TABLE 3 — COMPUTATION OF CHANNEL-OUTFLOW GRAPH — TIOGA RIVER NEAR ERWINS, N.Y.
RISE OF JULY 8, 1935

t_1	t_2	$2t$ Seconds	I_1 c.s.m.	I_2 c.s.m.	$I_{av.}$ c.s.m.	$2t\,I_{av.}$ (Millions)	q_1 c.s.m.	q_1t	$2S_1$ (Millions) C.F. per S.M.	Z (10)+(7)−(9)	q_2 c.s.m.	S_2 (Millions) C.F. per S.M.
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)
Md't.	1a.m.	7200	0	4.17	2.08	0.0150	0.27	.0010	.0200	.0340	0.28	0.0100
1a.m.	2 "	"	4.17	8.34	6.25	.0450	.28	.0011	.0200	.0639	.30	.0100
2 "	3 "	"	8.34	12.51	10.42	.0750	.30	.0011	.0200	.0939	.40	.0320
3 "	4 "	"	12.51	16.68	14.59	.1050	.40	.0014	.0640	.1676	.60	.0900
4 "	5 "	"	16.68	20.85	18.76	.1351	.60	.0022	.1800	.3129	.90	.1580
5 "	6 "	"	20.85	25.02	22.93	.1651	.90	.0032	.3160	.4779	1.25	.2250
6 "	7 "	"	25.02	29.19	27.10	.1951	1.25	.0045	.4500	.6406	1.75	.3080
7 "	8 "	"	29.19	33.36	31.28	.2252	1.75	.0063	.6160	.8349	2.60	.4150
8 "	9 "	"	33.36	37.53	35.44	.2552	2.60	.0094	.8300	1.0758	3.80	.5400
9 "	10 "	"	37.53	41.70	39.62	.2853	3.80	.0137	1.0800	1.3516	5.65	.6800
10 "	11 "	"	41.70	45.87	43.78	.3152	5.65	.0203	1.3600	1.6549	7.95	.8200
11 "	noon	"	45.87	50.04	47.96	.3453	7.95	.0286	1.6400	1.9567	10.65	.9600
noon	1p.m.	"	50.04	54.21	52.13	.3753	10.65	.0383	1.9200	2.2570	13.75	1.1000
1p.m.	2 "	"	54.21	58.38	56.30	.4054	13.75	.0495	2.2000	2.5559	16.80	1.2400
2 "	3 "	"	58.38	62.55	60.47	.4347	16.80	.0605	2.4800	2.8542	20.10	1.4000
3 "	4 "	"	62.55	66.72	64.63	.4653	20.10	.0724	2.8000	3.1929	23.50	1.5500
4 "	5 "	"	66.72	70.35	68.53	.4934	23.50	.0846	3.1000	3.5088	26.75	1.7000
5 "	6 "	"	70.35	66.72	70.08	.5046	26.75	.0963	3.4000	3.8083	30.10	1.8500
6 "	7 "	"	66.72	55.60	61.16	.4403	30.10	.1083	3.7000	4.0320	32.75	2.0000
7 "	8 "	"	55.60	44.48	50.04	.3603	32.75	.1179	4.0000	4.2424	34.60	2.0500
8 "	9 "	"	44.48	33.36	38.92	.2802	34.60	.1245	4.1000	4.2557	34.75	2.0600
9 "	10 "	"	33.36	22.24	27.80	.2002	34.75	.1251	4.1200	4.1951	34.00	2.0300
10 "	11 "	"	22.24	11.12	16.68	.1201	34.00	.1224	4.0600	4.0577	32.60	1.9700
11 "	md't.	"	11.12	0	5.56	.0400	32.60	.1174	3.9400	3.8626	30.60	1.8700
md't.	1a.m.	"	0	0	0	0	30.60	.1102	3.7400	3.6298	29.00	1.78
1a.m	2 "	"					29.00	.1044	3.5600	3.4556	27.20	1.68
2 "	3 "	"					27.20	.0979	3.3600	3.2621	25.40	1.59
3 "	4 "	"					25.40	.0914	3.1800	3.0886	23.70	1.50
4 "	5 "	"					23.70	.0853	3.0000	2.9147	22.00	1.40
5 "	6 "	"					22.00	.0792	2.8000	2.7208	20.00	1.32
6 "	7 "	"					20.00	.0720	2.6400	2.5680	18.35	1.25
7 "	8 "	"					18.35	.0661	2.5000	2.4339	16.95	

Voorheesville, New York

FLOOD-CREST REDUCTION BY CHANNEL-STORAGE

Robert E. Horton

Conditions of similarity of channel-outflow graphs--The hydrograph of a stream-rise or a channel-outflow graph represents the areal rainfall-excess graph for the drainage-basin as modified by (a) surface-detention, (b) channel-storage. It is desirable for many reasons to be able to derive a channel-outflow graph from the areal rainfall-excess graph, or at least to determine approximately the crest-outflow intensity therefrom. The virtual channel-inflow graph described in another paper [see 1 of "References" at end of paper] makes it possible to determine easily from an outflow-graph (a) the virtual channel-inflow graph, (b) the channel-storage characteristics, particularly at the time of the crest.

With reference to determining the crest-outflow rate from rainfall-data, two methods of procedure are available:

(1) The first depends on the fact that the storage-equation applies equally well to all forms of storage, whether channel-storage or surface-detention, or the two combined. It is therefore possible to use the same method as that used in determining virtual channel-inflow graphs but applying this directly to the areal rainfall-excess graph and thereby obtaining storage-characteristics for both channel-storage and surface-detention, which, once known, may be applied to the determination of crest-outflow intensities for other rainfall-excess patterns.

(2) From the V-I graph and the rainfall-excess graph, to determine the surface-detention effect separately. Then apply this to the areal rainfall-excess graph to derive a channel-inflow graph, and from the latter derive the channel-outflow graph, or at least the reduction in crest-intensity.

The latter method has the advantage that the operation of surface-detention storage and channel-storage may not be identical in two different storms. Consequently the relationships between areal rainfall-excess graphs and channel-outflow graphs are not likely to be as uniform or consistent as the relationships between V-I graphs and channel-outflow graphs. The present paper is devoted entirely to the latter relationships.

It is obvious from the storage-equation that for the same rainfall-excess pattern on two adjacent drainage-basins or at two different gaging-stations on the same drainage-basin, the channel-outflow graphs will be closely similar if and only if the channel-storage characteristics are similar. Likewise, outflow-graphs for the same stream and station will be similar if the

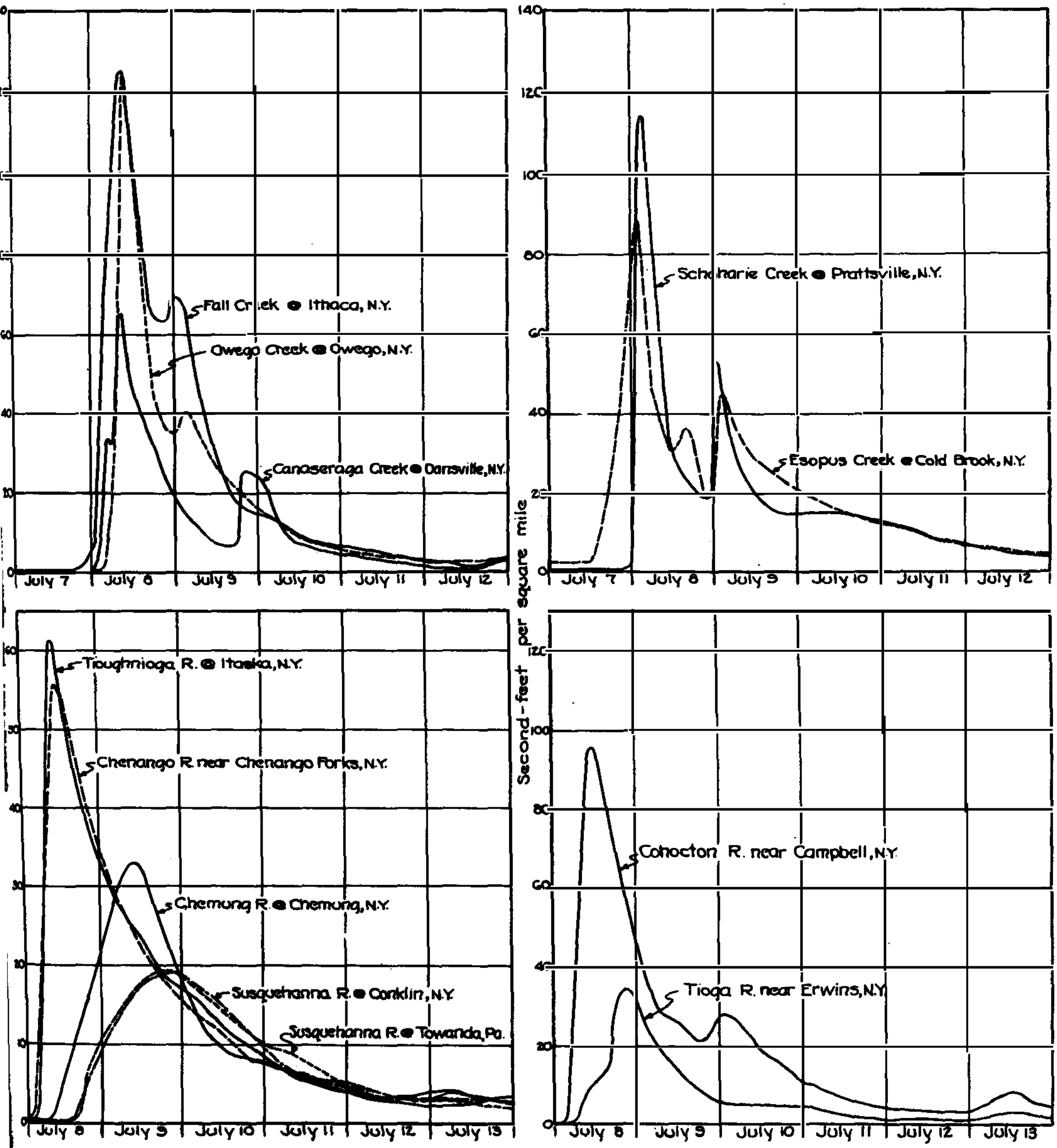

FIG. 1 -HYDROGRAPHS OF DISCHARGE OF VARIOUS STREAMS, N.Y. STATE FLOOD OF JULY, 1935

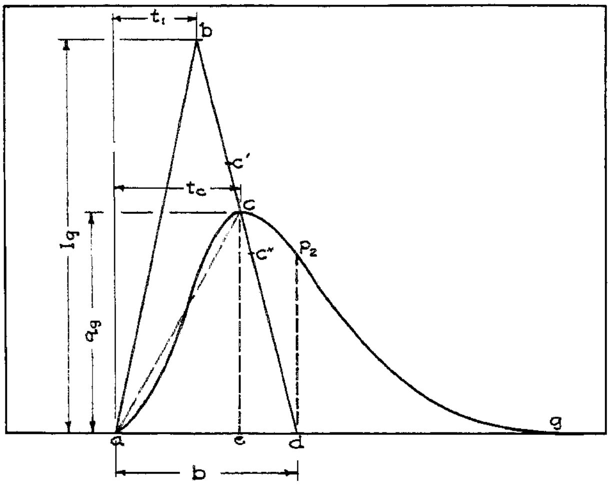

FIG.2-RELATION OF INFLOW- AND OUTFLOW-GRAPHS

channel-inflow graphs are similar. Illustrations of the close similarity of channel-outflow graphs on adjacent drainage-basins with similar rainfall-excess patterns and similar channel-storage characteristics are afforded by the flood of July, 1935, in central New York. Figure 1 shows the outflow-graphs on different streams. There is a close similarity in the outflow-graphs for Fall Creek, Owego Creek, and Canaseraga Creek; also for Tioughnioga River and Chenango River. These are, however, different from the three preceding. The last two streams have adjacent drainage-basins and closely similar physiographic characteristics, drainage-density, slope, etc. The same is true of Chemung River at Chemung, New York and Susquehanna River at Towanda, Pennsylvania. Likewise, Schoharie Creek at Prattsville, New York, and Esopus Creek at Cold Brook, New York, are adjacent and similar in physiographic characteristics and produced nearly identical channel-outflow graphs in this flood.

Relation of inflow- and outflow-crests--The storage-equation applies equally well to an entire flood-graph or to any segment thereof. Hence it can be applied at one operation to the portion of the flood-graph from the beginning of the rise to the outflow-crest. The following analysis was made with reference to maximum channel-storage which occurs at about the outflow-crest time, with a view to arriving at a method of determining approximately the outflow-crest reduction by channel-storage in a simple manner that avoids the somewhat laborious computation of an outflow-graph from the inflow-graph by the method described in a previous paper [1].

Referring to Figure 2, abd is a channel-inflow graph and acg the corresponding outflow-graph at a given location. Let I_g = maximum channel-inflow rate; b = time base of channel-inflow graph; t_1 = time of occurrence of channel-inflow crest; t_c = time of occurrence of channel-outflow crest, both t_1 and t_c being measured from beginning of runoff; q_g = maximum outflow-rate; Q_s = total flood-volume, excluding base-flow. This is equal both to the area of the inflow-graph and that of the outflow-graph. S_g = maximum channel-storage; Q_c = total outflow down to time of crest t_c; c = ratio of total outflow Q_c at crest-time to the area of the triangle ace. All volumes should be expressed in the same units, as, for example, c.f.s-days.

From Figure 2

$$Q_s = (bI_g/2)$$

and

$$Q_c = (cq_g t_c/2)$$

Also, from Figure 2, the total channel-inflow ΣI_g down to the time t_c is

$$\Sigma I_g = (bI_g/2) - [(b - t_c)q_g/2]$$

The storage equation gives

$$\Sigma I_g = (Q_c + S_g)$$

or

$$(bI_g/2) - (bq_g/2) + (t_c q_g/2) = [(ct_c q_g/2) + S_g]$$

$$(bI_g/2) = (bq_g/2) - [(1 - c)\ t_c q_g/2] + S_g$$

$$(q_g/I_g) - [(1 - c)\ t_c/b](q_g/I_g) + (S_g/Q_s) = 1$$

Hence

$$[1 - (1 - c)\ t_c/b](q_g/I_g) + (S_g/Q_s) = 1$$

Let $(1/\rho) = [1 - (1 - c)\ t_c/b]$, then (1)

$$(q_g/I_g) = [\rho(1 - S_g/Q_s)] \tag{2}$$

This equation makes it possible to determine the outflow-crest where the inflow-graph is known, together with the maximum channel-storage and the factor ρ.

Application of equation (2)--The equation

$$(q_g/I_g) = [\rho(1 - S_g/Q_s)] \tag{2}$$

may be applied to the determination of flood-crest reduction by channel-storage in connection with several problems:

(1) Determination of outflow-crest at a given station where hydrographs of other floods are available.

(2) Determination of flood-crest at a given station where hydrographs of floods are available at other stations on the same stream.

(3) Determination of flood-outflow crest at a given station on a stream on which no gagings are available but flood-hydrographs are available on adjacent streams with similar physiographic characteristics.

To apply equation (2) to any of these cases, four things are required:

(1) The channel-inflow graph which is assumed is available.

(2) The maximum channel-storage or the ratio (S_g/Q_s) of maximum channel-storage to total surface-runoff.

(3) The ratio of c of runoff antecedent to the crest to the triangle ace (Fig. 2).

(4) The ratio of inflow-crest time t_c to inflow-time base b. Having given c and (t_c/b), the value of ρ can be determined from equation (1)

The practicability of applying equation (2) to problems of flood-crest reduction depends on the accuracy with which the values of these quantities applicable to a given stream and flood can be determined from data of (a) other floods at the same station or (b) data of floods at other stations on the same stream or adjacent streams.

For the purpose of determining values of (S_g/Q_s), c, and (t_c/b), determinations have been made of these quantities for four conditions. These include:

(1) For the same natural flood or stream-rise at different gaging-stations on the same stream (Delaware River, Figs. 3-6).

(2) For an artificial flood produced by release of water from a storage-reservoir and for different gaging-stations on the same stream (North Platte River, Fig. 7; data from daily discharges published in U. S. Geol. Surv. W.-S. Paper 786, pp. 168-179, partly as interpreted by the author and supplemented by detailed data furnished by the U. S. Geol. Surv.).

(3) For the same flood on adjacent drainage-basins (central New York flood of July 1935, Figs. 8-12).

(4) For different floods at the same gaging-station (Delaware and Genesee rivers).

In all these cases the base-flow, whether ground-water flow or initial channel-storage, has been eliminated so as to obtain the outflow-graph or net surface-runoff for comparison with the virtual channel-inflow graph. (Computations can equally well be carried out without deducting base-flow or ground-water flow, but if so carried out, the base or ground-water flow or both must be determined and included in the channel-inflow or V-I graph.)

For the purpose of checking the determinations of channel-storage, the crest-portion of the outflow-graph was computed in each case by the method of the V-I graph, and reference to Figures 3 to 12 shows substantial agreement between the observed and computed outflow-crests.

Data were tabulated for all the cases for which computations were made, as shown on Table 1. Column (2) shows the ratio of the maximum channel-storage at or near the crest, to the total surface-runoff. It is interesting to note that in case of all of these floods, 48 to 75 per cent of the total flood-volume, and sometimes more, remained in the stream-system as channel-storage at the time of the outflow-crest. Column (3) of the Table shows the ratio of the outflow-crest to the channel-inflow crest. This quantity subtracted from unity represents the fraction of crest-reduction by channel-storage.

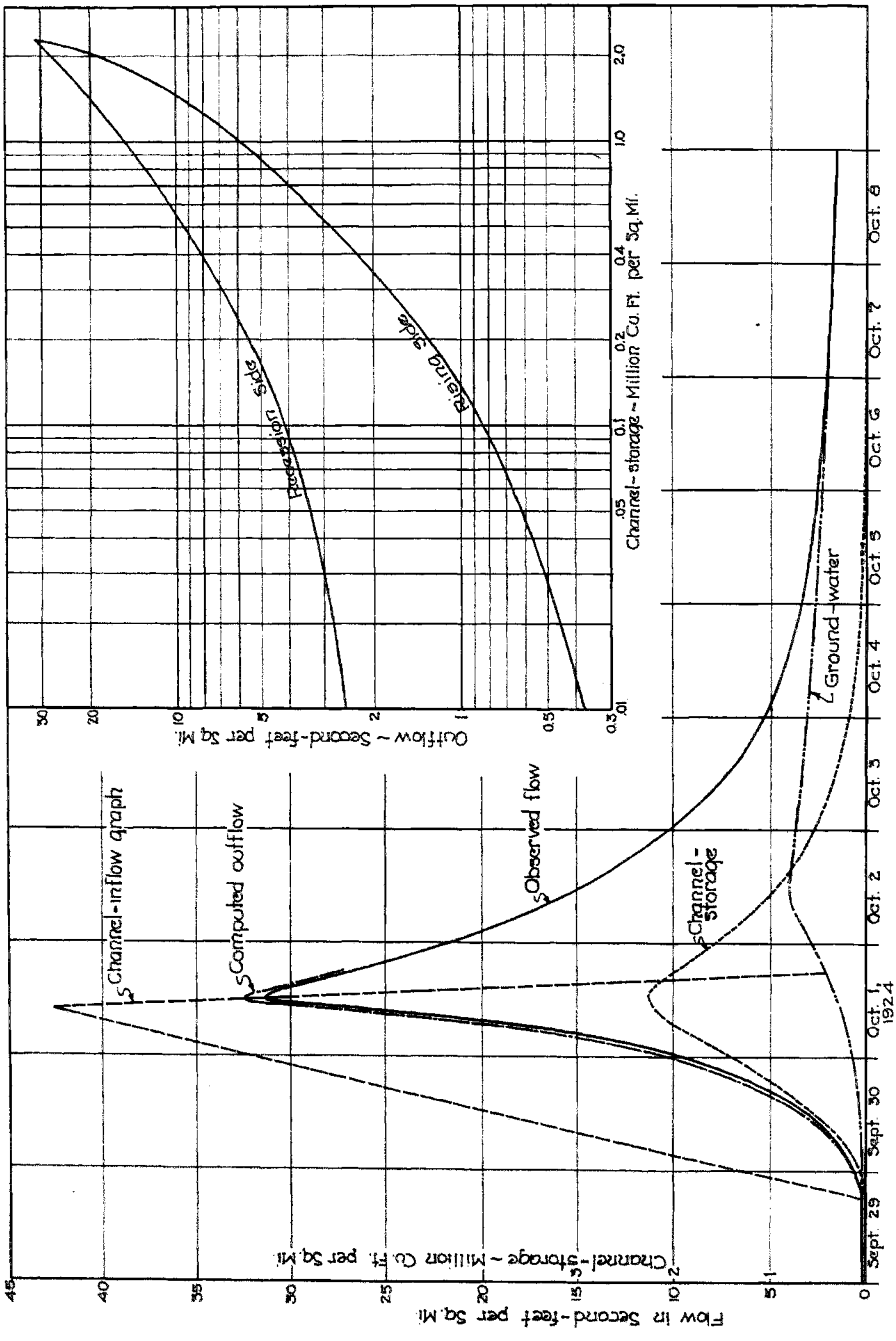

FIG. 3—DELAWARE RIVER AT PORT JERVIS, N.Y.—DRAINAGE-AREA, 3076 SQ. MI.

In the examples given on Table 1 the flood-crest reduction ranged from less than 30 per cent to more than 80 per cent.

The ratio (S_g/Q_s)--The maximum channel-storage is easily determined from inflow- and outflow-graphs, since it is the area between these graphs from the beginning of the rise to the outflow-crest. The data given on Table 1 show that the ratio (S_g/Q_s) is relatively constant, its usual value being between 50 and 70 per cent. This ratio varies, however, directly with the ratio of outflow-crest to flood-volume, and determinations of these two ratios for different floods will supply data useful as a guide in selecting appropriate values of the ratio for ap-

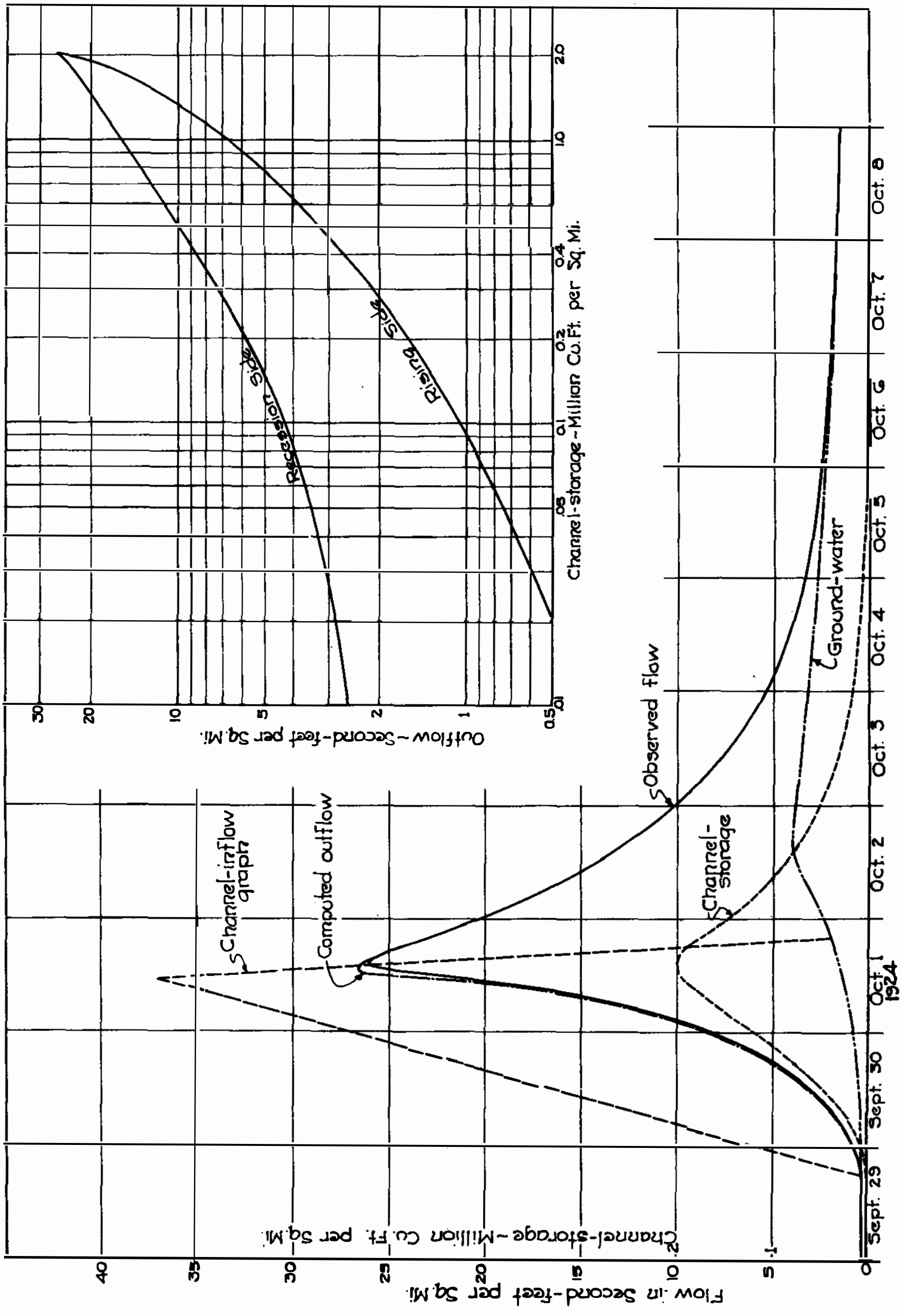

FIG.4-DELAWARE RIVER AT BELVIDERE,N.J. -DRAINAGE-AREA, 4542 SQ.MI.

plication to other cases. In some instances the value of this ratio is much higher than 70 per cent, as, for example, in case of the floods of the Tioughnioga and Chenango rivers listed. These floods on adjacent streams were, as shown by Figure 1, closely similar and have similar values of the maximum storage-ratio. In case of Fall Creek and Owego Creek, with flood-graphs of similar form, as shown on Figure 1, there are large differences in the values of the (S_g/Q_s)-ratio. This is, however, due to the fact that while the graphs are of similar form, the flood was double-crested and the secondary crest, and consequently the value of Q_s, was much higher on Fall Creek than on Owego Creek. With reference to the flood on North Platte River, the (S_g/Q_s)-ratio is nearly constant. For the flood of the Delaware River on October 1, 1924, this ratio is

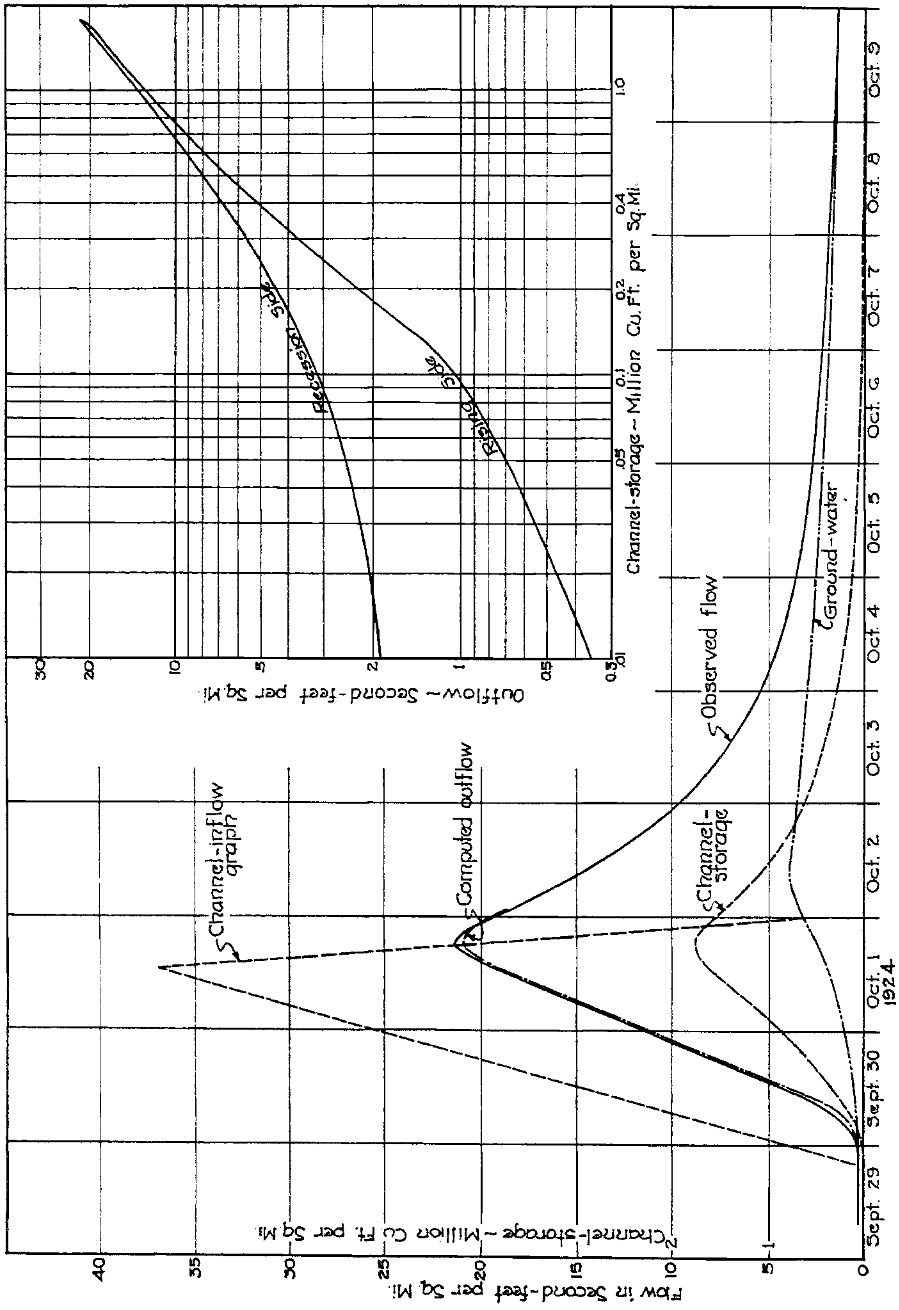

FIG. 5-DELAWARE RIVER AT RIEGELSVILLE, N.J.~DRAINAGE-AREA, 6344 SQ.MI.

practically identical for Port Jervis and Belvidere; also identical, but lower, for Riegelsville and Trenton. The last-named stations are below the mouth of Lehigh River and the channel-storage characteristics are similar for the two upstream stations and for the two downstream stations but dissimilar as between the upstream and downstream stations.

If two stations, one for comparison, the other for determination of flood-crest reduction, are both on the same stream, then a portion of the channel-storage is common to both stations and the value of the ratio (S_g/Q_s) will usually be nearly the same unless, as in the case of the Delaware River, a large tributary enters between the stations. The data indicate that a fairly close determination of the ratio (S_g/Q_s) can be made for a given flood at a given location from data of other floods at the same station or of the same flood at adjacent stations.

At or near a flood-crest the stream-slope is normal, that is, parallel to the stream-channel, and the channel-storage is sensibly the same in the vicinity of the crest for rising and receding

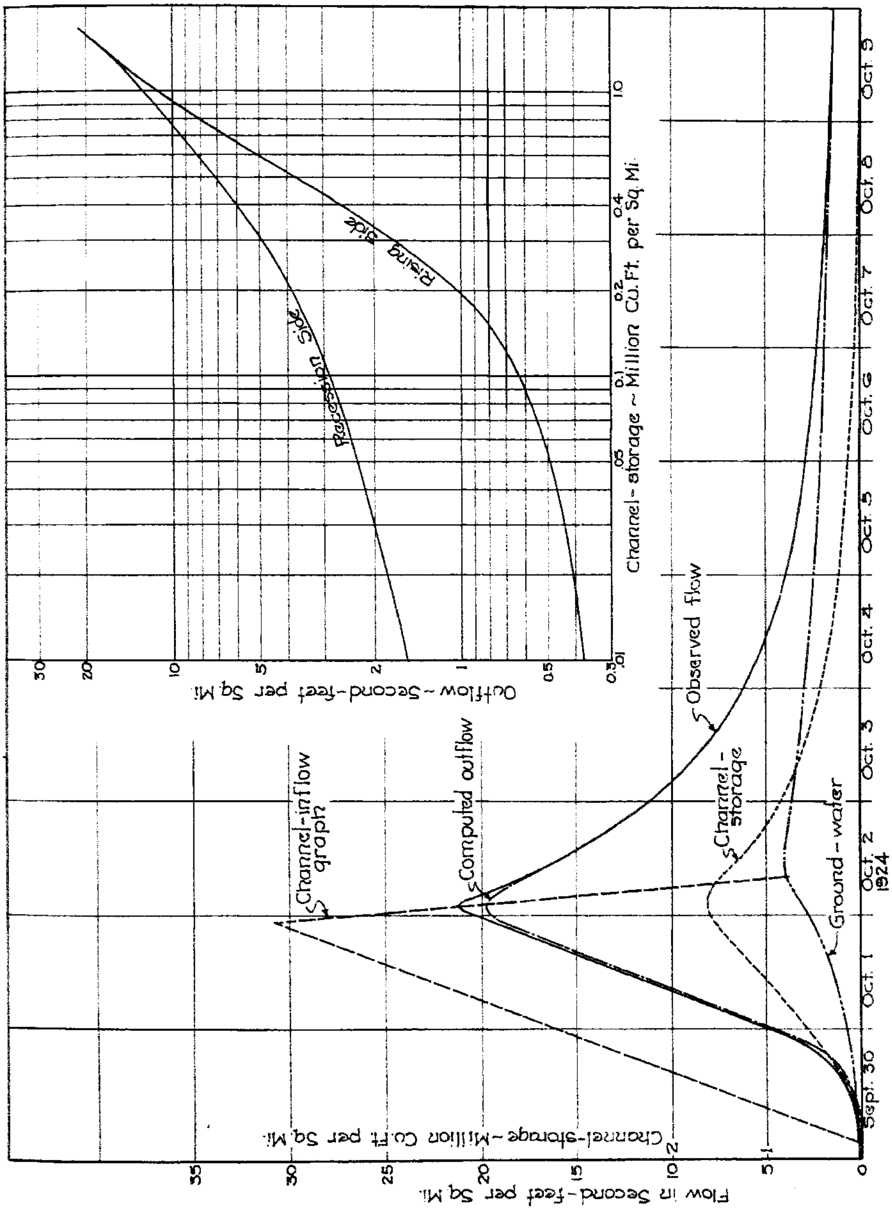

FIG. 6 ~ DELAWARE RIVER AT TRENTON, N.J. ~ DRAINAGE-AREA, 6796 SQ.MI.

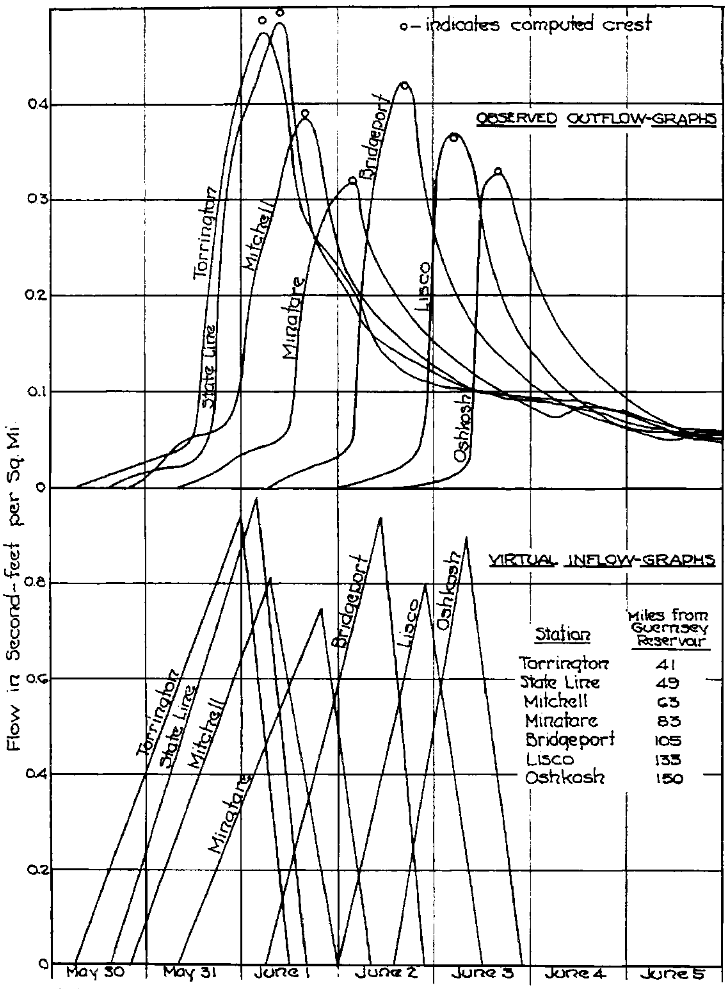

FIG. 7 –VIRTUAL INFLOW-AND OBSERVED OUTFLOW-GRAPHS FOR FLOW RELEASE FROM GUERNSEY RESERVOIR, NORTH PLATTE RIVER – MAY 31, 1935

stages. If the maximum channel-storage has been determined for lower floods at a given station, these values can be platted in terms of flood-volume and the line through the platted points can be used to determine approximately the maximum channel-storage for a higher flood from the known flood-volume derived from the channel-inflow graph.

The ratio of (t_c/b)--Values of this ratio are given in column (5), Table 1, from which it appears that this ratio is relatively constant, ranging, in the 31 cases listed, from 0.80 to 0.95.

At first it might appear that since this ratio is so nearly constant, its average value could be used directly to determine the outflow-crest from the channel-inflow graph, since the outflow-crest occurs at a point on the recession-side of the inflow-graph corresponding to the time t_c. Actually this mode of determining the outflow-crest serves only as a rough first approximation, for the reason that the recession-side of the channel-inflow graph has usually a very steep slope, and a small variation in the value of t_c, applied in the manner described, may induce a large variation in the resulting computed value of the outflow-crest. The relative constancy of the ratio (t_c/b) serves, however, to simplify the determination of the ratio ρ, in the manner subsequently described.

The factor c--This, as already described, is the ratio between the total outflow down to the time of the outflow-crest, and the triangle having as its vertices the point of beginning of run-off, the outflow-crest and a point on the base-line under the outflow-crest, as shown by column (7) of Table 1. This ratio varies in the examples given from 0.085 to 1.19, although in most cases its value lies between 0.50 and unity. The selection of the correct value of c is perhaps the most difficult factor in connection with the application of equation (2). The value of c depends on the form of the outflow-graph antecedent to the crest, which can in general be fairly closely predicted from that of the inflow-graph, and a value of c selected which has been derived from another outflow-graph of similar form.

The ratio ρ--When the values of (t_c/b) and of c are known, the value of ρ can be determined from equation (1). The values of ρ given in column (6), Table 1, were platted in terms of c, as shown on Figure 13. It will be seen that within the range in which the values of c usually oc-

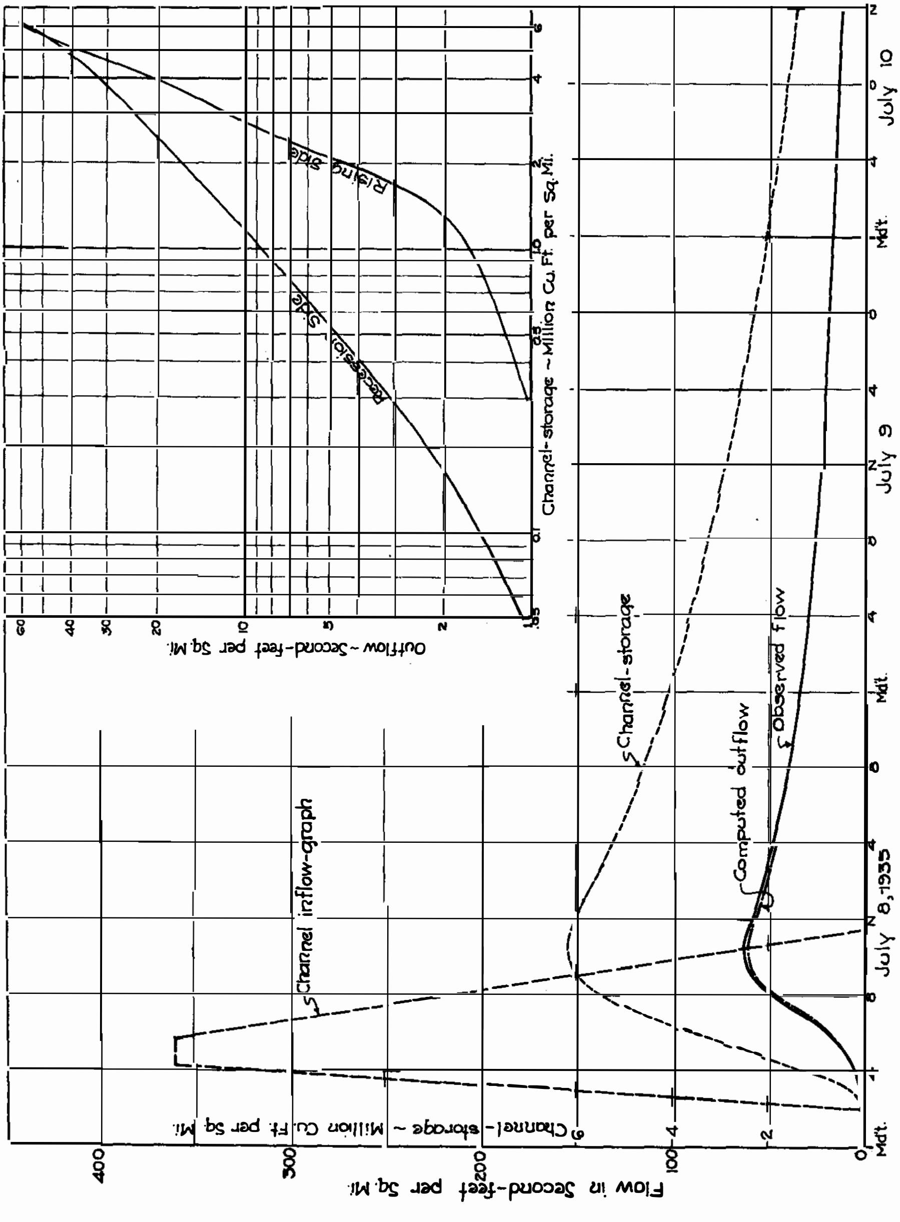

FIG. 8--TIOUGHNIOGA RIVER AT ITASKA, N.Y.--DRAINAGE-AREA, 735 SQ. MI.

cur, a variation of c produces relatively much smaller variation in the value of ρ. Hence some uncertainty in the value of c will not induce any large error in the computed outflow-crest.

Assuming the ratio (t_c/b) to be constant and with an average value 0.83, the relation of c

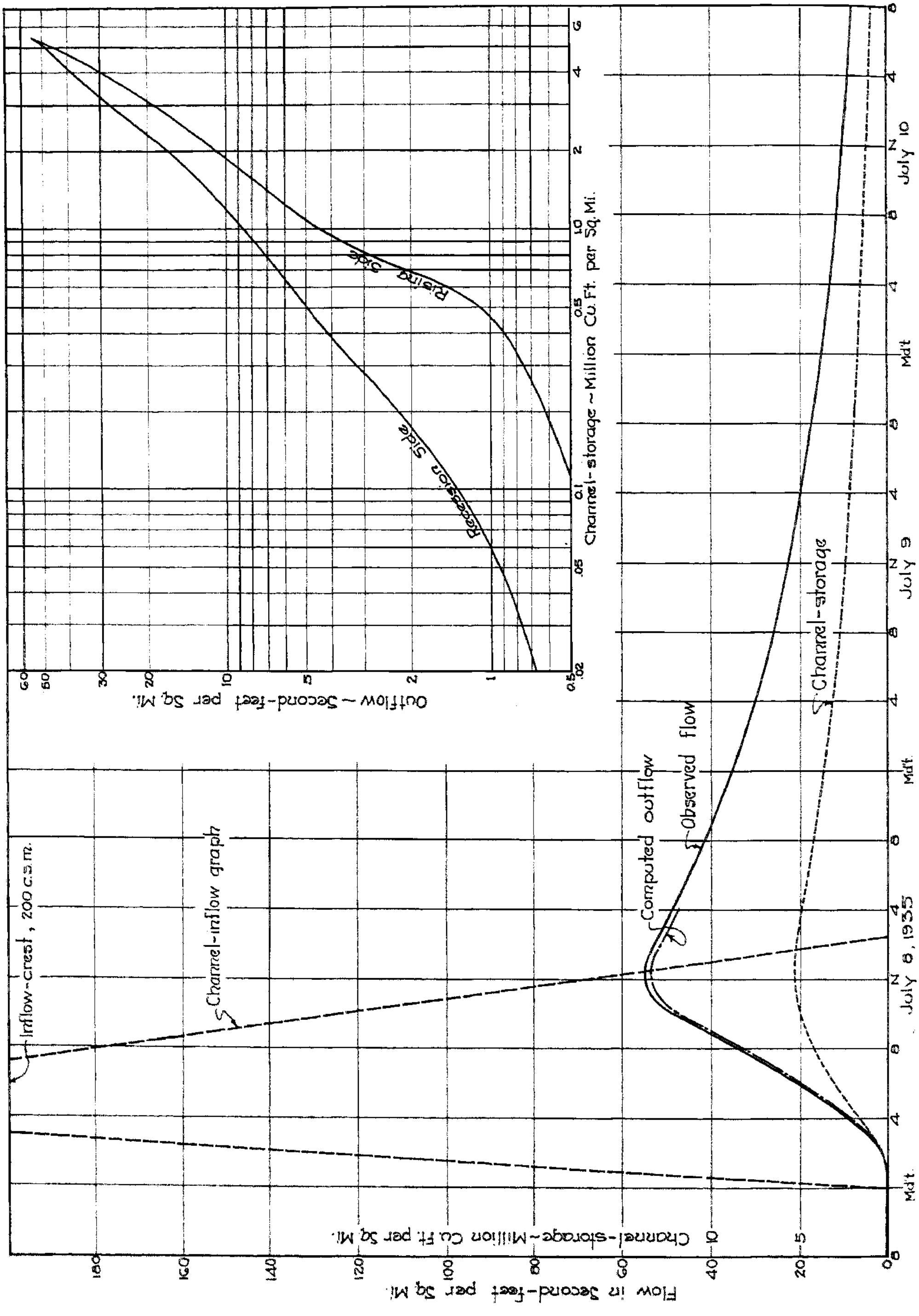

FIG. 9—CHENANGO RIVER NEAR CHENANGO FORKS, N.Y.—DRAINAGE-AREA, 1492 SQ. MI.

to ρ is given by the equation

$$c = [1 - 1.20(\rho - 1)/\rho] = [(1.20/\rho) - 0.20] \tag{3}$$

Values of ρ computed by this equation are shown by crosses on Figure 13 and it will be seen that

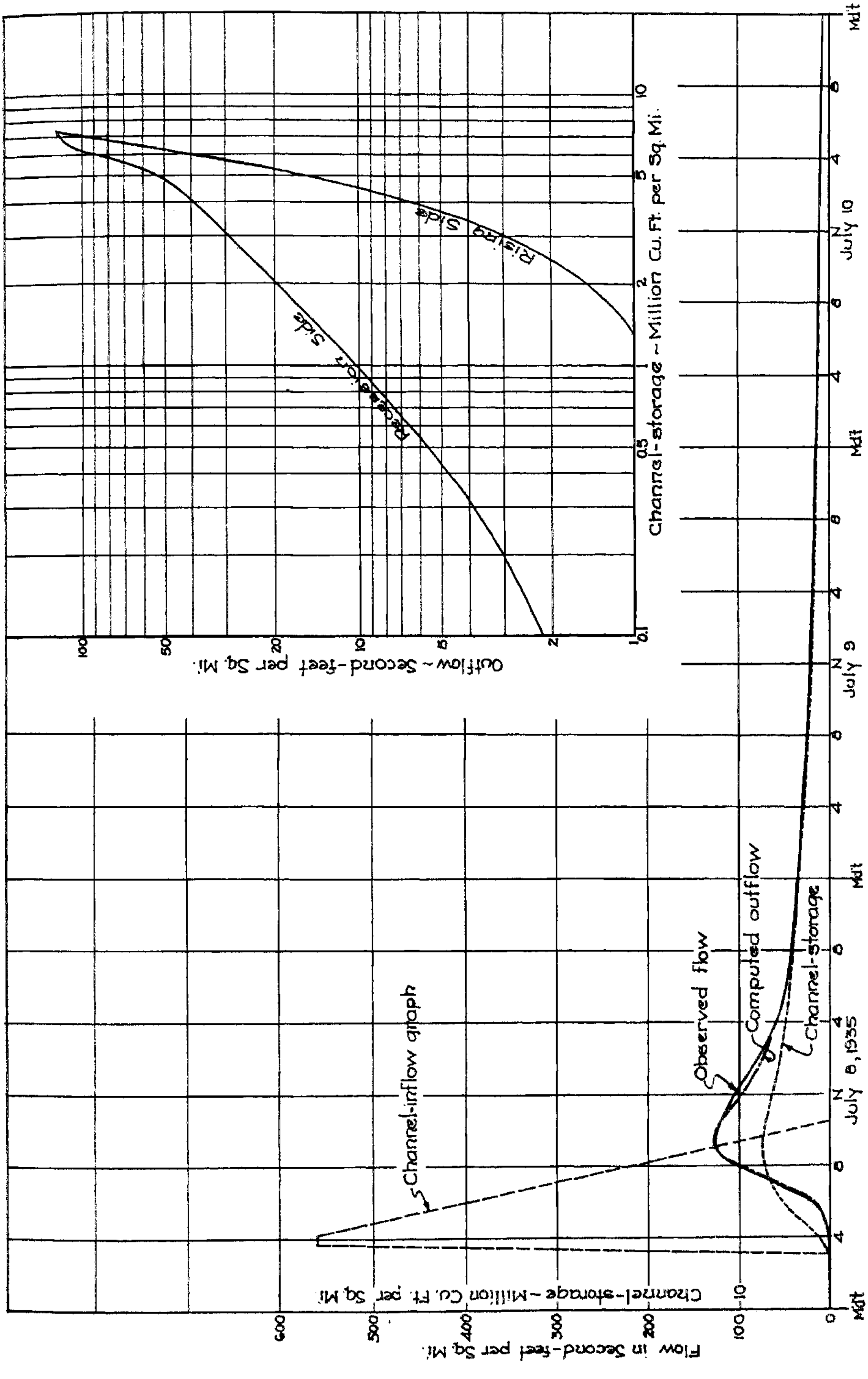

FIG.10-OWEGO CREEK NEAR OWEGO,N.Y. -DRAINAGE-AREA, 186 SQ. MI.

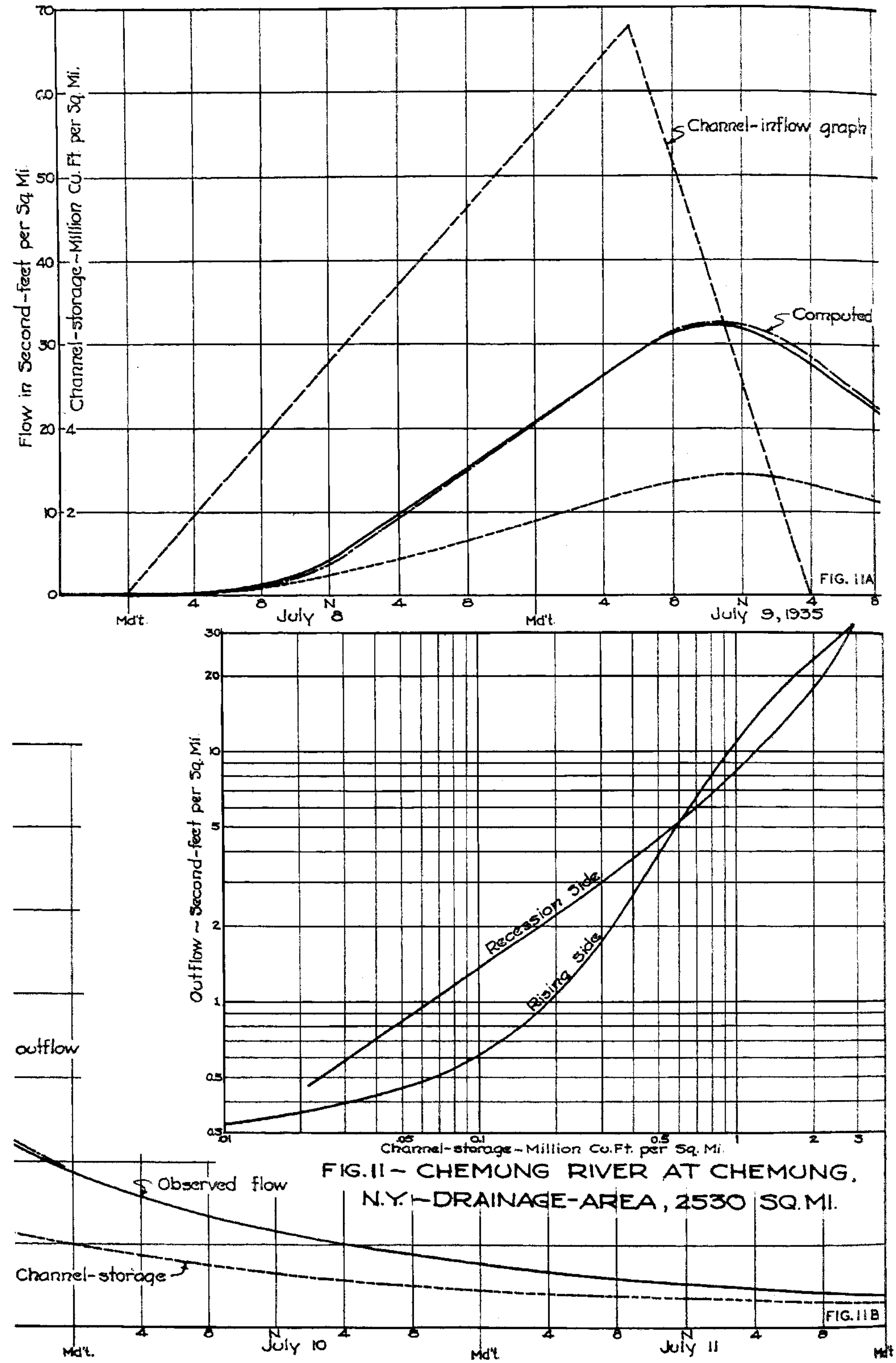

FIG. 11 — CHEMUNG RIVER AT CHEMUNG, N.Y. — DRAINAGE-AREA, 2530 SQ. MI.

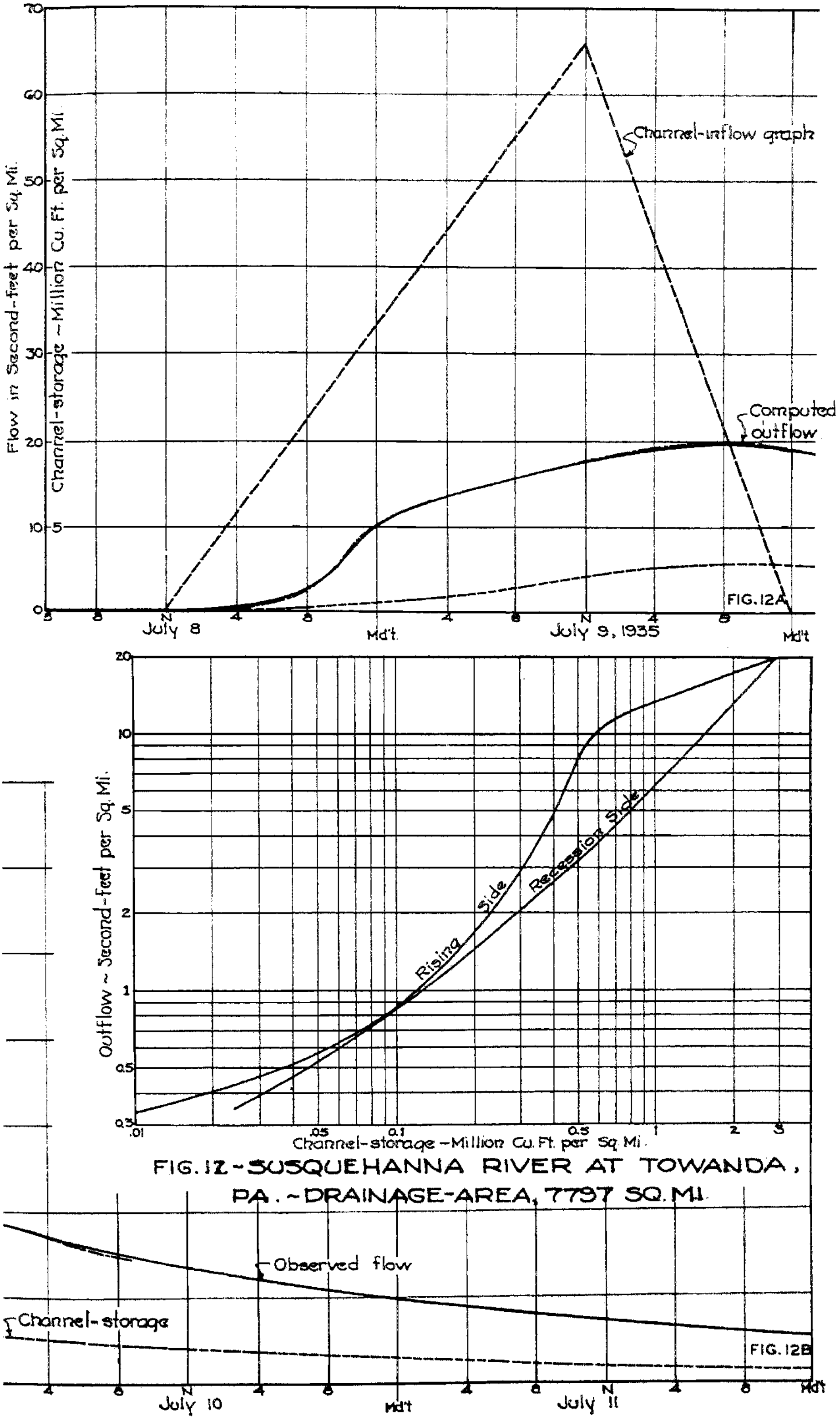

FIG. 12 - SUSQUEHANNA RIVER AT TOWANDA, PA. - DRAINAGE-AREA, 7797 SQ. MI.

Table 1--Values of ρ, (t_c/b), and other factors for various floods

Flood (1)	(S_g/Q_s) (2)	(q_g/I_g) (3)	$1 - (S_g/Q_s)$ (4)	(t_c/b) (5)	ρ (6)	c (7)
Central New York, July 8, 1935						
Fall Creek, Ithaca	.485	.527	.515	.809	1.03	0.964
Owego Creek, Owego (1)	.902	.225	.098	.800	2.30	0.293
Tioughnioga River, Itaska (a)	.848	.170	.152	.895	1.12	0.880
Tioga River, Irwins	.655	.472	.345	.875	1.37	0.691
Chenango River, Chenango Forks (a)	.941	.280	.059	.861	4.75	0.083
Chemung River, Chemung	.598	.486	.402	.875	1.21	0.802
Susquehanna River, Towanda (b)	.672	.288	.328	.903	0.88	1.15
North Platte River, May 31, 1935						
Torrington, Wyoming	.716	.505	.284	.889	1.78	0.506
State Line, Nebraska	.663	.502	.337	.878	1.39	0.680
Mitchell, Nebraska	.658	.477	.342	.844	1.40	0.661
Minatare, Nebraska	.707	.426	.293	.895	1.45	0.653
Bridgeport, Nebraska	.681	.450	.319	.850	1.41	0.658
Lisco, Nebraska	.750	.458	.250	.805	1.83	0.436
Oshkosh, Nebraska	.788	.366	.212	.844	1.73	0.499
Delaware River, October 1, 1924						
Port Jervis, New York	.617	.722	.383	.875	1.89	0.461
Belvidere, New Jersey	.612	.694	.388	.880	1.79	0.499
Riegelsville, New Jersey	.540	.549	.460	.885	1.19	0.819
Trenton, New Jersey	.548	.643	.452	.910	1.42	0.675
Delaware River, August 25, 1933	(c)	(c)	(c)			
Port Jervis, New York				.942	1.69	0.566
Belvidere, New Jersey				.946	1.52	0.641
Riegelsville, New Jersey				.927	1.30	0.751
Trenton, New Jersey				.902	1.26	0.774
Delaware River, September 17, 1933	(c)	(c)	(c)			
Port Jervis, New York				.932	1.61	0.596
Belvidere, New Jersey				.944	1.60	0.604
Riegelsville, New Jersey				.947	1.56	0.622
Trenton, New Jersey				.910	1.27	0.767
Genesee River, St. Helena, New York, November 28, 1925	(c)	(c)	(c)	.787	1.13	0.849
Genesee River, St. Helena, New York, November 18, 1927 (b)	(c)	(c)	(c)	.918	0.850	1.191
West Branch, Delaware River, Hale Eddy, New York, November 19, 1929	(c)	(c)	(c)	.793	1.02	0.974
West Branch, Delaware River, Hale Eddy, New York, June 11, 1930	(c)	(c)	(c)	.850	1.20	0.804
Susquehanna River, Conklin, New York, October 26, 1925 (b)	(c)	(c)	(c)	.870	0.988	1.013

(a) = trapezoidal-channel inflow-graphs. (b) = broad-crested floods. (c) = values not determined.

these values are in close agreement with the observed values. Consequently equation (3) may be used without sensible error for the determination of ρ.

Conclusions--Equation (2)

$$(q_g/I_g) = \rho(1 - S_g/Q_s) \qquad (2)$$

is not offered as a ready-made solution of problems of flood-crest reduction. Many more determinations of (S_g/Q_s), c, and (t_c/b) are needed to aid in its application. The accuracy with which this equation can be applied will increase as such data become available.

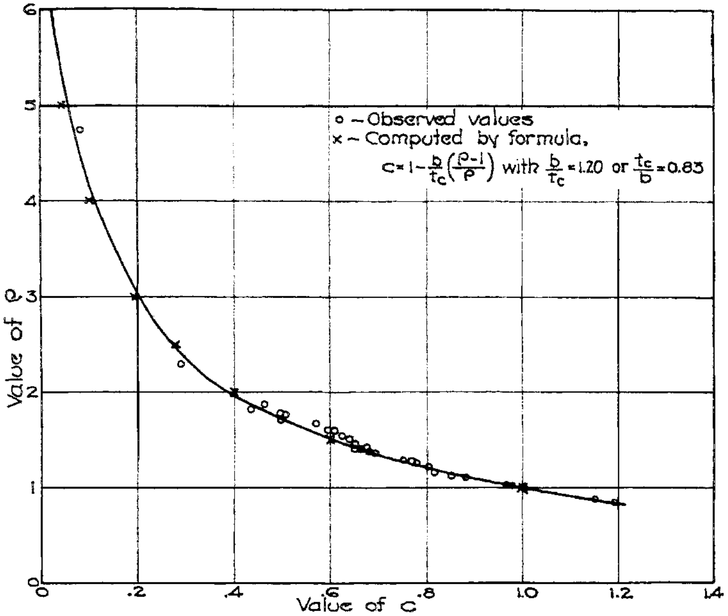

FIG. 13 ~ RELATION OF OBSERVED AND COMPUTED VALUES OF c AND ρ

Some factors determined by judgment must always be used in determining flood-crest reduction where no gagings are available, whatever method is applied. The method here given is simple and separates the factors involving judgment and reduces them to quantities capable of direct measurement in other floods or at other locations. The application of equation (2) is therefore like the application of the Manning formula, where the value of the roughness-factor n must be selected by judgment from previously measured values. Since equation (2) is based directly on relationships between inflow- and outflow-graphs which necessarily follow from the storage-equation, it will give correct results if correct values of the factors (S_g/Q_s), c, and (t_c/b) are used in its application.

Reference

[1] Robert E. Horton, Virtual channel-inflow graphs, Trans. Amer. Geophys. Union, 1941.

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