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TP-51

DESIGN OF FLOOD CONTROL IMPROVEMENTS
BY SYSTEMS ANALYSIS: A CASE STUDY[1]

by

Howard O. Reese,[2] Arnold V. Robbins,[3] John R. Jordan,[4]
and Harold V. Doyal[5]

ABSTRACT

A hydrologic-economic simulation model was developed to evaluate alternative protection schemes in the design of an authorized federal flood control project for 125 miles of the Tibbee River flood plain in Mississippi. The model requires input consisting of unit hydrographs, streamflow routing coefficients and storage functions, a pattern storm, rainfall loss rate functions, and flow-damage-frequency relations. A single synthetic pattern storm was used in conjunction with flow-frequency curves at index locations to generate a series of floods for comparing alternative protection schemes with existing conditions. The effect of channel improvements on flood runoff characteristics was evaluated by using storage routing functions that account for changes in storage-discharge relations. Based on results obtained from using the model, a channel improvement plan was tentatively selected for the Tibbee River basin from the alternative schemes evaluated.

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INTRODUCTION

A federal project involving extensive stream clearing, straightening and enlargement was authorized by Congress in 1958. The purpose of the project is to achieve flood control and drainage on 466 miles of flood plain along 22 tributary streams of the upper Tombigbee River in Mississippi and Alabama. A current study conducted on a cooperative basis by the Mobile District and The Hydrologic Engineering Center, Corps of Engineers, is concerned with a portion of the overall project, namely 125 miles of flood control improvements authorized for a system of 10 streams in the Tibbee River basin, Mississippi (figure 1). The objectives of the study are to determine the effect of alternative channel improvement schemes on flood runoff characteristics in the stream system, to determine the reductions in flood damage associated with the alternative plans, and to select from among the alternatives the plan that would most economically achieve the flood control objectives.

The methodology adopted for the study required the development of a generalized hydrologic-economic mathematical model to simulate the flood runoff characteristics of the basin under existing conditions and for alternative improvement schemes, including detention structures that are planned by the U. S. Soil Conservation Service. This paper describes the simulation model and study procedures and presents some of the results of the study.

DESCRIPTION OF SYSTEM

Physiography. The total area of the Tibbee River basin is 1,121 square miles, of which about 130 square miles are in the flood plain of the 10 streams authorized for improvement. The basin has a maximum width of 30 miles, an average width of 21 miles, and a stream length of 74 miles (from the mouth of Tibbee River to the head of Sakatonchee Creek, its longest tributary). The terrain is fairly rugged with rather high relief varying from elevation 160 to 400 feet, m.s.l.

The Tibbee River is formed at the junction of Line and Sakatonchee Creeks and it flows easterly about 24 miles to join the Tombigbee River through the right bank about 35 miles northwest of Columbus, Mississippi. It has an average gradient of 1.5 feet per mile. Its tributaries range in length from about 5 miles to 50 miles with gradients generally steeper than that of the main stem. The flood plain along the Tibbee River and its tributaries averages about 1 mile in width and is subject to frequent flooding.

The basin area is located within the Tombigbee Hills and Black Prairie districts of the Gulf Coastal Plain physiographic province. The downstream 4 or 5 miles of the Tibbee River traverses the Tombigbee Hills district with topography ranging from low, smoothly rounded hills to hills and ridges separated by narrow valleys. The upstream reach of the Tibbee River and its tributaries is located in the Black

Prairie district where the topography varies from nearly flat to smoothly rounded hills or low relief.

Climatology. The Tibbee River basin has a temperature climate with warm summers and mild winters. The normal annual temperature is 64 degrees with monthly normals ranging from 47 degrees in January to 81 degrees in July. The minimum recorded temperature is -10 degrees and the maximum is 113 degrees. The frost-free period normally lasts from April to November.

Precipitation during the year is abundant and fairly well distributed. The normal annual rainfall is almost 49 inches, of which 58 percent falls in the winter and spring, 24 percent in the summer, and 18 percent in the fall. The average annual snowfall is about 35 inches.

Flood producing storms may occur at any time but are more frequent during the winter and spring. Such storms are usually of the frontal type covering large areas and lasting from 2 to 4 days. Summer storms are generally of the thunderstorm type with high intensity over small areas. Recorded rainfalls in the basin include maximums of 3.20 inches in a 1-hour period, 6.53 inches in 12 hours, and 7.43 inches in 24 hours. The 1- and 12-hour maximums occurred during a storm on June 1-2, 1947, and the 24-hour maximum occurred in January 1950.

Land Use. About half of the total basin area is in farms. Sixty percent of the farmland acreage is about equally divided between cropland and other uses such as house lots, roads, pastures and wasteland. The remaining 40 percent is woodland. More than 80,000 acres are in the flood plain along the 10 project streams. It is estimated that 30 percent of this flood plain land is in cultivation, 15 percent is in pasture or idle, and 55 percent is woodland. It is estimated that flood damages to flood plain developments average $1,837,000 a year, consisting mainly of agricultural losses. The improvement of the project streams would reduce these flood damages and permit more intensive agricultural use of the flood plains.

INVESTIGATION

General. To accomplish the study objectives, it was concluded that a systems analysis of various alternative schemes of basin development for the Tibbee River was required, and that a hydrologic-economic simulation model should be developed to facilitate the analysis. It was recognized that extensive channel improvement works in a river system could cause an adverse peaking effect on runoff; i.e., peak runoff rates could likely be larger because of the more rapid concentration of runoff resulting from more efficient conveyance. Therefore, the model was developed primarily for the purpose of evaluating the effects of alternative channel improvement plans on the flood runoff characteristics of timing and magnitude of peak runoff rate. Another major purpose of the model was to determine the reductions in flood damage for the alternative

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plans. A generalized computer program [1/] (rainfall-runoff model) developed by The Hydrologic Engineering Center was used for modeling purposes.

The application of the generalized simulation model required the development of certain hydrological and economic inputs, such as (1) unit hydrograph and loss rate criteria, (2) channel routing criteria, (3) synthetic pattern storm, (4) discharge-frequency and stage-discharge relations, and (5) stage-damage relations.

Economic Studies. The procedure used for determining reductions in flood damage attributable to channel improvement works was to compute the difference in average annual flood damages[1] between existing conditions and improved conditions. Average annual flood damages for existing conditions were computed from known or derived stage-discharge, discharge-frequency, and stage-damage relationships. For improved conditions, average annual flood damages are usually computed from these same relationships with the stage-discharge relationship modified to reflect the changes in stage. However, for this study it was also necessary to modify the discharge-frequency relationship to reflect the magnitude of the peaking effect on runoff resulting from upstream channel improvement works. The need for modifying this relationship made the determination of flood damage reduction more difficult.

In formulating the optimal plan of channel improvement works for the Tibbee River basin, estimates of flood damage reduction attributable

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[1]Average annual flood damage is defined as the expected value of annual flood damage computed by integrating the damage-exceedence frequency function.

to each alternative plan evaluated were determined. For this determination, the flood plains of the Tibbee River and its tributaries were subdivided into 21 planning reaches varying in length from 2 to 17 miles (figure 1). Based on detailed economic studies, flood damages were determined for each planning reach and related to stage at the index station (representative reference point) selected for the reach. Using stage-discharge and discharge-frequency relationships, average annual flood damages were computed at each index station for existing conditions and for each alternative plan as described later in the paper.

Hydrologic and Hydraulic Studies. A discharge-frequency statistical analysis was made from streamflow data for gaging stations located on the Tibbee River and its tributaries and on adjacent streams of similar size and comparable hydrologic characteristics. A relationship of drainage area versus the annual mean was developed. A skew coefficient of zero and a standard deviation of 0.24 were adopted and used with this relationship for determining the discharge-frequency relationship at each index station for existing conditions in the basin.

Extensive backwater computations for existing conditions and for alternative plans of improvement were made to determine stage-discharge relations at each index station, pertinent water surface profiles, and storage-outflow relations for the selected channel routing reaches. Data on surveyed cross-sections and topographic maps were available. The roughness coefficients used in Manning's formula were based on known high water marks and rating stations in the basin.

For study purposes, the Tibbee River basin was subdivided into 216 subareas. Synthetic unit hydrographs were derived for each subarea by the Clark unit hydrograph method 2/ using generalized coefficients. Unit hydrograph and rainfall loss rate coefficients were derived for 22 stream gaging locations in the Tibbee River basin and other adjacent stream basins from an analysis of streamflow and rainfall data for a total of 89 runoff events (2 to 8 per location). The results of this analysis were used for developing generalized coefficients for application to ungaged locations.

The methodology adopted for evaluating the effect of channel improvements on flood runoff characteristics required the development of a single representative synthetic pattern storm for the Tibbee River basin. It also provided for computing a synthetic pattern flood for each subarea from the pattern storm and, using multiples of the pattern flood, for determining other floods of pertinent magnitudes or frequencies.

A uniform areal distribution of rainfall was used for computing the pattern storm. In this way, each portion of the basin had a representative effect on flood determinations. Although a single pattern storm may not be totally representative for the entire Tibbee River basin as well as the headwater areas, it would have been extremely difficult and laborious to attempt many representative storm centerings within the basin. Also, it is doubtful that results would have been substantially different than those obtained from a single uniform storm pattern. While the effects of tributary runoff would actually vary, depending on storm centering, the net effect of all centerings and all storm magnitudes would probably not be substantially different from that computed using a uniform distribution.

The area-depth-duration relation adopted for the pattern storm was of particular importance because the resulting pattern floods were to be representative of historical floods. It was determined that if the peak-to volume relationships of the pattern floods are representative of historical floods throughout the basin, then other floods derived as multiples of the pattern floods would be equally representative because peak-to-volume ratios of historical floods are relatively independent of flood magnitude. The adopted criteria for the storm were a rainfall intensity of 5-year recurrence interval, a rainfall duration of 48 hours, and an area size of 200 square miles. Based on rainfall data in Weather Bureau Technical Papers 40 and 49, it was determined that the total storm rainfall was 5.7 inches.

For this study, the pattern flood at any location in the basin is defined as the runoff from the pattern storm. The pattern flood hydrograph for each subarea was computed by applying the pattern storm rainfall excess to the synthetic unit hydrograph. The pattern flood hydrographs for the other locations in the basin were determined by routing and combining these subarea pattern flood hydrographs. The

Muskingum routing method was used for the smaller streams in the headwater areas and the nonlinear storage routing method (modified Puls) was used for the other stream reaches. The latter method required the development of storage-outflow relations for each selected channel routing reach for existing and improved conditions. In this relation, the storage value is the volume of water in the channel and overbank within the routing reach corresponding to a given steady state water surface profile. The storage-outflow relation for existing conditions was adjusted to reflect the changes in storage for each plan of channel improvement considered. Therefore, although the same pattern storm was used, the resulting pattern floods at a given location were different for each alternative plan as illustrated in figure 2 for one of the index stations on Catalpa Creek.

A series or set of nine synthetic flood hydrographs at all locations in the basin was developed for existing conditions and for each considered plan of improvement. The set of flood hydrographs was synthesized by multiplying all of the subarea pattern flood hydrograph ordinates by nine predetermined ratios and by routing and combining the subarea pattern floods computed for each multiple. The same multiples used for existing conditions were used for each plan of improvement. Multiples were selected to produce flood magnitudes corresponding to a frequency range from four to twelve times per year (zero flood damage stage) to approximately once in 200 years.

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Using discharge-frequency curves, an exceedence probability was assigned to each multiple flood at each index station location for existing conditions. For each plan of improvement, the exceedence probability for each multiple flood was assumed to be the same as that established for existing conditions. The probabilities associated with each multiple were used, in conjunction with flow-damage curves, to compute average annual flood damages at each index station for existing conditions and for each plan of improvement. The assigned range of probability of each multiple flood is multiplied by the damage caused by that flood, and the sum of these cross products for all of the nine multiple floods is the average annual damage for the given condition.

RESULTS

Some of the results of the investigation are illustrated on figures 2 through 6 for two of the planning reaches analyzed. The results for these two locations are representative of the other locations in the basin.

Examples of computed flow-probability-damage relations and average annual flood damages for existing conditons and various alternative plans of basin development are shown on figures 3 and 5. The flood damage reduction attributable to the alternative plans is also shown on these figures. For the alternative plan providing for channel improvements on all 10 streams in the Tibbee River basin, the increase in the peak flow rate of the pattern flood (flood 6 on figure 5)

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at river mile 17.7 on the Tibbee River would be 35 percent. However, because of changes in the stage-discharge relation, flood damage reduction in the planning reach would decrease 62 percent. Shown on figure 6 is a comparison of stage-frequency relations at this location for existing conditions, channel improvements on all 10 streams, and channel improvements on Tibbee River only. The difference between the two relations for improved conditions is due to the peaking effect caused by upstream channel improvements.

The effects of various upstream alternative plans of basin development on the runoff characteristics of timing and magnitude of peak flow rate are illustrated by the pattern flood hydrographs shown on figures 2 and 4 and the flow-probability data tabulated on figures 3 and 5. The results of the investigation at all index station locations show the following general trends on increases in peak flow rates from upstream channel improvements:

(1) Peak flow rates increase as the percentage of stream length improved increases, as would be expected.

(2) For given length of stream to be improved, peak flow rates increase as the degree of protection (design capacity of improved channel) increases. This effect is illustrated by the pattern flood hydrographs shown on figure 2 for existing conditions and four alternative plans.

(3) For given improved conditions, the increase in peak flow rates decreases percentagewise with increases in flood magnitude.

CONCLUSIONS

The most important concept of the investigation was the determination of the runoff peaking effect of channel improvement works based on changes in the storage-outflow relation of the flood plain and streams. Another important and unique concept was the computation of synthetic flood hydrographs at numerous locations as multiples of pattern floods derived from one single representative synthetic pattern storm for a stream system.

Upstream channel improvement works for flood control would tend to increase the magnitude of peak flow rates now experienced on the Tibbee River main stem. They would also tend to increase the average annual flood damages on the main stem unless it was enlarged to accommodate the increased discharges. The magnitude of these effects was assessed with a reasonable amount of computation using a simplified hydrologic-economic simulation model of the basin, along with certain necessary assumptions and generalizations.

The procedure described herein for the evaluation of flood control channels in rural areas could also be applied to the study of urban flood problems. The generalizations would, of course, be tailored to the specific area of study, but the methodology and computational procedure would be the same. Future studies should investigate the possibility of adding to the model an optimization routine to provide for the selection of projects involving a combination of two or more structural measures (dentention structures together with levees or channels, etc.) which are to achieve a given objective (protection against a specified flood).

ACKNOWLEDGMENTS

Many persons in the Mobile District Corps of Engineers office have been involved in this study. Mr. Leo R. Beard, Director of The Hydrologic Engineering Center, who developed the simulation model described herein, has given his support and suggestions for its use in this study. Mr. Herbert W. Hereth and Mrs. Marilyn Hurst of the HEC staff, and Mr. Lewis G. Hulman, formerly of the HEC staff and now of the Atomic Energy Commission, furnished valuable assistance.

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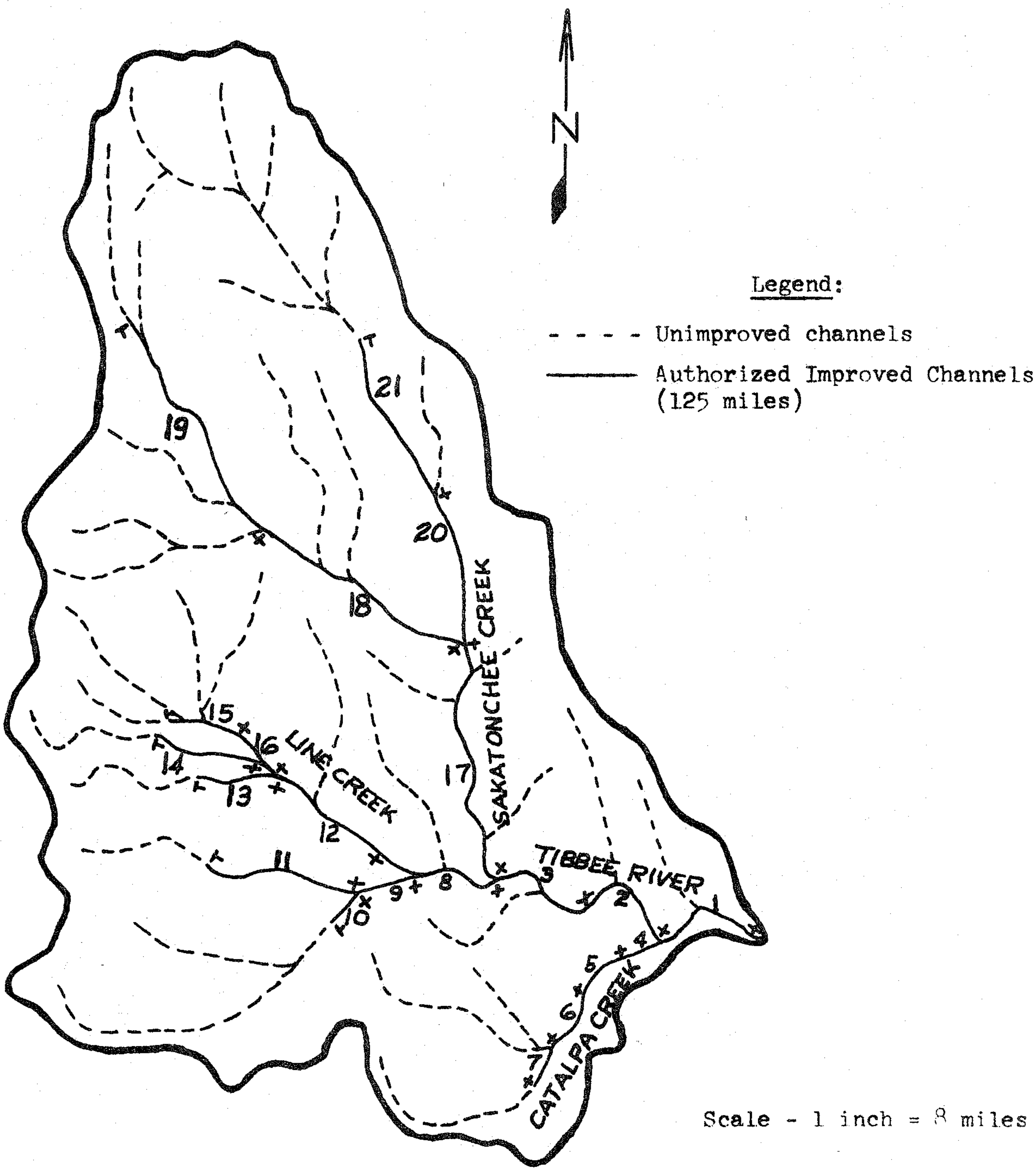
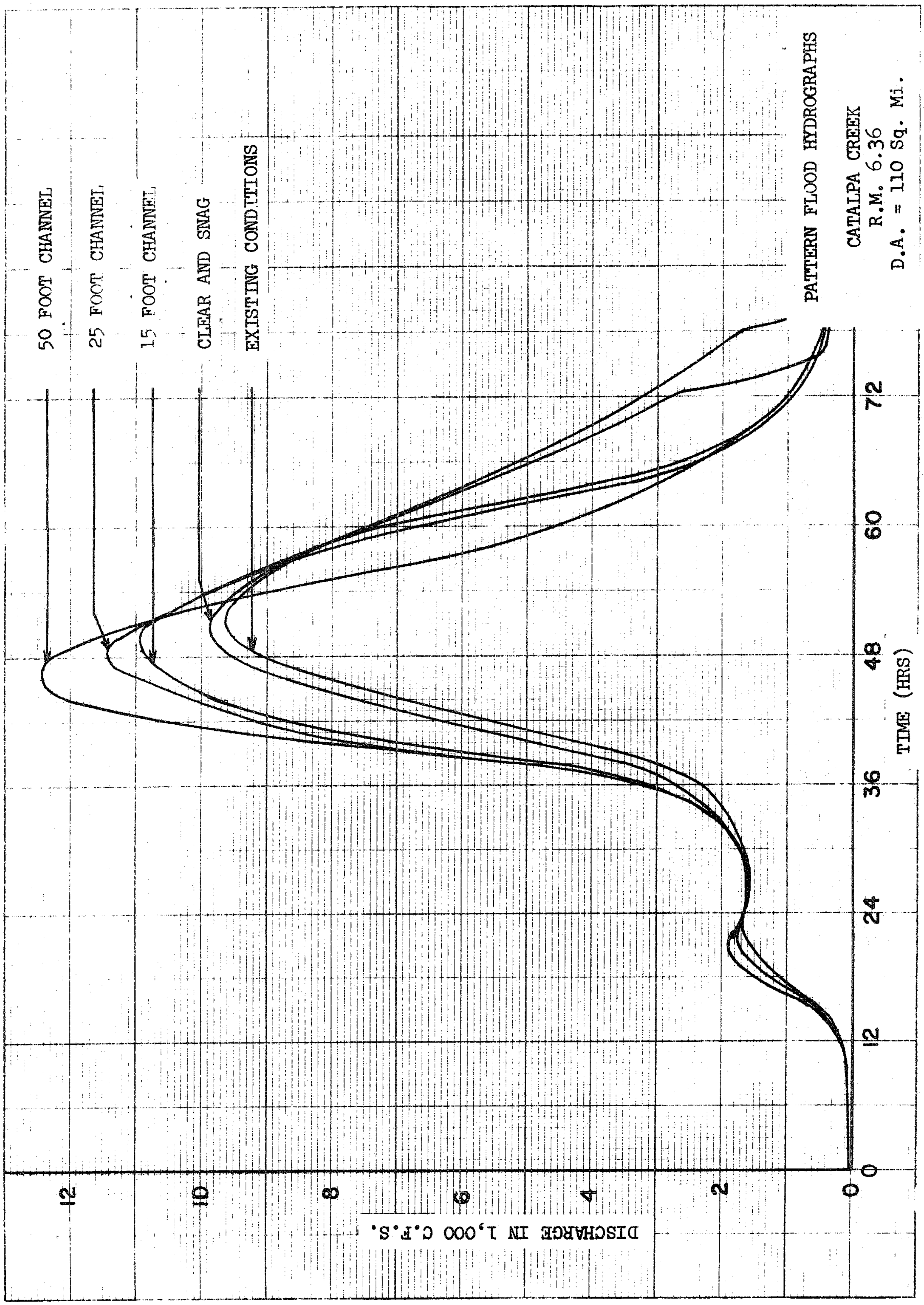
2. Clark, C. O., "Storage and the Unit Hydrograph," Trans. ASCE, 1945.



TIBBEE RIVER BASIN (1,121 sq. mi.)

FIGURE 1



50 FOOT CHANNEL
25 FOOT CHANNEL
15 FOOT CHANNEL
CLEAR AND SNAG
EXISTING CONDITIONS
PATTERN FLOOD HYDROGRAPHS
CATALPA CREEK
R.M. 6.36
D.A. = 110 Sq. Mi.
DISCHARGE IN 1,000 C.F.S.
0
2
4
6
8
10
12
TIME (HRS)
0
12
24
36
48
60
72

FIGURE 2

FLOW-PROBABILITY-DAMAGE RELATIONS
(NOTE: Pattern Flood is Flood 6)

EXISTING CONDITIONS

FLOOD DAMAGES FOR STATION

NO.	FLOW	PROB	SUM
1	2017.	.804	.12
2	2625.	1.270	2.64
3	3761.	1.067	4.26
4	5146.	.827	4.77
5	6967.	.465	3.47
6	9608.	.330	3.24
7	13947.	.162	2.09
8	19556.	.061	1.02
9	27206.	.024	.50

AVG ANN DMG 22.09

ALTERNATIVE PLAN
Clear and Snag

FLOOD DAMAGES FOR STATION

NO.	FLOW	PROB	SUM
1	2272.	.804	.00
2	3110.	1.270	.01
3	4153.	1.067	1.45
4	5566.	.827	3.17
5	7292.	.465	2.72
6	9861.	.330	2.67
7	14114.	.162	1.82
8	19621.	.061	.91
9	27264.	.024	.46

AVG ANN DMG 13.20

DAMAGE REDUCTION 8.89

RECOMMENDED PLAN
15 Foot Channel

FLOOD DAMAGES FOR STATION

NO.	FLOW	PROB	SUM
1	2426.	.804	.00
2	3617.	1.270	.00
3	5345.	1.067	.00
4	6933.	.827	.00
5	8567.	.465	.00
6	10937.	.330	.59
7	14873.	.162	.84
8	20174.	.061	.54
9	27697.	.024	.31

AVG ANN DMG 2.29

DAMAGE REDUCTION 19.81

ALTERNATIVE PLAN
25 Foot Channel

FLOOD DAMAGES FOR STATION

NO.	FLOW	PROB	SUM
1	2434.	.804	.00
2	3655.	1.270	.00
3	5432.	1.067	.00
4	7229.	.827	.00
5	8822.	.465	.00
6	11420.	.330	.30
7	15181.	.162	.71
8	20418.	.061	.48
9	27853.	.024	.29

AVG ANN DMG 1.78

DAMAGE REDUCTION 20.31

ALTERNATIVE PLAN
50 Foot Channel

FLOOD DAMAGES FOR STATION

NO.	FLOW	PROB	SUM
1	2431.	.804	.00
2	3662.	1.270	.00
3	5440.	1.067	.00
4	7398.	.827	.00
5	9705.	.465	.00
6	12456.	.330	.00
7	15738.	.162	.21
8	20916.	.061	.31
9	28241.	.024	.23

AVG ANN DMG .74

DAMAGE REDUCTION 21.35

CATALPA CREEK
R.M. 6.36

FIGURE 3

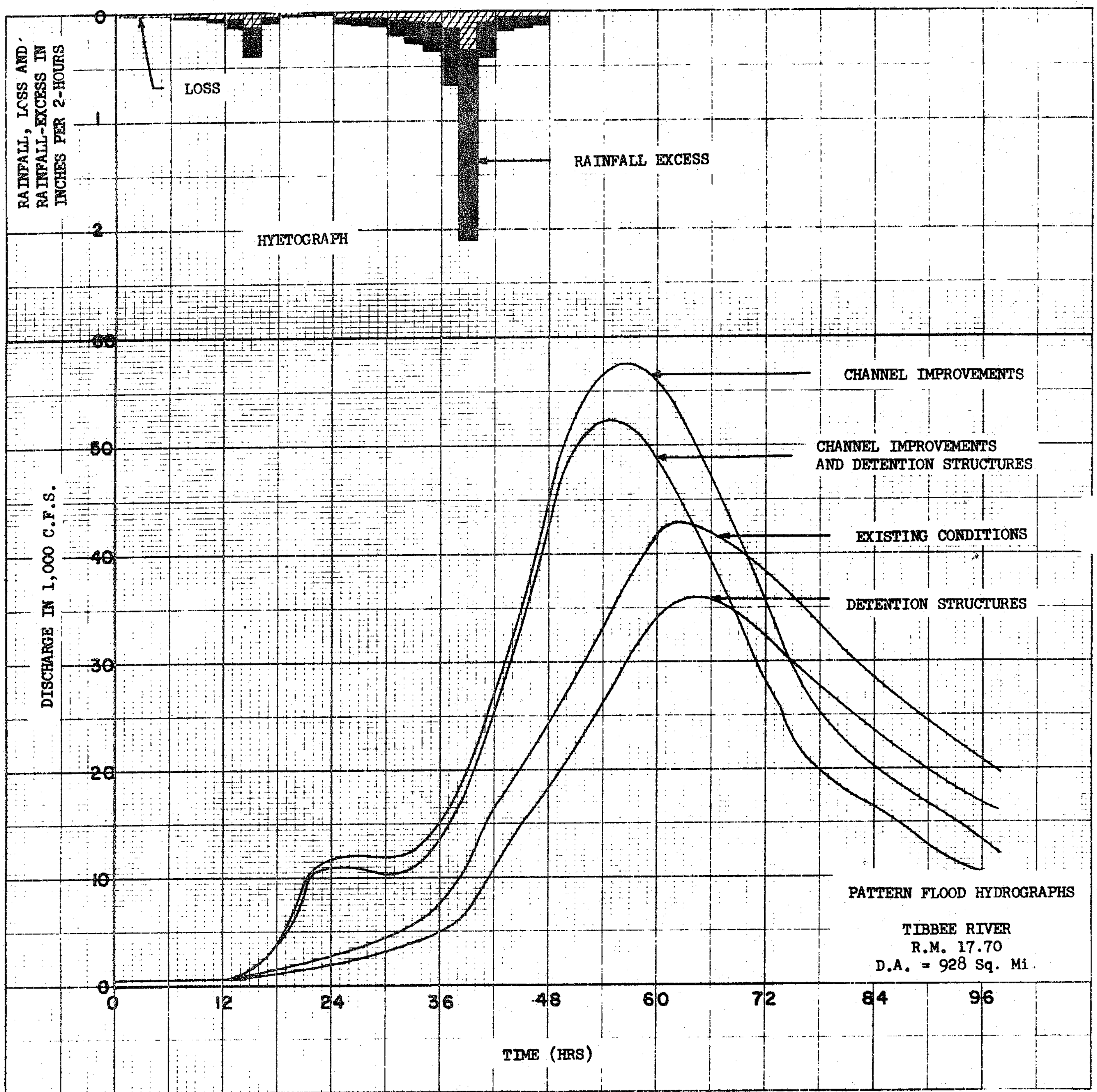

RAINFALL, LOSS AND RAINFALL-EXCESS IN INCHES PER 2-HOURS
0
1
2
LOSS
RAINFALL EXCESS
HYETOGRAPH
DISCHARGE IN 1,000 C.F.S.
60
50
40
30
20
10
0
CHANNEL IMPROVEMENTS
CHANNEL IMPROVEMENTS AND DETENTION STRUCTURES
EXISTING CONDITIONS
DETENTION STRUCTURES
PATTERN FLOOD HYDROGRAPHS
TIBBEE RIVER
R.M. 17.70
D.A. = 928 Sq. Mi
0
12
24
36
48
60
72
84
96
TIME (HRS)

FIGURE 4

FLOW-PROBABILITY-DAMAGE RELATIONS
TIBBEE RIVER
R.M. 17.70

EXISTING CONDITIONS

FLOOD DAMAGES FOR STATION

NO.	FLOW	PROB	SUM
1	6449	3.269	16.83
2	9712	1.237	20.97
3	14663	.896	23.27
4	20554	.646	22.87
5	28948	.455	21.73
6	42723	.304	18.43
7	62073	.134	9.71
8	90665	.048	4.39
9	133410	.022	2.56
	AVG ANN DMG		140.76

DETENTION STRUCTURES

FLOOD DAMAGES FOR STATION

NO.	FLOW	PROB	SUM
1	5786	3.269	13.13
2	8802	1.237	18.46
3	12989	.896	20.92
4	17963	.646	20.11
5	24925	.455	19.39
6	35973	.304	16.72
7	52740	.134	8.93
8	76572	.048	3.94
9	113200	.022	2.29
	AVG ANN DMG		123.90
DAMAGE REDUCTION			16.87

NOTE: Pattern Flood is Flood 6

CHANNEL IMPROVEMENTS

FLOOD DAMAGES FOR STATION

NO.	FLOW	PROB	SUM
1	15029	3.269	0.
2	20448	1.237	1.53
3	27221	.896	5.21
4	34666	.646	11.65
5	44442	.455	12.40
6	57666	.304	11.39
7	77062	.134	6.66
8	106189	.048	3.34
9	149526	.022	2.06
	AVG ANN DMG		54.23
DAMAGE REDUCTION			86.54

CHANNEL IMPROVEMENTS AND
DETENTION STRUCTURES

FLOOD DAMAGES FOR STATION

NO.	FLOW	PROB	SUM
1	13767	3.269	0.
2	19046	1.237	.65
3	25614	.896	3.44
4	32242	.646	8.99
5	40671	.455	11.00
6	52450	.304	10.25
7	68274	.134	5.93
8	92347	.048	2.88
9	129277	.022	1.80
	AVG ANN DMG		44.93
DAMAGE REDUCTION			95.83

FIGURE 5

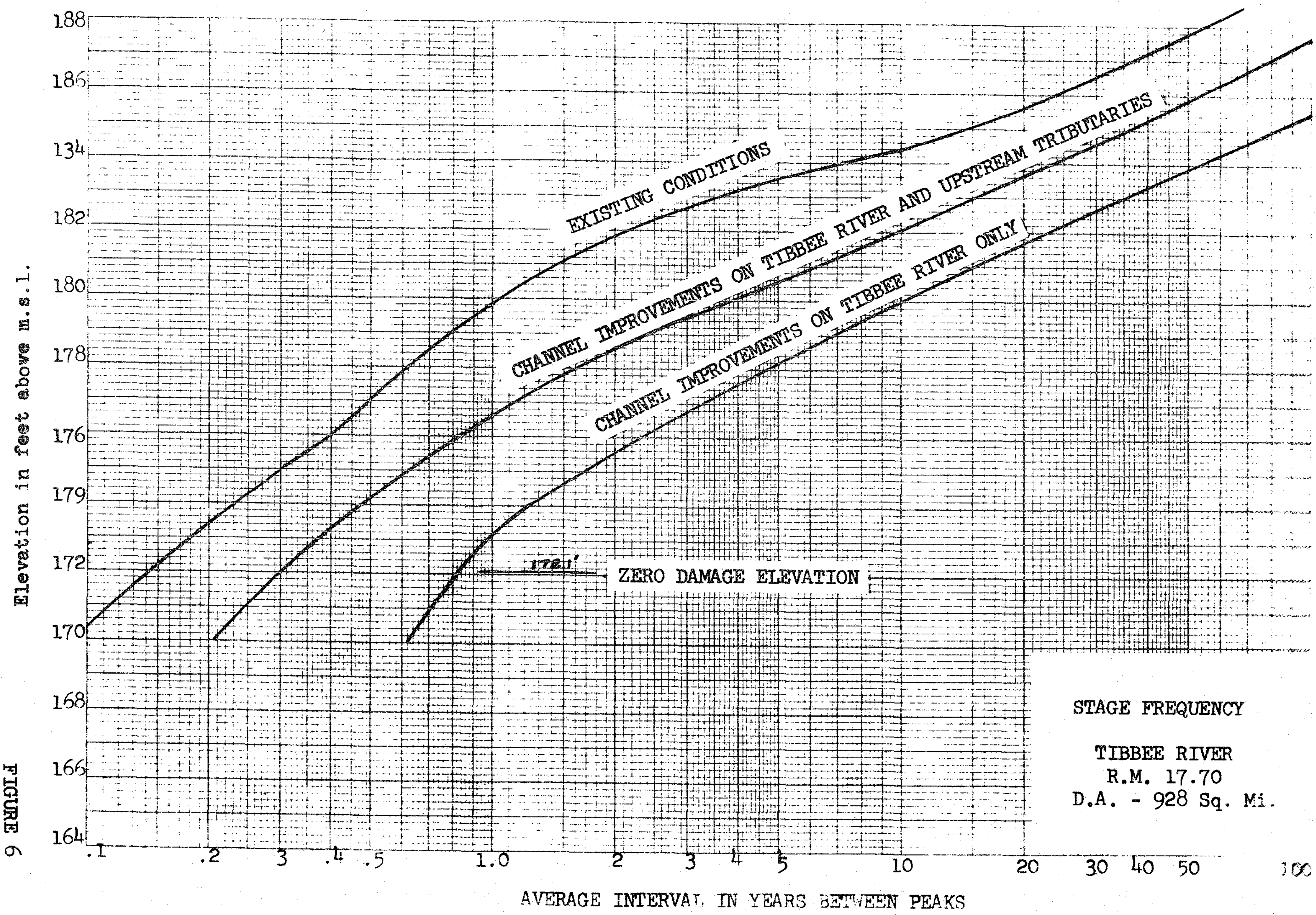

STAGE FREQUENCY
TIBBEE RIVER
R.M. 17.70
D.A. - 928 Sq. Mi.
EXISTING CONDITIONS
CHANNEL IMPROVEMENTS ON TIBBEE RIVER AND UPSTREAM TRIBUTARIES
CHANNEL IMPROVEMENTS ON TIBBEE RIVER ONLY
ZERO DAMAGE ELEVATION
172.1'
Elevation in feet above m.s.l.
AVERAGE INTERVAL IN YEARS BETWEEN PEAKS
188
186
134
182
180
178
176
179
172
170
168
166
164
.1
.2
3
.4
.5
1.0
2
3
4
5
10
20
30
40
50
100

FIGURE 6

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