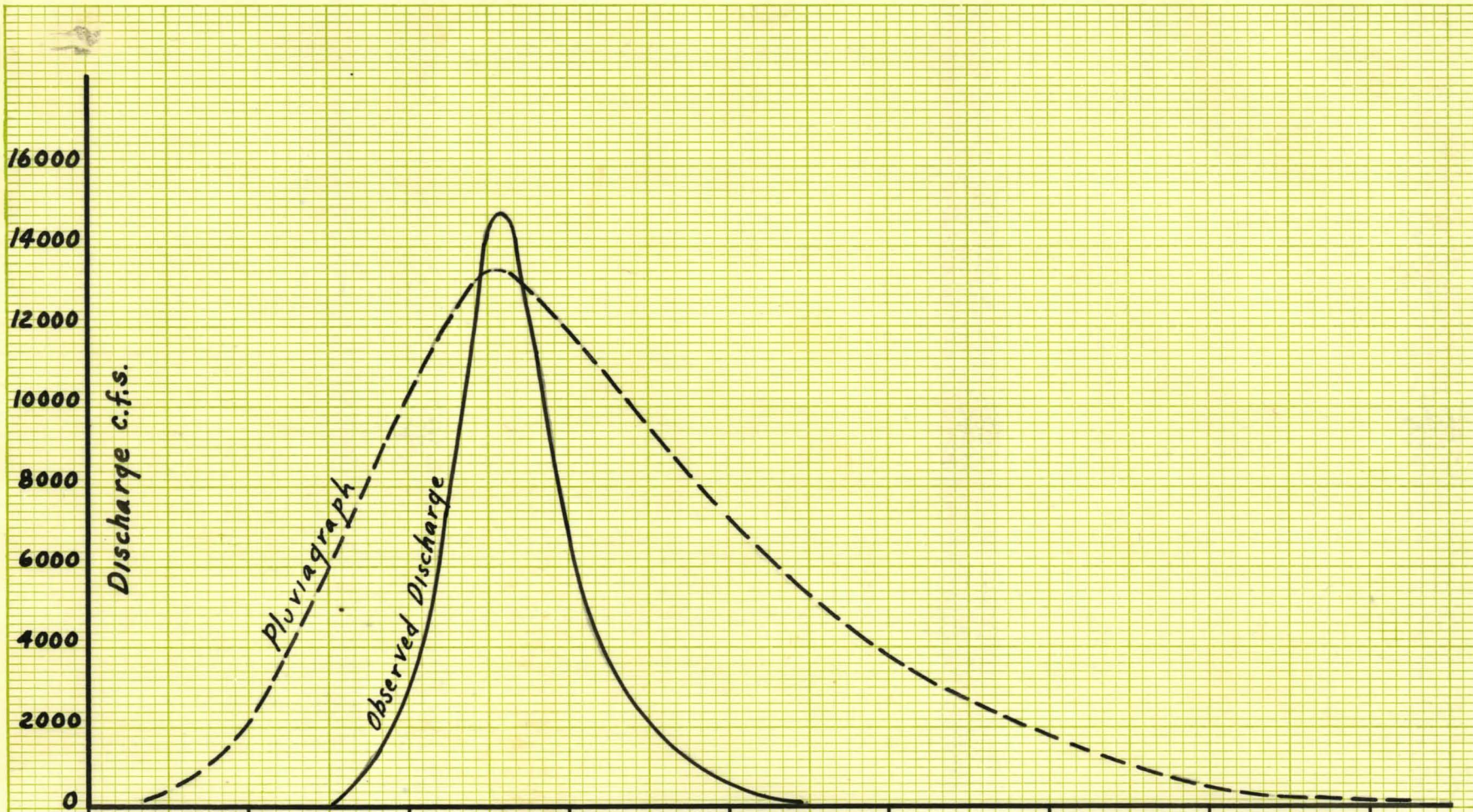
g. The available discharge hydrographs for the 1935 flood are not sufficiently accurate to produce reliable results. The Buffalo Bayou hydrograph published in H. D. 456, 75th Congress, 2nd Session, is an adjusted hydrograph and that portion of the hydrograph below the peak is not based on actual records. The peak values are probably reliable, but the hydrographs indicate lower run-off values than appear consistent with the results obtained with the lesser floods of 1929 and 1938. These adjusted observed hydrographs are included with the computed pluviagraphs on Figs. 32 and 33. The pluviagraph on Fig. 32 computed for Buffalo Bayou at Waugh Drive bridge and the observed hydrograph is described by the city of Houston as having been obtained "above Main Street." (For location, see Fig. 2). The observed peak occurred about 24 hours earlier than the computed peak and is about 8% higher than the pluviagraph.



Note: Waugh Drive is approximately 2 miles above Main Street.

HYDROGRAPH DEC. 1935
BUFFALO BAYOU AT MAIN STREET

Fig. 32



HYDROGRAPH
DEC. 6-14, 1935
WHITE OAK BAYOU - YALE ST.

Fig. 33

The total indicated run-off was about 75% of that indicated by the pluviagraph, but the relatively lower value is partly due to overflow of Buffalo Bayou into Bray's Bayou above the city. (See Fig. 2). No overflow seems to have occurred in either the 1929 or 1938 storms, but there was inflow from Mound Creek on both occasions.

h. On White Oak Bayou in 1935 a stage hydrograph was observed at the M.K. & T. R.R. bridge on West 7th Street about 1.3 miles above Yale Street. A rating curve was derived also at the M.K. & T. R.R. bridge west of Stude Park. (See Fig. 2 for these locations). Unfortunately, no stage relation was established for the various flows. Therefore, it is impossible to construct complete reliable hydrographs. The peak discharge obtained by transferring the peak stage from M.K. & T. R.R. bridge on West 7th Street to the rating curve at the M.K. & T. R.R. bridge west of Stude Park by the use of the highwater profile agress satisfactorily with the U. S. Geological Surveys published estimate of the flow at Yale Street. No further comparison with 1935 data is possible because of the lack of observed data for that storm.

3. Discussion of flood coefficients.

a. Both inflows from other basins and outflows to other basins are functions of the rainfall. It is obvious from the study of the hydrographs that the ratios of observed to computed peak discharges are also functions of the rainfall. Therefore, it follows that it is possible to obtain a relationship that should aid in extrapolating the observed data to cover design storm conditions by plotting the apparent flood coefficients against the mean rainfall over the basin.

b. The computations in Part E 2, pertaining to the application of distribution graphs to Buffalo Bayou, indicate that for the May 1938 storm the flood coefficient is 0.55. For the 1929 storm the flood coefficient is 0.91 and for the 1935 storm the flood coefficient was 1.08. These values appear reasonable. In the comparatively small storm of May 1938 there was no outflow to Bray's Bayou. However, there was some inflow from Mound Creek. The rain fell on summer vegetation which had some retarding effect. In 1929 there was more inflow from Mound Creek, no outflow to Bray's Bayou, and a more prolonged and heavier rainfall. In 1935 there was large inflow from Mound Creek, some inflow from White Oak Bayou, and outflow to Bray's Bayou. However statements by witnesses, verified by the topographic features of the various basins, indicate that during rains as heavy as those in 1935 the entire country is covered by a sheet of moving water. The result is that for very heavy rains there is practically 100 per cent run-off. That fact, coupled with the various indeterminate inflows from other basins,

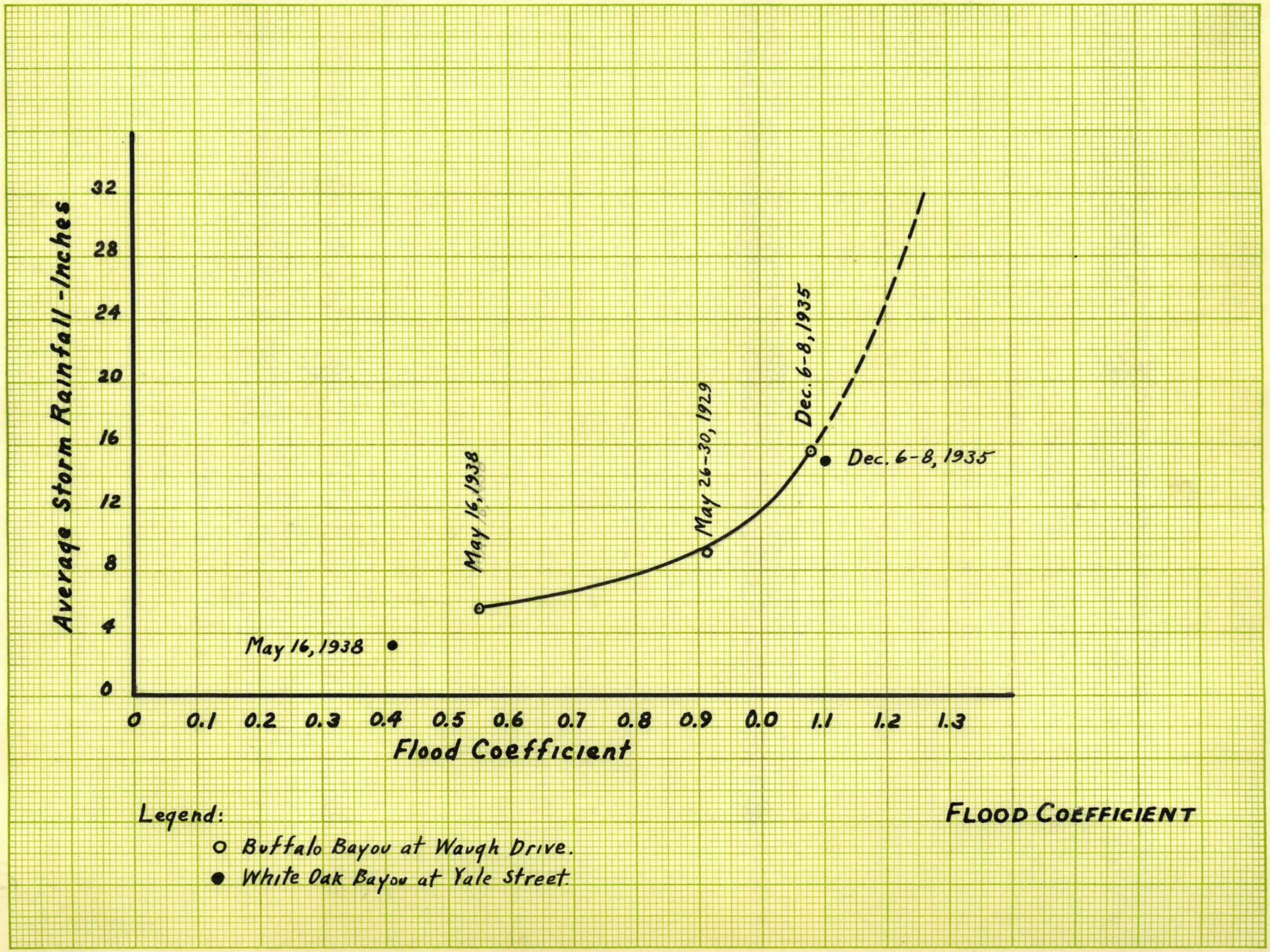


Fig. 34

verifies, in part, the unusual flood coefficient of 1.08. The curve obtained by plotting flood coefficients against mean railfall is included herewith as Fig. 34. This curve has been extended arbitrarily to cover the average of the design storm rainfall and shown by dashed line.

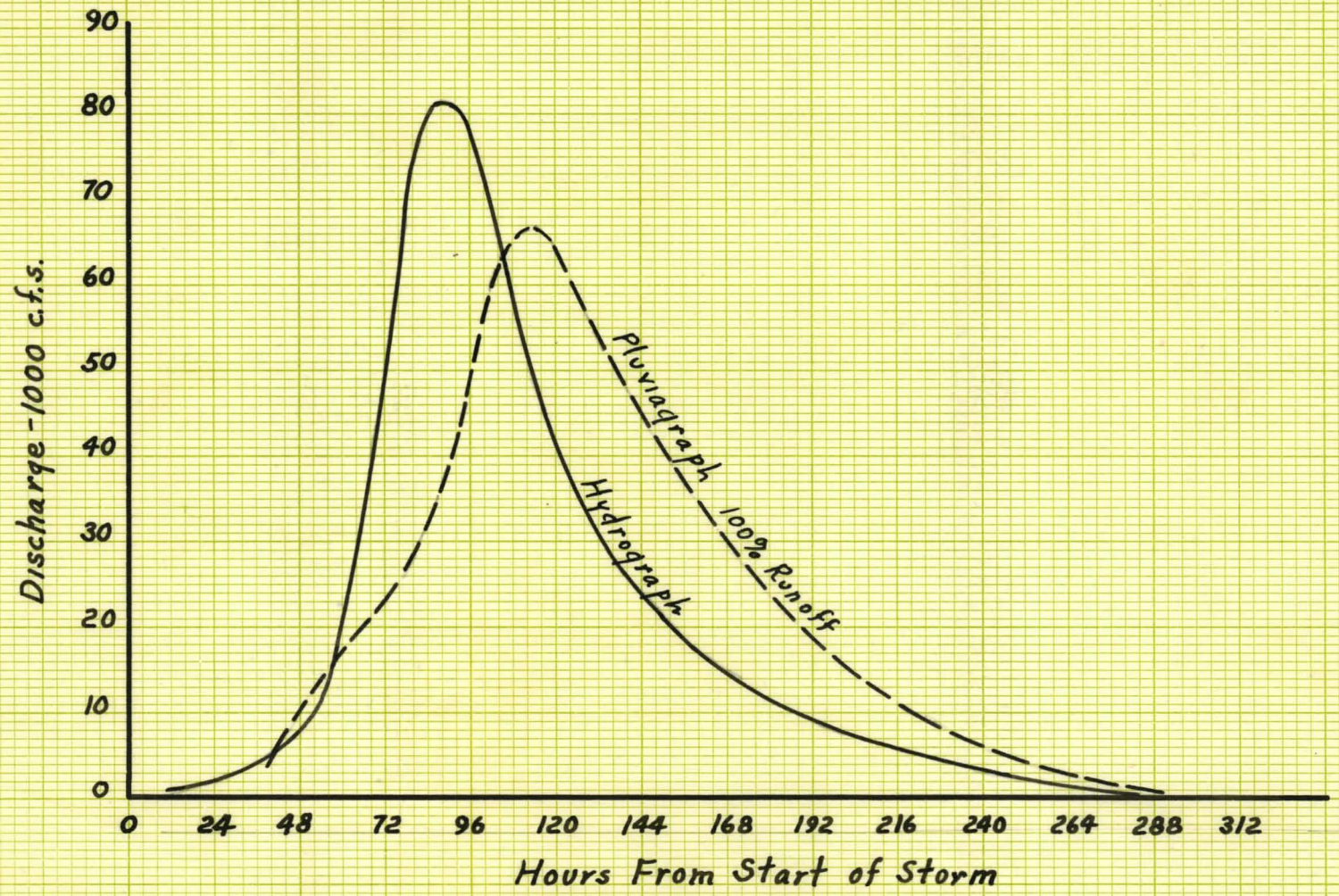
c. Due to the limited data available on White Oak Bayou, only two points can be obtained. One is for the 1938 flood and the other for that of 1935. These points are shown on the same sheet as those for Buffalo Bayou, Fig. 34.

4. Application of Design Storm to Buffalo Bayou and White Oak Bayou.

a. It was pointed out in Part C, Par. 1, that the evidence indicates that a storm producing a rainfall equal to that observed at Hearne in 1899 may occur over Buffalo Bayou. Accordingly, the Hearne center of the 1899 storm was transposed to the basin as shown in Fig. 22. The average rainfall over the basin was computed from the isohyetals. The mean rainfall was distributed in 12-hour periods in proportion to the mass rainfall curve of the design storm. (See Fig. 24). By applying the distribution percentages from Fig. 27 to the design rainfall, a pluviagraph for Buffalo Bayou at Waugh Drive was computed, and is included as Fig. 35. There is little doubt that the pluviagraph is not the curve that would actually be produced by the design storm since it neglects inflow from and outflow to other adjacent basins. In order to draw a curve representing more nearly the flow that probably would occur, certain reasonable adjustments were made as outlined in the following discussion.

b. In 1935 the flow actually reached its peak about 24 hours previous to the time indicated by the computed pluviagraph as shown on Fig. 32. Therefore, the peak for the design storm should be shifted accordingly. The value of 24-hours seems to be about as much as it is desirable to use, although the tendency seems to be toward an earlier time of peaking for the higher rainfalls.

c. For a storm as large as the design storm, there would be overflow from Mound Creek and perhaps from other areas that would



Note: 1. Hydrograph plotted assuming flow confined to Buffalo Bayou.
2. Peak of pluviagraph increased 22% to obtain hydrograph peak in accordance with results for 1929 and 1935 floods.
3. Peak of hydrograph displaced 24 hours ahead of pluviagraph peak as indicated by results for 1935 flood.
4. Total runoff 90%.

HYDROGRAPHS OF DESIGN STORM
BUFFALO BAYOU AT WAUGH DR.

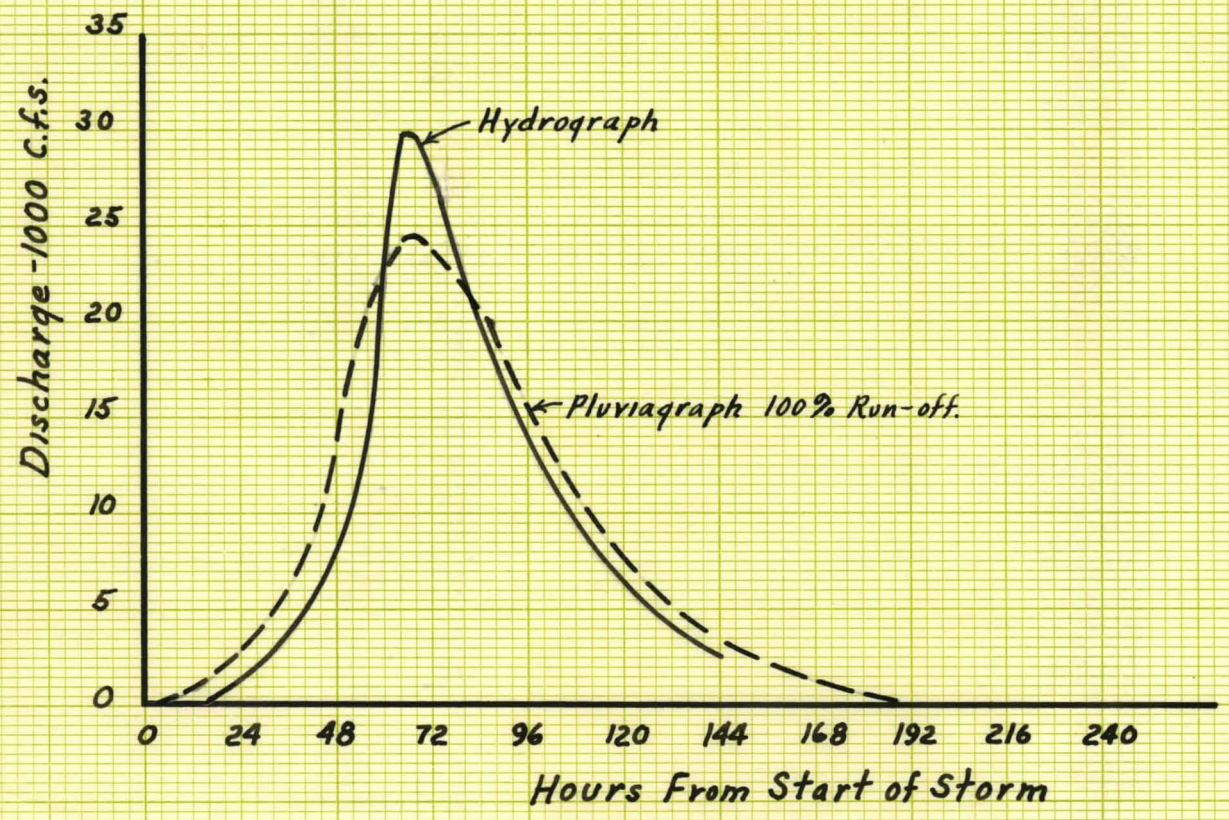
Fig. 35

not contribute under less severe conditions. (See Fig. 1). The extension of the flood coefficient curve, shown by dashed line in Fig. 34, gives a value of 1.22, to be used in converting the peak pluviagraph value to the peak hydrograph value. By shifting the peak 24 hours, using the flood coefficient of 1.22, and assuming a ratio of run-off to rainfall on the Buffalo Bayou basin of 0.9, the predicted hydrograph is obtained as shown on Fig. 35. It is possible that the peak value is high due to the necessity of extending the flood coefficient curve. However, the hydrograph is conservative.

d. White Oak Bayou presents a problem similar to Buffalo Bayou, complicated by the flow from Little White Oak Bayou, entering at a point below which the data on White Oak Bayou has been observed. The problem was solved in the following manner.

e. White Oak Bayou above Yale Street was treated in the same manner as Buffalo Bayou. The mean rainfall over the basin was computed for the 1899 Hearne storm transposed and located as shown on Fig. 22, and distributed by the May 1938 distribution graphs, shown as Fig. 28 to obtain a pluviagraph at Yale Street. This pluviagraph, shown as Fig. 36, was converted to a hydrograph by using a run-off factor of 0.9 and a flood coefficient of 1.22.

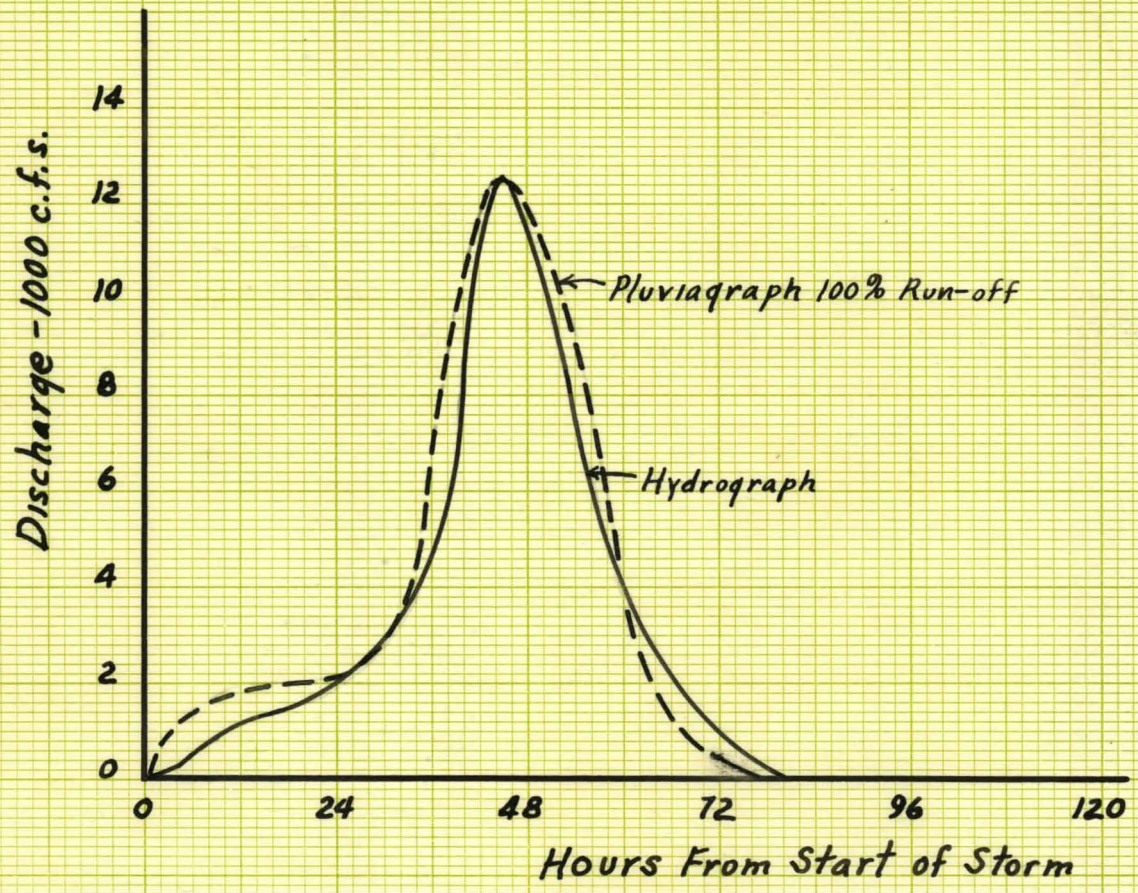
f. In order to obtain a reasonable discharge hydrograph at the mouth of White Oak Bayou, it was necessary to compute the inflow from Little White Oak Bayou, a tributary with a drainage area of about 20 square miles entering about one mile above the mouth of



Note: 1. Hydrograph plotted assuming flows confined to White Oak Bayou.
2. Peak of pluviagraph increased 22% to obtain hydrograph peak in accordance with results for 1929 and 1935 floods.
3. Total run-off estimated 90%.

HYDROGRAPHS OF DESIGN STORM
WHITE OAK BAYOU AT YALE ST.

Fig. 36



Note: 1. Hydrograph estimated as 90% of run-off indicated by the rational method pluviagraph.

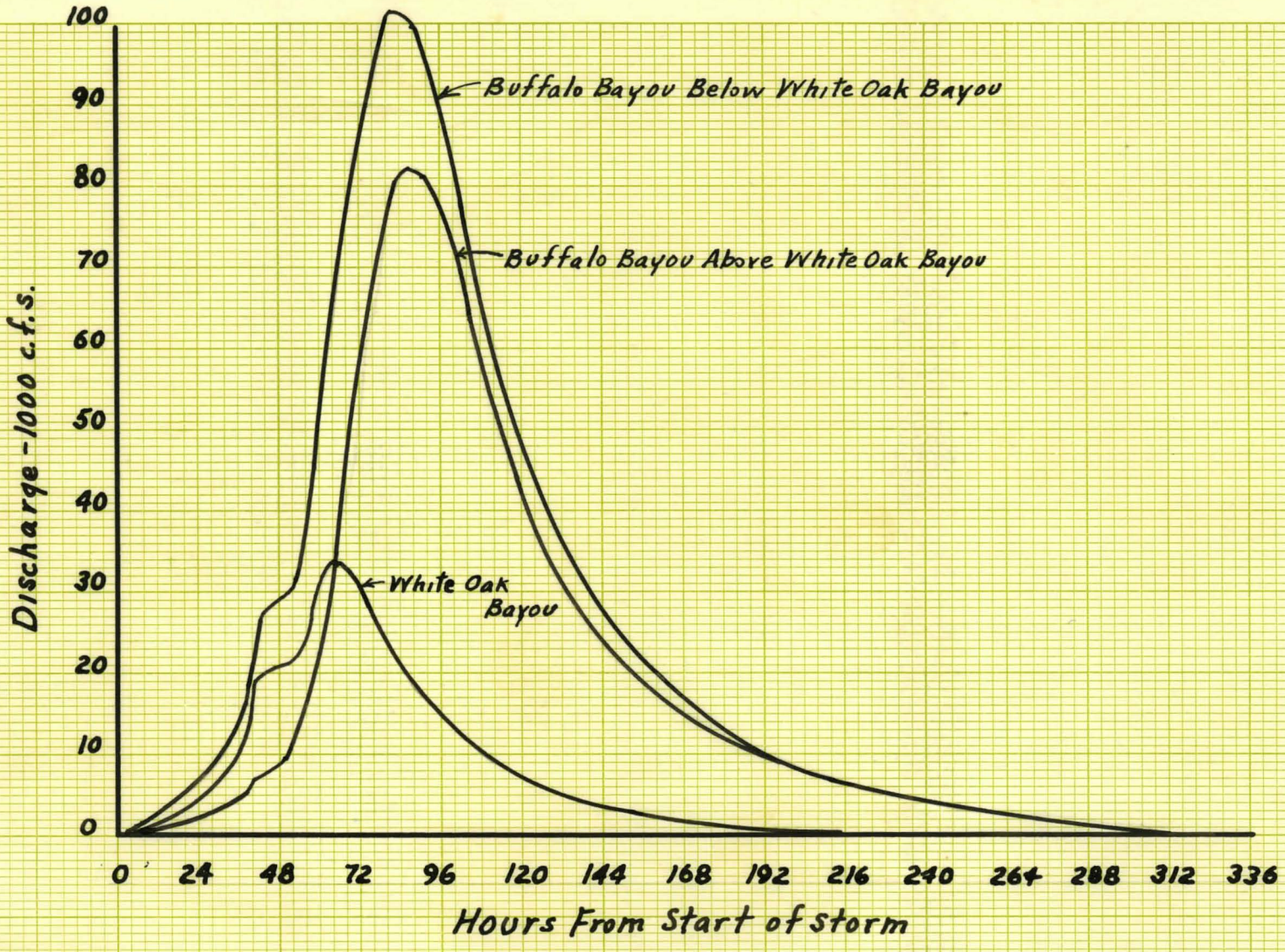
HYDROGRAPHS OF DESIGN STORM
LITTLE WHITE OAK B. AT MOUTH

Fig. 37

White Oak Bayou. The basin was divided into zones from which it was believed that water would run off in 8 hours, assuming rates of flow of 3 feet per second in channels and 0.4 feet per second over land. The average rainfall was then distributed by using the ratio of zone areas to the total area in the same manner as using a distribution graph, to produce a pluviagraph at the mouth of Little White Oak Bayou. A hydrograph was then computed by using a run-off factor of 0.9 and flood coefficient of 1.0. The pluviagraph and hydrograph are included as Fig. 37.

g. By combining the hydrograph at Yale Street for White Oak Bayou, Fig. 36, with the hydrograph at the mouth of Little White Oak Bayou, a hydrograph for the flow of the former was produced. To transfer it to the mouth of White Oak Bayou, the ordinates were increased by 3 per cent to correct for the additional land included in the drainage area in moving downstream one mile. The maximum flow predicted for White Oak Bayou is 33,000 c.f.s. (See Fig. 38 for the hydrograph).

h. With the hydrographs for Buffalo Bayou at Waugh Drive, and White Oak Bayou at its mouth, it is possible to combine the two to obtain the flow below the junction of the streams at Main Street. The combined hydrograph is included on Fig. 38.



Note: Hydrographs are based on assumption that all flows are confined to their respective channels. Under natural conditions considerable overflow into adjoining basins occurs at stages lower than the peaks indicated above.

HYDROGRAPHS OF DESIGN STORM AT MAIN STREET

Fig. 38

F. CONCLUSIONS.

1. From a careful study of the isohyetal maps of some of the largest storms in Texas during the last forty years, it is concluded that the Balcones Escarpment is the zone near which large storms are the most frequent. However, there are a sufficient number of large storms occurring away from the fault zone to warrant consideration of the largest storms in a flood control plan for Houston. Air mass conditions over Buffalo Bayou can be favorable for the production of the largest rainfalls, as was demonstrated by the December 1935 storm. During that storm approximately 21 inches of rain fell in 34 hours, with approximately 10 inches having fallin in 13 hours. In addition to exposure to conditions similar to those producing the rainfall of the 1935 storm, the basin is in the path of tropical hurricanes with their attendant heavy rainfalls.

2. To insure adequacy of a flood control plan, the greatest storm of record should be considered in the design. The 34.5 inches at Hearne in 1899, or the 36 inches reported for the vicinity of Taylor in 1921 are probably the highest rainfalls to be considered. An adequate factor of safety is included in the assumption that such storms could occur at Houston, undiminished in magnitude. The "Design Storm" outlined in Part C, Pars. 3, c and d, is believed adequate.

3. Because of the lack of definite topographic features bounding the basins along the Gulf coast, the flow from Buffalo Bayou is complicated by inflow from other basins and its own overflow to other basins. Due to the lack of definite information as to the quantities

involved in such overflows, it is impracticable to take them into consideration quantitatively. The hydrographs, shown on Fig. 38, making no reductions for losses due to overflow to other basins, indicate that the maximum flow from White Oak Bayou and Little White Oak Bayou with the design storm is about 33,000 c.f.s.; from Buffalo Bayou about 82,000 c.f.s. and that taking into account the difference in time of peaking, the flow below Main Street would be about 100,000 c.f.s. Such flows would not be possible under present natural conditions permitting overflow, but any flood control plan, to be adequate, should prevent the overflows, especially in the developed areas. Therefore, the flows indicated by the hydrographs must be considered in the development of a feasible plan for flood control.

4. A comparison of the storms and run-off quantities developed as a result of this study verifies in a satisfactory manner those included in House Document 456, 75th Congress, 2nd Session; and indicates that for a satisfactory and safe solution of the flood control problem it is necessary to consider flows of the magnitude outlined.

BIBLIOGRAPHY

1. Major Texas Floods of 1935, U. S. Geological Survey Water Supply, Paper No. 796-G, 1939
2. Numerous unpublished reports of the Corps of Engineers
3. Excessive Rainfall in Texas, State of Texas Reclamation Department, 1934
4. Maximum Recorded Experience--Flood Flows, State Board of Water Engineers, Austin, Texas, 1937
5. Low Dams, National Resources Committee, 1938
6. Rainfall Data for 1935 storm, W. E. White, Assistant City Engineer, Houston, Texas
7. Floods in Texas, 1921, U. S. Geological Survey Water Supply Paper No. 488
8. Special Report on Hydrological Studies for the Possum Kingdom Project, Brazos River Basin, U. S. Engineer Office, Mineral Wells, Texas, 1937
9. Climatological Data 1877-1938, U. S. Weather Bureau
10. Miami Conservancy District Technical Report, Part V
11. U. S. Geological Survey Water Supply Paper No. 816. (Storms of 1932 and 1936)
12. House Document 456, 75th Congress, 2d Session, 1937

13. Houston "Press", "Chronicle" and "Post" files 1900-1938

14. Journal of the Boston Society of Civil Engineers, September 1930, Report of Committee on Floods

15. Studies of Relations of Rainfall and Run-off in the United States, U.S.G.S. Water Supply Paper 772, 1936

16. An Approach to Determinate Stream Flow, Merrill M. Barnard, Trans. A.S.C.E., 1935

17. Streamflow from Rainfall by Unit-Graph Method, L.K.Sherman, E.N.R., April 7, 1932

18. Relation Between Rainfall and Run-Off from Small Urban Areas, Transaction A.S.G.E., 1936

19. An Introduction to Air Mass Analysis, Jerome Namias and others, Blue Hill Observatory, Massachusetts