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# DETERMINATION OF INFILTRATION-CAPACITY FOR LARGE DRAINAGE-BASINS

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Introduction-synopsis--This paper describes a method which may be used for determining the average infiltration-capacity over a drainage-basin during large storms where a runoff-record, together with adequate rainfall-data, are available. The application of the method requires that in each drainage-basin there shall be at least one rain-intensity record kept with a recording rain-gage. The method is based on the observed fact that in great general storms, while there may be two or more different types of rain-intensity graphs in different parts of the storm-area, locally the rain-intensity graphs are statistically very much alike.

Two general cases are considered:

(1) Where the rain-intensity rises for a time above the infiltration-capacity of the soil in all parts of the drainage-area, so that the entire drainage-basin contributes runoff. This is designated a "full-area flood" or stream-rise.

(2) Where the rain-intensity on part of the area does not at any time rise to a point equal to the infiltration-capacity, so that part of the area does not contribute runoff. This is designated a "partial-area flood."

The methods described in the paper are applied to two general cases:

(1) The New England flood of November 2-5, 1927.

(2) A series of stream-rises on each of the following streams: Delaware River, Embarrass River, Wabash River, French Broad River, Susquehanna River, and Muskingum River.

The infiltration-capacities are least for the rocky and mountainous basins of the French Broad, Delaware, and upper Susquehanna rivers. For the latter basins the infiltration-capacities range from minima in spring and fall of 0.05 to 0.10 inch per hour to maxima in July and August of 0.30 to 0.40 inch per hour. For the generally flatter, permeable basins of the Wabash, Embarrass, and Muskingum rivers, the soil is largely of glacial origin and mostly under cultivation. Infiltration-capacities range from spring and fall minima of 0.15 to 0.30 inch per hour up to maxima of 0.80 to 1.20 inch per hour. Values close to the spring and fall minima may occur in midsummer if the soil is wet and rain-packed from recent antecedent rains.

Taken together there are shown (1) infiltration-capacities on many different areas in the same storm, (2) infiltration-capacities in several different storms on the same drainage-basins. The determinations of infiltration-capacity in the New England flood range from 0.05 inch per hour in the rocky and mountainous upper Connecticut Basin to 0.56 inch per hour in the highly permeable Quinebaug Drainage-Basin.

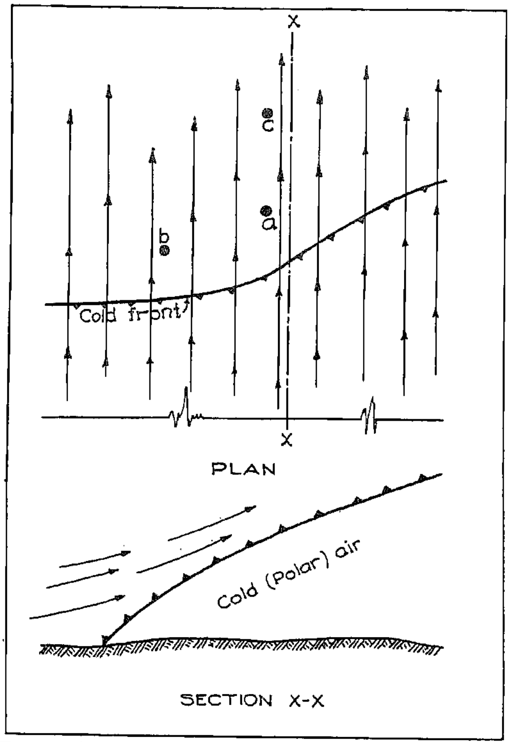

FIG. 1 - RELATION OF STATIONARY COLD FRONT TO DURATION OF STORM-RAINFALL

All of the determinations have been platted so as to show the seasonal march of infiltration-capacity. This is a maximum in August and the infiltration-capacity during midsummer storms is usually around a maximum value, ranging, in the examples given, from about 0.6 to 0.9 inch per hour or else it is close to the minimum value of about 0.1 inch per hour. Both the seasonal march of infiltration-capacity and the absolute values determined from these large drainage-basins are in good agreement with values of infiltration-capacity derived from laboratory and runoff-plat experiments and from smaller areas.

Meteorologic basis--The basis of the determination of infiltration-capacity in this paper is the fact that surface-runoff approximately equals the difference between the rainfall and the infiltration during the part of the storm in which the rain-intensity exceeds the infiltration-capacity. This difference is called the rainfall-excess or total supply.

The determination of infiltration-capacity f consists in finding a value of f such that the product of f and the duration of rainfall at intensities in excess of f subtracted from the total rainfall for the same interval will leave a remainder equal to the surface-runoff.

Since rainfall-records must be used which for the most part give only the total amount of rainfall, the determination of infiltration-capacity involves the problem of determining the hourly rain-intensity distribution at such stations. It is assumed that at least one record of hourly rain-intensity is available. This is called the base-station. If the duration of rainfall is the same and the rain-graphs are statistically similar at the base-station and at an adjacent station, the hourly distribution of rainfall at the second station may be obtained by multiplying the ratios of hourly to total rainfall at the base-station by the total rainfall at the second station. This is precisely the same as the use of the unit-graph method for distribution of runoff, although this method was applied to rainfall by the author 20 years earlier.

Application of this method requires that the time-bases of the rain-graphs at adjacent stations shall be approximately equal but not necessarily simultaneous. This is usually not true of local storms of the convectional type, as has been shown by Thornthwaite [see 1 of references at end of paper]. It may not be true of general storms where the cold front or fronts move rapidly. Unless correction is made for varying rain-duration in the manner subsequently described, the use of the method should be limited to general storms with nearly stationary cold fronts.

Since the impression prevails that rain-intensity distribution is highly erratic and uncertain, it is important to discuss briefly the characteristics of rain-intensity graphs in general storms.

Dr. C. F. Brooks [2] has recently pointed out that in general two conditions are necessary to the production of a major storm: (1) The existence of one or more stationary or nearly stationary high-pressure areas, with accompanying cold fronts; (2) the existence of an adequate supply of warm, moist air flowing up the faces of the air-mountains produced by the cold fronts.

Differences in amount of rainfall in the same storm and adjacent to the same cold front may be due to (1) difference of rain-intensities, (2) difference of rainfall-duration, (3) both combined. Consider a great storm with a more or less stationary cold front, as shown schematically in plan and section by Figure 1. Two adjacent rainfall-stations may be either: (1) Similarly situated relative to the cold front, as a and b; (2) located on the same stream-line or line of air-flow but at different distances from the cold front, as a and c; (3) differently situated relative to the cold front, as in case of b and c. Except as modified by topographic conditions, stations a and b will in general have similar rain-intensity graphs but with some difference on duration of rainfall, especially if one station is near the center, the other near the edge of the warm air-current. Stations a and c will in general have nearly the same rainfall-duration but are likely to show large differences in rain-intensity and total amount. All stations controlled by this particular cold front will therefore show, in general, statistically similar rain-intensity graphs, with small or moderate variations in total duration of rainfall, these differences increasing with distance between the stations. Two or more fronts are often involved in the same storm, in which case the characteristics of rainfall in the rain-smear controlled by the different cold fronts may be widely different, but, for stations controlled by a given front, the assumption that the duration of rain is similar at two adjacent stations will usually be nearly true. This is clearly shown by Table 1, which shows total duration of rain and intensity at recording rain-gage stations subject to control by the eastern and western cold fronts, respectively, in the New England storm of November 2-5, 1927.

Table 1--Storm rainfall, New England flood of November 2-5, 1927

| Station (1) | Rainfall-duration, hours (2) | Total rainfall, inches (3) | Average hourly intensity, inches (4) | Maximum hourly rainfall, inches (5) |
|---|---|---|---|---|
| | Western cold front | | | |
| Albany, N. Y. | 40 | 3.86 | 0.0965 | 0.31 |
| Burlington, Conn. | 33 | 5.51 | 0.167 | 0.50 |
| Hartford, Conn. | 38 | 3.57 | 0.094 | 0.44 |
| New Haven, Conn. | 31 | 3.78 | 0.122 | 0.53 |
| New York, N. Y. | 32 | 1.83 | 0.057 | 0.27 |
| Northfield, Vt. | 43 | 8.63 | 0.201 | 0.62 |
| Springfield, Mass. | 39 | 4.28 | 0.110 | 0.55 |
| West Hartford, Conn. | 36 | 3.92 | 0.109 | 0.35 |
| Monroe, Mass. (a) | 36 | 6.20+ | 0.172 | 0.35 |
| Shelburne Falls, Mass. (a) | 26 | 3.80+ | 0.146 | 0.38 |
| Whitingham, Vt. (a) | 34 | 5.51+ | 0.162 | 0.38 |
| Somerset, Vt. (a) | 22 | 8.47+ | 0.385 | 0.65 |
| Vernon, Vt. (a) | 27 | 3.73+ | 0.138 | 0.35 |
| | Eastern cold front | | | |
| Blue Hill Observatory, Milton, Mass. | 18 | 2.16 | 0.120 | 0.45 |
| U.S. Weather Bureau, Boston, Mass. | 18 | 1.81 | 0.100 | 0.41 |
| Brookline, Mass. | 13 | 1.33 | 0.102 | 0.28 |
| Concord, N. H. | 15 | 4.03 | 0.269 | 0.80 |
| Eastport, Me. | 11 | 3.14 | 0.286 | 0.77 |
| Lowell, Mass. | 12 | 3.26 | 0.272 | 1.04 |
| Pawtucket, R. I. | 14 | 2.24 | 0.160 | 0.35 |
| Portland, Me. | 11 | 0.75 | 0.068 | 0.25 |
| Providence, R. I. | 14 | 1.26 | 0.090 | 0.25 |
| Hope Reservoir, Providence, R. I. | 15 | 1.57 | 0.105 | 0.32 |
| Winter Hill Observatory, Worcester, Mass. | 18 | 4.26 | 0.237 | 0.68 |
| Sewage Plant, Worcester, Mass. | 19 | 5.10 | 0.268 | 1.42 |

(a) Initial rain omitted; duration exceeded number of hours in column (2); maximum intensity is average for highest two hours.

Determination of storm-rainfall--It is assumed that the surface-runoff (that is, total runoff minus ground-water) is known. The next step is the determination of rainfall-stations to be included and the total storm-rainfall at each. The Thiessen-Horton method [3] furnishes an accurate criterion for determining stations to be included in calculating the mean rainfall on a given area for any storm or time-interval. In general, all stations within the basin should be included, together with those outlying stations which would be included if the Thiessen-Horton method was applied. This can be determined quickly by inspection.

Determination of storm-rainfall at a given station is complicated by the fact that rainfall is not recorded at the same hours. Climatological Data, published by the United States Weather Bureau, gives the times of reading at United States Weather Bureau stations. These times are usually either 8 to 9 a.m. or 5 to 6 p.m. at voluntary stations, and midnight at regular stations. The rain recorded on a given date is that which fell in the 24 hours preceding the time of reading. With the list of stations there should be set down the times of observation. The days of record to be included or excluded at a given station can then be readily determined from the record at the recording gage or base-station in the manner illustrated by the following example.

Suppose, for example, at the recording station, the storm lasted from 6 a.m. to 11 p.m. on May 10. There was no antecedent or subsequent rain on May 10 or 11. Therefore, at other stations the records to be included are the recorded amounts for May 10 and 11, whether the reading was taken in the morning or afternoon, since in both cases the rain began before and continued after the time of observation on May 10.

If, on the other hand, the storm had begun at 10 a.m. and ended at 4 p.m. on May 10, and there had been antecedent rain, then obviously at stations where readings are taken in the morning the amount recorded on May 10 should not be included, and rain in any shower between 4 p.m. and the next 8 a.m. of the following morning, and recorded on the 11th, should not be included. For stations where readings are taken in the evening, if there was no antecedent rain, all rain recorded on the 10th should be included, but nothing included which was recorded on the 11th.

Suppose in the last case the storm which produced the stream-rise lasted from 10 a.m. to 4 p.m. on the 10th, but there was another shower from 3 to 7 a.m. on the 11th.

Consider first a station where readings are taken in the morning. The record on the morning of the 11th includes both showers and the amount to be included at a given station may be taken as the same proportion of the total recorded amount as the amount which fell in the first shower is to the total rain during the same 24-hour period at the base-station. If the reading was taken in the afternoon, the recorded rain on the 10th should be included, and that on the 11th excluded.

Determination of infiltration-capacity for full-area stream-rises--In detail the method used in this paper is as follows. For full-area stream-rises, a first approximation to the infiltration-capacity is obtained by subtracting the total runoff, after deducting ground-water flow, from the total rain at the base-station, and dividing the remainder by the duration of rainfall at the base-station. On large areas two or more base-stations may be used if available, each one being applied to rainfall-records at the nearest adjacent station. The percentage of total storm-rainfall which fell in each hour during the storm is first determined for the base-station.

Next, assuming a total rainfall of some number of even inches about equal to the average storm-rainfall on the given area, the hourly distribution of rainfall for this total amount of rainfall is computed by multiplying each of the hourly ratios at the base-station by the assumed rainfall. Next, assuming a series of infiltration-capacities varying by tenths of an inch and ranging from a value below to a value considerably above the trial value of f, the excess of rainfall is computed by subtracting the infiltration-capacity from the corresponding hourly amounts of rainfall if the latter are greater. This computation for a rainfall of four inches, distributed as shown by the recording rain-gage record at Vernon, Vermont, in the November 1927 flood is shown in columns (5) to (9) of Table 2. The sum of the items entered in the column corresponding to a given infiltration-capacity will then represent the excess of rainfall corresponding to a given assumed rainfall. Similar computations are made for other assumed total amounts of rainfall varying by even inches from the lowest up to the highest amount of rainfall occurring at any station within the drainage-basin. In this instance the computations are made for Millers River at Erving, Massachusetts. It will be noted from Table 2 that for a storm-rainfall of four inches there would be no excess of rainfall and hence no surface-runoff on the part of the drainage-basin with an infiltration-capacity of 0.4 inch per hour or more.

The total amounts of rainfall-excess for different assumed storm-rainfalls and infiltration-capacities are then plotted as shown on Figure 2. From the curves given on Figure 2, the excess of rainfall for various infiltration-capacities can be determined for any total amount of rainfall. The total storm-rainfall is tabulated for all stations applicable to the given drainage-basin and storm, as shown in column (6) of Table 3. The corresponding amounts of rainfall-excess are then taken off for each assumed infiltration-capacity and set down in columns (7) to (9), inclusive. The average of the determinations in any given column represents the average excess of rainfall over the drainage-basin. These averages are plotted in terms of the infiltration-capacity in Figure 3. The total surface-runoff at Erving in the November 1927 flood was 2.26 inches and, as shown at a of Figure 3, the corresponding infiltration-capacity f is 0.116 inch per hour.

Table 2--Rainfall-excess, based on Vernon, Vermont, recording record for storm of November 3, 1927

| Record at Vernon, Vermont | | | P = 4.0 inches | | | | | |
|---|---|---|---|---|---|---|---|---|
| Hour | Amount, inches | Portion of total | Total amount, inches | Infiltration-capacity f, inches per hour | | | | |
| | | | | 0.10 | 0.20 | 0.30 | 0.40 | 0.50 |
| (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) |
| | | | | Rainfall-excess | | | | |
| 5 a.m. | .05 | .013 | | | | | | |
| 6 | .05 | .013 | | | | | | |
| 7 | .03 | .008 | | | | | | |
| 8 | .02 | .005 | | | | | | |
| 9 | .05 | .013 | | | | | | |
| 10 | .05 | .013 | | | | | | |
| 11 | .07 | .019 | | | | | | |
| 12 m. | .08 | .022 | .088 | 0 | | | | |
| 1 p.m. | .20 | .054 | .216 | .116 | .016 | 0 | 0 | 0 |
| 2 | .20 | .054 | .216 | .116 | .016 | 0 | 0 | 0 |
| 3 | .13 | .035 | .140 | .040 | 0 | 0 | 0 | 0 |
| 4 | .12 | .032 | .128 | .028 | 0 | 0 | 0 | 0 |
| 5 | .03 | .008 | | | | | | |
| 6 | .02 | .005 | | | | | | |
| 7 | .15 | .040 | .160 | .060 | 0 | 0 | 0 | 0 |
| 8 | .15 | .040 | .160 | .060 | 0 | 0 | 0 | 0 |
| 9 | .35 | .094 | .376 | .276 | .176 | .076 | 0 | 0 |
| 10 | .35 | .094 | .376 | .276 | .176 | .076 | 0 | 0 |
| 11 | .35 | .094 | .376 | .276 | .176 | .076 | 0 | 0 |
| 12 p.m. | .35 | .094 | .374 | .276 | .176 | .076 | 0 | 0 |
| 1 a.m. | .25 | .068 | .272 | .172 | .072 | 0 | 0 | 0 |
| 2 | .25 | .068 | .272 | .172 | .072 | 0 | 0 | 0 |
| 3 | .15 | .040 | .160 | .060 | 0 | 0 | 0 | 0 |
| 4 | .15 | .040 | .160 | .060 | 0 | 0 | 0 | 0 |
| 5 | .05 | .013 | | | | | | |
| 6 | .05 | .013 | | | | | | |
| 7 | .02 | .005 | | | | | | |
| 8 | .01 | .003 | | | | | | |
| Totals | 3.73 | 1.000 | | 1.988 | .880 | .304 | 0 | 0 |

Table 3--Rainfall-excess for different assumed infiltration-capacities, Millers River at Erving, Massachusetts, flood of November 2-5, 1927 (rainfall-intensity base-station, Vernon, Vermont)

| Station, Massachusetts | November, 1927 | | | | Total rainfall, inches | Infiltration-capacity f, inches per hour | | |
|---|---|---|---|---|---|---|---|---|
| | 2 | 3 | 4 | 5 | | 0.10 | 0.20 | 0.30 |
| (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) |
| | | | | | | Total rainfall-excess | | |
| Wendell | | 1.81 | 4.10 | 0.12 | 5.91 | 3.65 | 2.22 | 1.27 |
| Warwick | 1.37 | 2.08 | 0.36 | | 3.81 | 1.82 | 0.77 | 0.20 |
| Fitzwilliam | 1.19 | 2.24 | 0.33 | | 3.76 | 1.76 | 0.74 | 0.18 |
| Winchendon | 0.91 | 3.80 | 0.33 | | 4.13 | 2.08 | 0.95 | 0.35 |
| Baldwinsville | 0.42 | 3.62 | 0.39 | | 4.01 | 2.00 | 0.90 | 0.30 |
| Gardner | | 4.06 | 0.03 | | 4.09 | 2.05 | 0.93 | 0.33 |
| Athol | 1.00 | 4.83 | 0.09 | | 4.92 | 2.76 | 1.48 | 0.74 |
| New Salem | | | 6.05 | 0.05 | 6.05 | 3.77 | 2.32 | 1.35 |
| Averages | | | | | 4.58 | 2.49 | 1.26 | 0.590 |

This method of procedure is direct and exact so far as determination of average excess of rainfall is concerned, provided the data are adequate. As regards determination of average infiltration-capacity, it is subject to the following qualifications:

(1) The term "runoff" as here used refers to surface-runoff. It is assumed that a ground-water depletion-curve has been obtained from records of the stream-flow, and the ground-water flow has been eliminated from the runoff-graph. It is assumed that the surface-runoff equals the rainfall-excess. Surface-runoff cannot, however, occur unless there is water standing on the ground-surface. This may be merely a film so thin as to be barely perceptible. When rainfall-excess ends there is always a certain amount of residual detention which continues to contribute surface-runoff for a short time. Part of this surface-detention is lost by infiltration, so that if there was no residual rain after rainfall-excess ends, surface-runoff would always be somewhat less than rainfall-excess. There is, however, always some residual rain at intensities less than infiltration-capacity, part of which is contributed to surface-runoff, so that actually the surface-runoff ranges from values a little less than to values a little greater than the total rainfall-excess or supply. In general, the error resulting from the assumption that rainfall-excess or supply and surface-runoff are equal is relatively small.

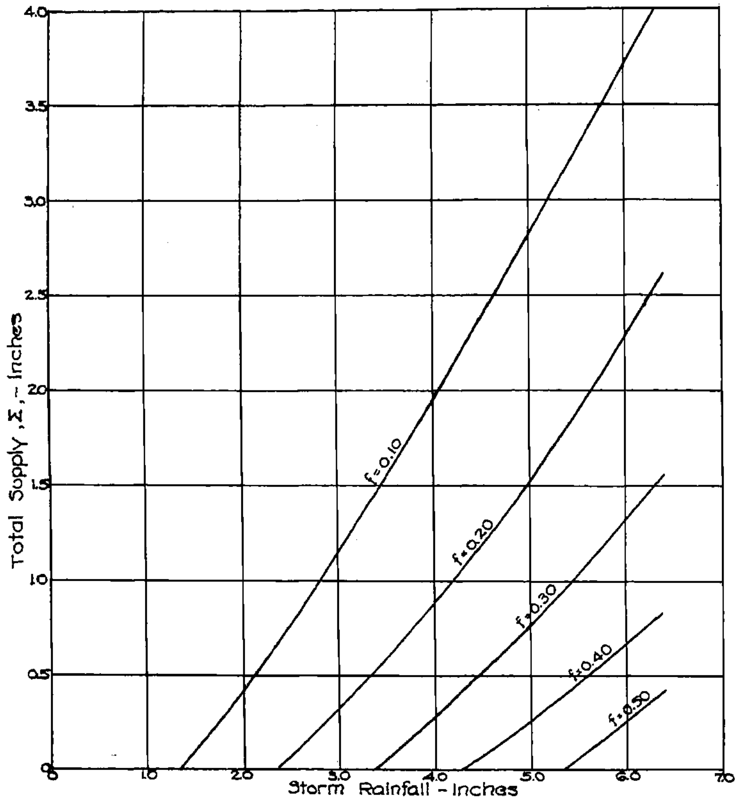

FIG. 2 – RAINFALL-EXCESS CURVES FROM VERNON, VT. RECORDING-GAGE RECORD FOR STORM OF NOV. 3, 1927. MILLERS RIVER ABOVE ERVING, MASS.

(2) A second qualification arises from the fact that infiltration-capacity may vary in different parts of the drainage-basin. This will have little effect on the accuracy of the determination of average infiltration-capacity if the rain-intensity exceeds the actual infiltration-capacity on every part of the area. In general, the method is applicable only in cases where this is true.

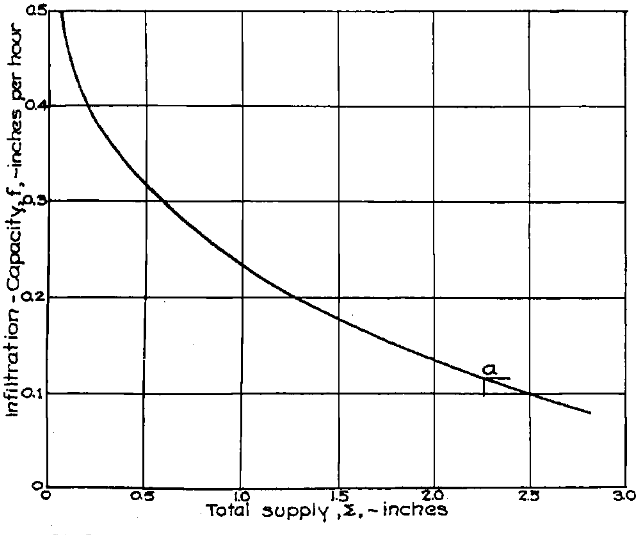

FIG. 3 – TOTAL-SUPPLY CURVE; STORM OF NOV. 2-5, 1927; MILLERS RIVER ABOVE ERVING, MASS.

It is of course possible to weight the individual determinations of rainfall-excess by the Thiessen-Horton method. This is somewhat laborious and does not add materially to the accuracy of the result if the rainfall-stations are (1) uniformly distributed or (2) if there are eight or more stations appurtenant to the given area.

In the determinations of infiltration-capacity given in this paper a direct average of

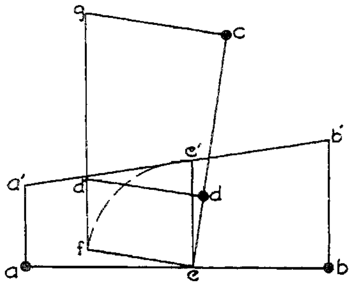

FIG. 4 - DETERMINATION OF RAINFALL - DURATION

rainfall-excess was used. Subject to the exceptions noted, the number of rainfall-stations was sufficient to give an accurate result without weighting. The exceptions are the drainage-basins mostly in Maine and New Hampshire, in the November 1927 New England flood. For some of these basins only two to five rainfall-stations were available. For these basins there may be considerable error in the computed infiltration-capacity.

<u>Extension to varying rain-bases</u>--The method described is capable of extension to cases where the rain-base is not the same at adjacent stations provided there are available three recording rain-

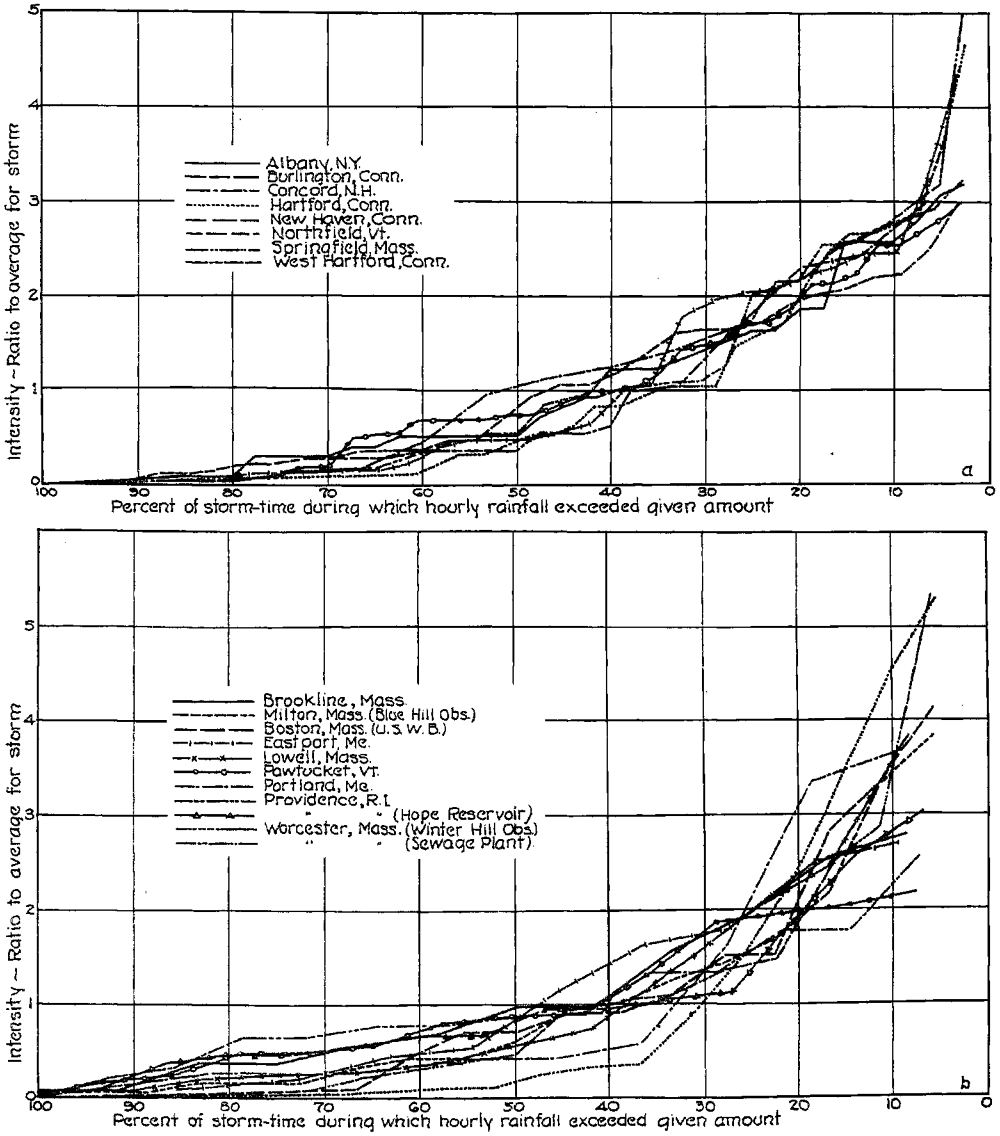

FIG. 5 - RAIN-INTENSITY DISTRIBUTION-GRAPHS FOR NEW ENGLAND FLOOD, NOV. 2-5, 1927
(a) - WESTERN COLD FRONT (b) - EASTERN COLD FRONT

gage records at stations not too remote from the region under study. The first step is to determine the approximate duration of rainfall at stations where only total amount of rainfall is given. This is accomplished by the inclined-plane method, as shown by Figure 4, on which a, b, and c are the locations of recording rain-gages. The duration of rainfall at a station d is to be determined. Erect ordinates aa' and bb' proportional to the duration of rainfall at a and b. Draw a line ce through d and erect the perpendicular ee' and the perpendiculars ef and cg, making ef = ee' and cg equal to the duration of rainfall at c. Then the scale-equivalent of the perpendicular dd' will be the approximate rainfall-duration at d. Since d lies nearest to station b, the hourly distribution of rainfall at d will be nearly the same as at b. If a rain-intensity distribution-graph, such as those shown on Figures 5-a and 5-b, is available at station b, then one hour at b corresponds to a fraction 1/n of the base of the graph at b. The total rain at d multiplied by the middle ordinates of n equal divisions of the base b will give the hourly amounts of rainfall at d.

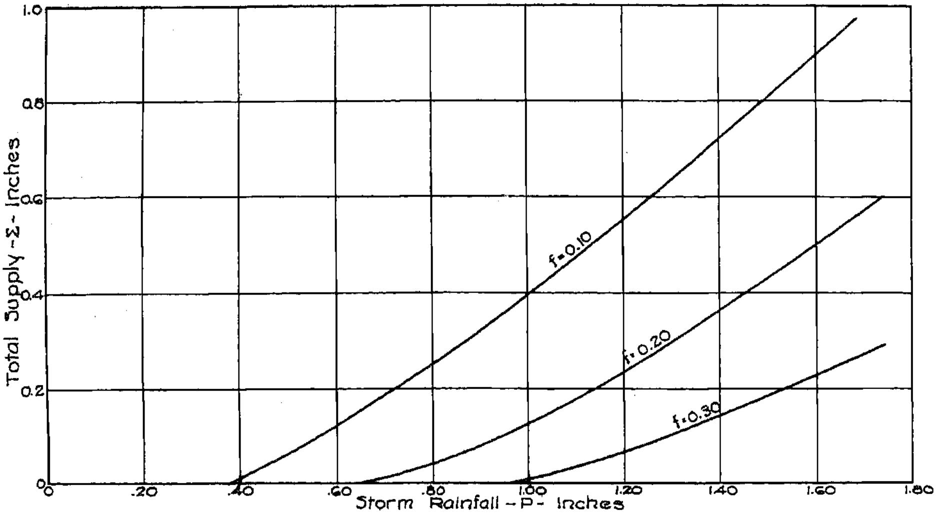

FIG. 6 – RAINFALL-EXCESS CURVES FROM COLUMBUS, OHIO, RECORDING-GAGE RECORD FOR STORM OF JUNE 8, 1929, MUSKINGUM BASIN ABOVE DRESDEN, OHIO

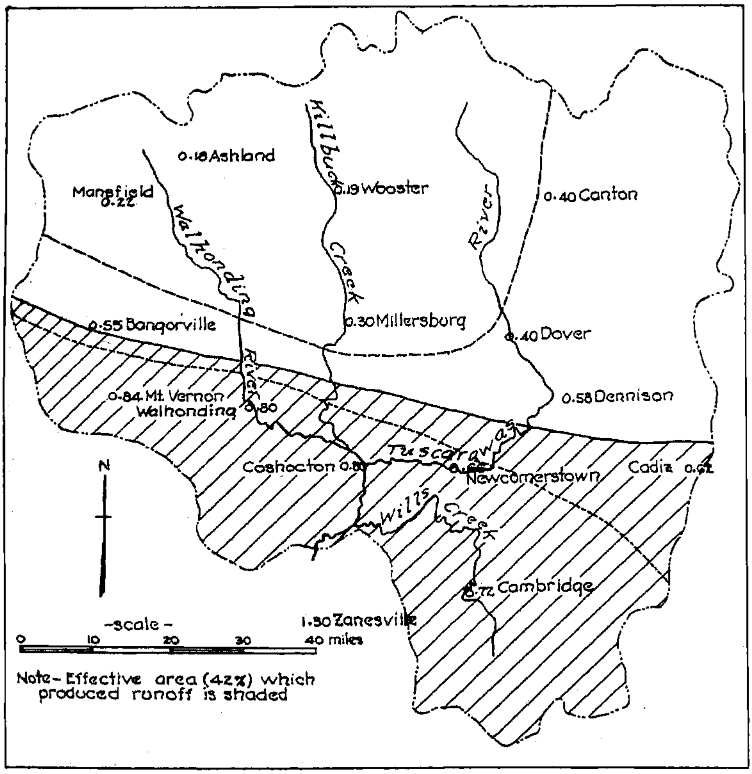

FIG. 7 – MUSKINGUM RIVER BASIN ABOVE DRESDEN, OHIO RAINFALL FOR STORM OF JUNE 8, 1929

Correction for varying duration of rain has not been made in this paper. In case of the New England flood the duration of rain was unusually constant in each of the two controlling storm-areas. In case of the other areas adequate recording rain-gage records were not in general available.

Extension of method to partial-area stream-rises--In case the rain-intensity does not exceed the infiltration-capacity for any single hour at a given rainfall-station, there will be no net supply and no surface-runoff. If this condition exists it will at once appear in the table of computed net supply for different infiltration-capacities. In this case it is necessary to determine both the percentage of the area which produced runoff and the infiltration-capacity on the same part of the area. For the purpose of showing the method of procedure, the rise of Muskingum River at Dresden, Ohio, on June 8, 1929, has been used. The computation of supply-curves is carried out in the same manner as before and these curves, using Columbus as the base-station, are shown on Figure 6. The total rainfall and the computed net supply at the different stations are shown on Table 4. Column (6) shows zero net supply or runoff at four stations for $f = 0.10$. The total significant items in the column for each infiltration-capacity is obtained and divided by the number of stations showing a net supply. The resulting figures represent average net supply on the part of the area which produced surface-runoff.

Table 4--Supply $\Sigma$ on effective area, Muskingum River above Dresden, Ohio, storm of June 8, 1929 (rainfall-intensity base-station, Columbus, Ohio)

| Station, Ohio | June, 1929 | | | Total rainfall, inches | Infiltration-capacity f, inch per hour | | |
|---|---|---|---|---|---|---|---|
| | 7 | 8 | 9 | | 0.10 | 0.20 | 0.30 |
| (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) |
| | | | | | Total rainfall-excess | | |
| Ashland | | 0.18 | | 0.18 | 0 | 0 | 0 |
| Bangorville | 0.28 | 0.27 | | 0.55 | 0.09 | 0 | 0 |
| Cadiz | 0.51 | 0.11 | | 0.62 | 0.13 | 0 | 0 |
| Cambridge | | 0.72 | | 0.72 | 0.20 | 0.02 | 0 |
| Canton | | 0.40 | | 0.40 | 0.01 | 0 | 0 |
| Coshocton | 0.80 | | | 0.80 | 0.25 | 0.04 | 0 |
| Dennison | | 0.58 | | 0.58 | 0.11 | 0 | 0 |
| Dover | | 0.40 | | 0.40 | 0.01 | 0 | 0 |
| Mansfield | | 0.22 | | 0.22 | 0 | 0 | 0 |
| Millersburg | 0.03 | 0.27 | | 0.30 | 0 | 0 | 0 |
| Mount Vernon | 0.41 | 0.43 | | 0.84 | 0.28 | 0.06 | 0 |
| Newcomerstown | | 0.66 | | 0.66 | 0.16 | 0 | 0 |
| Walhonding | | 0.80 | | 0.80 | 0.25 | 0.04 | 0 |
| Wooster (No. 1) | | 0.19 | | 0.19 | 0 | 0 | 0 |
| Zanesville | | 1.30 | | 1.30 | 0.64 | 0.30 | 0.11 |
| Averages | | | | 0.57 | 0.19 | 0.09 | 0.11 |
| Percent of area | | | | | 65.5 | 30.0 | |
| Runoff from whole area, inches | | | | | 0.05 | 0.05 | |
| Runoff from net area, inches | | | | | 0.076 | 0.167 | |

The supply-curves, Figure 6, for $\Sigma = 0$ show the amounts of rainfall for which the net supply would be zero with different infiltration-capacities. These are: $f = 0.1$, $p = 0.38$; $f = 0.2$, $p = 0.65$; and $f = 0.3$, $p = 0.97$.

Figure 7 shows the observed storm-rainfall at the different stations of record. On this map a dashed rainfall-contour-line has been drawn corresponding to 0.38 inch of rain and 0.1 inch infiltration-capacity. Also a rainfall-contour (dotted line) has been drawn corresponding to 0.65-inch rain and 0.2-inch infiltration-capacity. The percentage of the total area with greater rainfalls than these amounts were next determined and set down underneath the corresponding infiltration-capacities on Table 4. The total runoff was 0.05 inch, measured on the total area, but all this runoff took place from the part of the area having requisite rainfall, and the runoff, reduced to the net effective area for each infiltration-capacity, is next set down in Table 4. The supply on the net area corresponding to different infiltration-capacities is then plotted in the same manner as before in Figure 8, line A. Line B is also drawn showing the percentage of the area which yielded runoff with different infiltration-capacities, together with line C, showing corresponding depths of runoff reduced to net effective area. Opposite the intersections of lines A and C will be found the infiltration-capacity $f$ for which the supply on the net area will equal the runoff-depth from the net effective area. Also opposite the same point on line B will be found the percentage of the total area which produced runoff. From

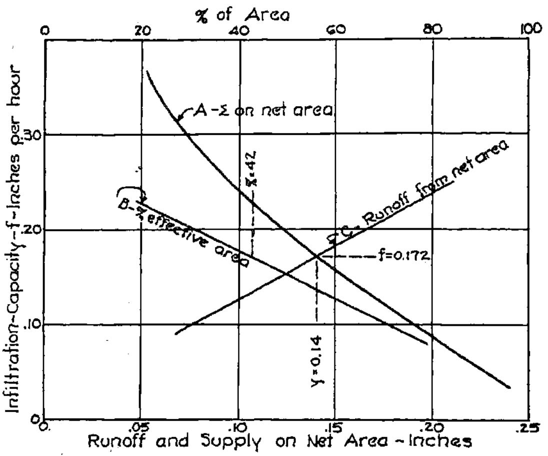

FIG. 8 - DETERMINATION OF INFILTRATION-CAPACITY ON EFFECTIVE AREA FOR STORM OF JUNE 8,1929, MUSKINGUM BASIN ABOVE DRESDEN, OHIO

Figure 6 the rainfall corresponding to zero-supply for this infiltration-capacity can be determined and a contour drawn (solid line) on Figure 7 which shows the part of the area which produced runoff during this stream-rise. This gives, finally, an infiltration-capacity f = 0.172 inch per hour on 42 per cent of the area.

Infiltration-capacity in the New England flood of November 2-5, 1927--The New England storm of November 2-5, 1927, involved two high-pressure areas, one northeast of New England, the other over and west of the northern Appalachians. These remained fairly stationary for several days, and between these was a barometric trough or "squeeze" into which flowed large volumes of moist, warm, tropical air.

TABLE 5—AVERAGE INFILTRATION, NEW ENGLAND BASINS, FLOOD OF NOV. 2-5, 1927

| No. | Stream | Location | Drainage-Area | Base Rainfall-Intensity Station | No. of Rainfall-Stations used | Crest-Discharge | Surface-Runoff on Area | Mean Rainfall on Drainage-Area | Infiltration Capacity |
|---|---|---|---|---|---|---|---|---|---|
| (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) | (10) |
|  | Penobscot Basin |  | Sq.Miles | Eastport, Me. |  | C.S.M. | Inches | Inches | Inches/Hr. |
| 1 | Penobscot | W. Enfield, Me | 4690 | " | 7 | 13.0 | 1.50 | 2.49 | 0.145 |
| 2 | E. Br. " | Grindstone, " | 1070 | " | 4 | 19.9 | 1.88 | 2.56 | .082 |
| 3 | Mattawamkeag | Mattawamkeag, " | 1500 | " | 4 | 11.3 | 2.07 | 2.39 | .058 |
|  | Piscataquis Basin |  |  |  |  |  |  |  |  |
| 4 | Piscataquis | Lows Bridge, Me. | 286 | " | 3 | 23.6 | 1.20 | 2.14 | .135 |
| 5 | " | Medford, " | 1170 | " | 4 | 15.6 | 1.47 | 2.53 | .152 |
| 6 | Pleasant | Milo, " | 325 | " | 3 | 22.4 | 2.54 | 2.89 | .035 |
| 8 | Dead | The Forks, " | 830 | " | 3 | 17.7 | 1.15 | 3.36 | .39 |
| 9 | Carrabassat | N. Anson, " | 351 | " | 2 | 53.0 | 2.89 | 2.94 | .026 |
|  | Saco Basin |  |  |  |  |  |  |  |  |
| 15 | Saco | Cornish, Me. | 1300 | Concord, N.H. | 7 | 8.3 | 1.91 | 4.39 | .285 |
| 18 | Ossipee | " , " | 455 | " | 4 | 5.1 | 1.18 | 4.38 | .415 |
|  | Merrimack Basin |  |  |  |  |  |  |  |  |
| 19 | Pemigewasset | Plymouth, N. H. | 599 | Northfield, Vt. | 4 | 100.0 | 5.78 | 5.18 | .028 |
| 22 | Merrimack | Franklin Jct., " | 935 | Concord, N. H. | 5 | 71.6 | 4.34 | 5.26 | .091 |
| 33 | Smith | Bristol, " | 78.5 | " | 2 | 74.0 | 3.23 | 6.08 | .315 |
| 34 | Nubanusit | Peterboro, " | 54.3 | " | 2 | 18.6 | 1.94 | 4.17 | .25 |
| 35 | Contoocook | N. Branch Village, " | 54.5 | " | 3 | 38.6 | 3.21 | 4.51 | .13 |
| 37 | Souhegan | Merrimack Village, " | 168 | " | 3 | 39.7 | 2.62 | 3.87 | .128 |
| 38 | Blackstone | Worcester, Mass. | 31.5 | Worcester, Mass. | 3 | 25.0 | 2.72 | 3.85 | .15 |
| 41 | Quinebaug | Jewett City, Conn. | 712 | " | 9 | 17.5 | 1.46 | 4.54 | .565 |
|  | Connecticut Basin |  |  |  |  |  |  |  |  |
| 43 | Connecticut | South Newbury, Vt. | 2750 | Northfield, Vt. | 14 | 28.4 | 3.22 | 4.28 | .052 |
| 45 | " | White River Jct., " | 4040 | " | 21 | 36.6 | 3.91 | 5.13 | .058 |
| 47 | " | Turners Falls, Mass. | 7170 | " | 27 | 23.8 | 3.21 | 4.94 | .063 |
| 48 | " | Sunderland, " | 7740 | " | 39 | 21.3 | 3.05 | 5.13 | .075 |
| 69 | Millers | Erving, " | 372 | Vernon, Vt. | 8 | 17.1 | 2.26 | 4.58 | .116 |
| 79 | Ware | Gibbs Crossing, " | 201 | Springfield, Mass. | 8 | 14.1 | 1.75 | 3.99 | .155 |
| 80 | Swift | West Ware, " | 186 | " | 10 | 12.0 | 1.70 | 4.19 | .178 |
| 86 | Westfield | Westfield, " | 496 | " | 13 | 85.6 | 4.28 | 5.76 | .075 |
| 106 | Housatonic | Falls Village, Conn. | 618 | " | 9 | 18.9 | 2.96 | 5.51 | .166 |
| Average |  |  |  |  |  |  |  |  | 0.16 |

A study of the rainfall-intensity graphs shows a sharp line of demarcation in the characteristics of the rain produced by these high-pressure areas. This line follows the Connecticut River closely. Throughout New England east of this line the rain lasted 12 to 18 hours, an average of 15 hours, and the average intensity at different stations ranged from about 0.1 inch to 0.28 inch per hour and the maximum hourly intensities ranged from 0.23 to 1.42 inch. West of the Connecticut River the rain lasted generally 33 to 43 hours, an average of about 36 hours. Average intensities at different stations ranged from 0.1 to 0.2 inch and the maximum intensities from 0.27 to 0.62 inch. The western cold front involved in this storm therefore produced a rain of more than twice as great a duration but of lower intensity than the eastern cold front. These facts are clearly brought out by Table 1, showing the storm-duration and average intensities at different recording gage-stations in the two regions. This storm produced a full-area flood on all the drainage-basins listed in Table 5.

Preceding the storm of November 2-5 there were light rains November 2 and October 28 and a period of four or five days of moderate to heavy rain throughout the entire region October 17 to 21. Owing to the low evaporation, the soil was well moistened and rain-packed. The storm occurred outside the season of earthworm- and insect-activity and the infiltration-capacity was at or close to the minimum for unfrozen ground. The drainage-basins ranged from high rocky mountainous areas, as in the upper Connecticut Valley, to extremely sandy areas, such as that of the Quinebaug River, and the infiltration-capacities given in Table 5 show corresponding variations. Those for the Connecticut River are particularly well determined because of the large number of rainfall-stations available. The values determined for different stations in the Connecticut Drainage-Basin are consistent, ranging from 0.05 inch per hour in the headwaters at South Newbury, Vermont, to 0.075 inch per hour at Sunderland, Massachusetts. The computed infiltration-capacities for the more generally sandy and somewhat less mountainous basins in Maine are higher, as would be expected. They are also less uniform but this may be in part due to paucity of rainfall-records. The computed values of infiltration-capacity on different areas are distributed as follows:

| | |
|---|---|
| Less than 0.1 inch per hour, | 11 areas |
| 0.1 to 0.2 inch per hour, | 10 areas |
| 0.2 to 0.3 inch per hour, | 2 areas |
| 0.3 to 0.4 inch per hour, | 2 areas |
| 0.4 to 0.5 inch per hour, | 1 area |
| 0.5 to 0.6 inch per hour, | 1 area |

The average for all the areas is 0.16 inch per hour.

Infiltration-capacities from stream-rises described in Water-Supply Paper 772--Table 6 contains the results of determinations of the infiltration-capacity f for several drainage-basins in the eastern-central states. Runoff and other data used in these determinations have been derived from United States Geological Survey Water-Supply Paper 772. Some of these cases represent partial-area rises and the portion of the drainage-basin which produced surface-runoff is indicated in the Table. In such cases the infiltration-capacity f is computed relative to the fraction of the area which produced surface-runoff. In case of partial-area stream-rises, Table 6 shows the part of the drainage-basin which produced runoff in each instance. Some of the difference of infiltration-capacity f for different storms on the same area is due to differences in the part of the drainage-basin for which f was determined.

Discussion of results--Figure 9 shows the locations of drainage-basins for which infiltration-capacities are given in Tables 5 and 6. Omitting smaller basins included in larger ones, the total area for which infiltration-capacity has been determined is:

| | |
|---|---|
| New England flood | 20,363 square miles |
| Eastern-central areas | 26,600 square miles |
| Total | 46,963 square miles |

Rainfall- and runoff-data for stream-rises suitable for determination of infiltration-capacity are available for nearly all drainage-basins in eastern-central United States and it is merely a matter of labor to extend the computation to cover the entire eastern part of the United States. In view of the now well-recognized fact that infiltration-capacity is a factor of primary importance in relation to surface-runoff, floods, and soil erosion, it is urged that computations be carried out and the results published for as many drainage-areas as possible. For reasons subsequently given it is desirable that a considerable part--preferably a dozen--determinations of infiltration-capacity should be made for each area at different times throughout the course of the year. On a given area, with the exception of highly impervious or highly

## TABLE 6 - AVERAGE INFILTRATION - CENTRAL AND EASTERN DRAINAGE-BASINS

| No. | Location Stream | Date | Drainage-Area Sq.Mi. | Base Rainfall-Intensity Station | No. of rainfall-stations used | Crest Discharge on whole area c.s.m. | Surface runoff on whole area inches | Effective Area | Runoff on Effective area inches | Mean rainfall on Effective area inches | Infiltr-Capacity on Effective area i.p.h. | Days since last wetting of soil (a) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| (1) | (2)(3) | (4) | (5) | (6) | (7) | (8) | (9) | (10) | (11) | (12) | (13) | (14) |
| 1 | Port Jervis, N.Y. | Oct. 30, 1917 | 3070 | Scranton and Binghamton | 8 | 29.6 | 1.34 | 100% | 1.34 | 2.27 | 0.055 | 1 L to M |
| 2 | Delaware | Oct. 7, 1918 | " | " | 7 | 5.15 | 0.28 | " | 0.28 | 0.97 | 0.11 | 4-7 L to M |
| 3 | " | June 3, 1922 | " | " | 8 | 12.70 | 0.80 | " | 0.80 | 2.23 | 0.072 | 6 L to M |
| 4 | " | Apr. 30, 1923 | " | " | 9 | 8.8 | 0.56 | " | 0.56 | 1.54 | 0.070 | 8 L |
| 5 | " | Sept. 30, 1924 | " | " | 8 | 31.0 | 2.01 | " | 2.01 | 4.79 | 0.11 | 8 L |
| 6 | " | Oct. 7, 1926 | " | " | 8 | 4.4 | 0.29 | 78% - upper | 0.41 | 1.95 | 0.235 | 5-9 L |
| 7 | " | Oct. 5, 1927 | " | " | 8 | 5.4 | 0.31 | 100% | 0.31 | 2.38 | 0.395 | 16 L to M |
| 8 | " | Oct. 13, 1927 | " | " | 9 | 7.65 | 0.50 | " | 0.50 | 1.65 | 0.275 | 5 L, 9 H |
| 9 | " | Sept. 4, 1933 | " | " | 8 | 7.7 | 0.52 | " | 0.52 | 1.93 | 0.14 | 8-12 H |
|  |  |  |  |  |  |  |  |  |  |  | 0.162 |  |
| 10 | Ste. Marie, Ill. | June 25, 1918 | 1540 | Urbana | 7 | 3.0 | 0.26 | 100% | 0.26 | 2.38 | 0.57 | 5 L to M |
| 11 | Embarrass | May 12, 1920 | " | " | 7 | 3.9 | 0.58 | " | 0.58 | 2.28 | 0.23 | 6 L to H, 8 L to M |
| 12 | " | Sept. 15, 1920 | " | " | 7 | 0.45 | 0.04 | " | 0.04 | 1.25 | 0.57 | 4-5 L to M |
|  |  |  |  |  |  |  |  |  |  |  | 0.457 |  |
| 13 | Logansport, Ind. | July 4, 1925 | 3830 | Ft. Wayne | 14 | 0.79 | 0.07 | 20% - Lower Center | 0.34 | 1.62 | 0.400 | 10-15 L to H |
| 14 | Wabash | Sept. 27, 1925 | " | " | 14 | 1.02 | 0.10 | 100% | 0.10 | 1.47 | 0.355 | 7-9 L to H |
| 15 | " | Aug. 3, 1929 | " | " | 14 | 1.72 | 0.15 | 19% - Upper Center | 0.80 | 3.70 | 0.495 | 10-12 L to H |
| 16 | " | Aug. 14, 1929 | " | " | 14 | 2.14 | 0.25 | 52% - center | 0.48 | 2.22 | 1.24 | 5 L to M |
| 17 | " | June 29, 1931 | " | " | 14 | 0.52 | 0.05 | 25% - upper | 0.20 | 1.53 | 1.08 | 8-10 L to H |
| 18 | " | Oct. 4, 1932 | " | " | 14 | 0.55 | 0.05 | 31% - center | 0.16 | 1.61 | 0.296 | 6-8 L to H |
|  |  |  |  |  |  |  |  |  |  |  | 0.643 |  |
| 19 | Danbridge, Tenn. | Aug. 3, 1921 | 4450 | Asheville | 12 | 8.53 | 0.57 | 100% | 0.57 | 1.25 | 0.127 | 3 L, 6 L to M |
| 20 | French Broad | Apr. 6, 1922 | " | " | 13 | 4.27 | 0.26 | 54% - upper | 0.49 | 1.19 | 0.116 | 5-9 L to H |
| 21 | " | Apr. 18, 1924 | " | " | 14 | 5.28 | 0.50 | 100% | 0.50 | 1.25 | 0.045 | 3 L to H |
| 22 | " | Oct. 12, 1927 | " | " | 14 | 1.73 | 0.13 | 37% - upper | 0.37 | 2.28 | 0.300 | 3-4 L to H |
| 23 | " | Apr. 27, 1928 | " | " | 14 | 4.95 | 0.45 | 100% | 0.45 | 1.28 | 0.075 | 4-7 L to H |
| 24 | " | Apr. 22, 1931 | " | " | 13 | 5.97 | 0.49 | " | 0.49 | 1.57 | 0.18 | 4 L, 11 L to H |
| 25 | " | Sept. 3, 1931 | " | " | 13 | 3.95 | 0.27 | " | 0.27 | 1.26 | 0.18 | 4 L, 6 L to H |
| 26 | " | May 1, 1932 | " | " | 13 | 6.51 | 0.56 | " | 0.56 | 1.83 | 0.255 | 7 L, 11 L |
|  |  |  |  |  |  |  |  |  |  |  | 0.160 |  |
| 27 | Towanda, Pa. | Oct. 6, 1918 | 7770 | Binghamton | 23 | 3.73 | 0.22 | 55% - Lower | 0.39 | 1.00 | 0.16 | 3 L to H |
| 28 | Susquehanna | July 15, 1921 | " | " | 20 | 1.17 | 0.07 | 26% - N. central | 0.27 | 1.69 | 0.53 | 5 L to H |
| 29 | " | Sept. 30, 1924 | " | " | 23 | 16.71 | 1.50 | 100% | 1.50 | 3.96 | 0.10 | 9 L to H |
| 30 | " | Oct. 2, 1929 | " | " | 19 | 3.60 | 0.29 | " | 0.29 | 2.81 | 0.33 | 15 L to H |
| 31 | " | June 10, 1930 | " | " | 20 | 1.16 | 0.09 | 54% - Lower | 0.17 | 1.36 | 0.27 | 12 L |
| 32 | " | Oct. 6, 1932 | " | " | 21 | 7.08 | 0.71 | 78% - N. Central | 0.90 | 4.36 | 0.23 | 9 L to H |
|  |  |  |  |  |  |  |  |  |  |  | 0.270 |  |
| 33 | Dresden, Ohio | June 4, 1927 | 5980 | Columbus | 14 | 4.00 | 0.44 | 100% | 0.44 | 1.39 | 0.23 | 5 L to H |
| 34 | Muskingum | June 8, 1929 | " | " | 15 | 0.87 | 0.05 | 42% - Lower | 0.14 | 0.70 | 0.172 | 10 L to H |
| 35 | " | Aug. 23, 1929 | " | " | 15 | 0.52 | 0.05 | 27% - Lower | 0.18 | 1.39 | 0.77 | 4 L to M |
| 36 | " | Aug. 17, 1932 | " | Akron | 16 | 0.45 | 0.05 | 26% - Upper | 0.19 | 2.20 | 0.98 | 6 L |
| 37 | " | July 2, 1933 | " | " | 16 | 0.90 | 0.08 | 44% - center | 0.17 | 1.85 | 0.75 | 7 L to H |
|  |  |  |  |  |  |  |  |  |  |  | 0.580 |  |

(a) L = Light rain - 0.0 to 0.5 inches
M = Medium " - 0.5 " 1.0 "
H = Heavy " - > 1.0 inches

sandy areas, there is usually a considerable range between the minimum and maximum values of infiltration-capacity. It is therefore desirable that enough determinations be made for each area to show the minimum, maximum, and seasonal variations.

The data given in Table 5 for the New England flood relate to the same storm on different areas and the antecedent conditions were nearly the same.

A column has been added to Table 6 showing the last previous wetting of the soil on the drainage-areas in the eastern-central states. A study of this Table shows that other factors besides the time elapsed since the last rain must necessarily be taken into account in order to understand variations of infiltration-capacity in different storms on the same area. In general,

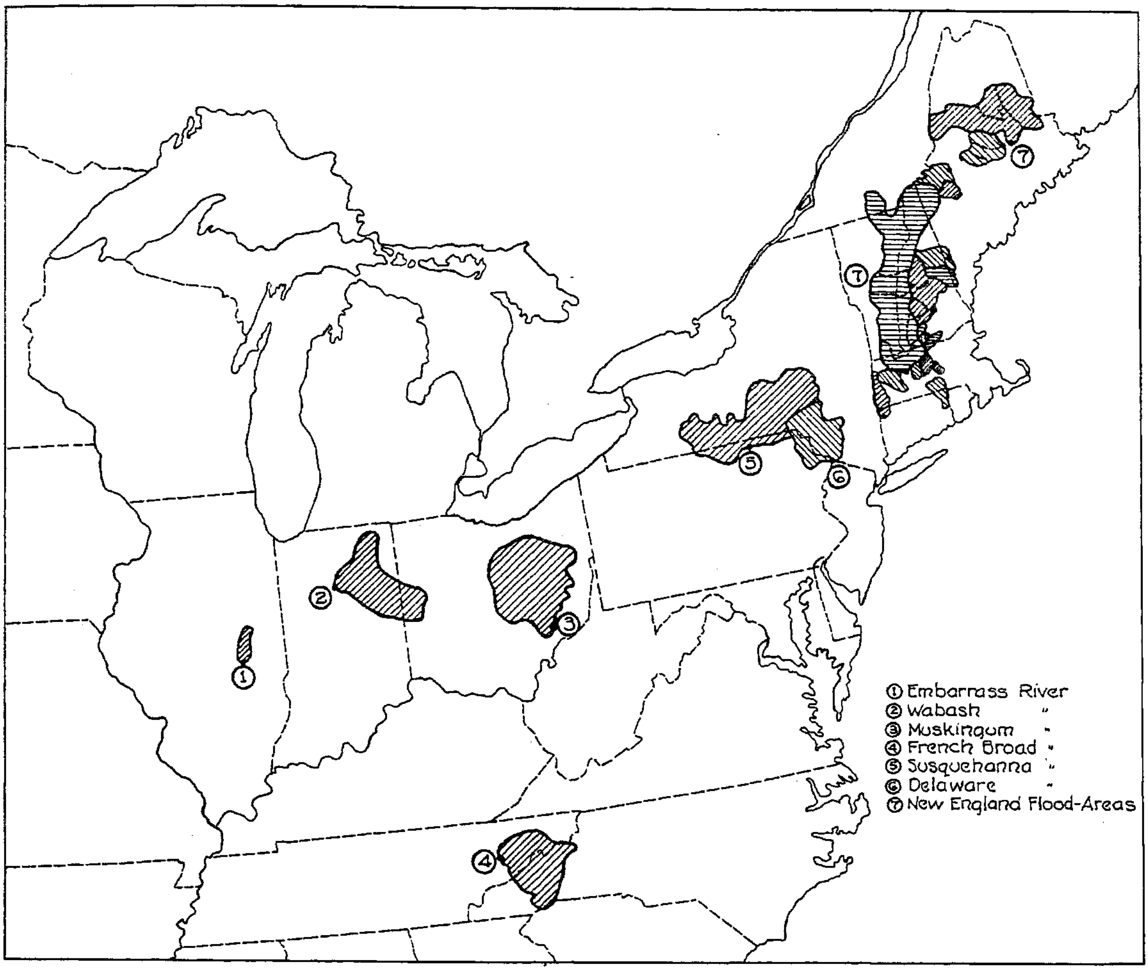

FIG.9-LOCATION OF DRAINAGE-BASINS FOR WHICH INFILTRATION-CAPACITIES HAVE BEEN DETERMINED

the greater the time elapsed from the last wetting of the soil, the greater the infiltration-capacity. This is true, for example, in case of the stream-rises listed on Susquehanna River in Table 6. In case of Muskingum River, infiltration-capacities for midsummer conditions ranging from 0.125 to 0.98 inch per hour were obtained when the soil was relatively dry in all cases. The highest value is for the August 17, 1932, flood, at the end of a long dry period. For Delaware River, Table 6 shows five infiltration-capacities in October floods. The highest is for October 5, 1927, at the end of a long dry period. The lowest two occurred when the soil had been moderately wetted by recent rains.

In some cases it is necessary to go back beyond the last antecedent rain to interpret the result. Observations at the author's laboratory have shown that on sodded loam-soils, earthworms go down and remain at considerable depths during long dry periods. Earthworm- and insect-perforations may become closed by light rains, cultivation, and other causes, giving a very low infiltration-capacity when the first heavy storm occurs after a long dry spell, especially if there have been light antecedent rains which wetted the soil-surface but did not penetrate to great depth. After the soil has once been wetted to a sufficient depth, earthworm- and insect-perforations again appear at the surface. The author has counted as many as a hundred earthworm-perforations per square foot in a sodded soil late in the fall under these conditions. If then a heavy rain occurs, the infiltration-capacity may be abnormally high.

Comparing the different areas listed in Table 6, the following averages are obtained:

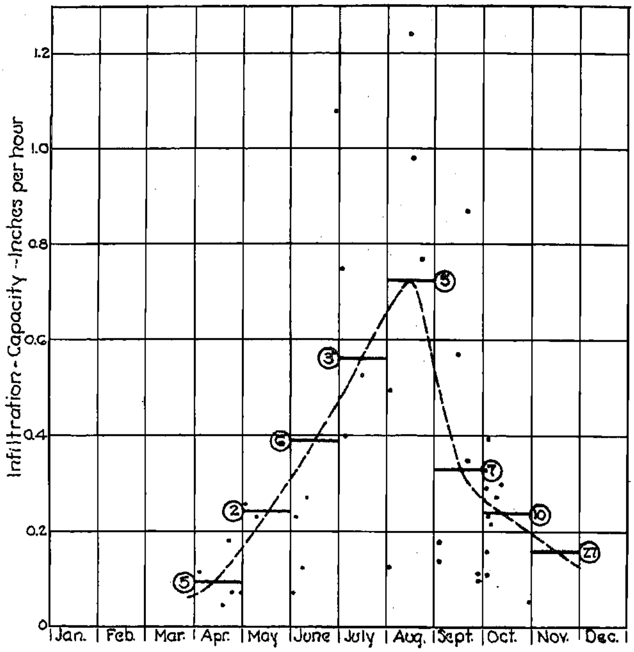

FIG. 10 — SEASONAL VARIATION OF INFILTRATION-CAPACITY
NUMBERS IN CIRCLES ARE NUMBER OF VALUES OF f INCLUDED IN MONTHLY AVERAGE

| Stream | Location | Number of storms | Average infiltration-capacity in/hour |
|---|---|---|---|
| Delaware River | Port Jervis, New York | 9 | 0.162 |
| Embarrass River | Ste. Marie, Illinois | 3 | 0.457 |
| Wabash River | Logansport, Indiana | 6 | 0.643 |
| French Broad River | Dandridge, Tennessee | 9 | 0.160 |
| Susquehanna River | Towanda, Pennsylvania | 6 | 0.270 |
| Muskingum River | Dresden, Ohio | 5 | 0.580 |

It will be noted that the highest average values are those obtained for the Embarrass, Wabash, and Muskingum rivers, the drainage-basins of which are relatively flat, with permeable, cultivated soils, partly of glacial origin. Lower values were obtained for the Delaware, Susquehanna, and French Broad rivers. The upper Delaware and French Broad rivers are rocky, mountainous areas, uncultivated, and mostly forest-covered. The upper Susquehanna is mixed mountainous and agricultural land.

Table 5 shows a similar result with reference to the New England flood. The precipitous, rocky, mountainous, and forest-covered areas, such as the upper Connecticut Drainage-Basin, show generally lower infiltration-capacities than the flatter agricultural areas.

All of the infiltration-capacities given in Tables 5 and 6 have been averaged by months and the individual values and averages plotted, as shown on Figure 10. The average line shows a marked seasonal cycle of infiltration-capacity. The average curve is in good agreement with that obtained by the author showing seasonal variation of infiltration-capacity on Ralston Creek Drainage-Basin, Iowa (R. E. Horton, The role of infiltration in the hydrologic cycle, Trans. Amer. Geophys. Union, 1933, p. 482).

Figure 10 and data from laboratory and runoff-plat experiments and other areas indicate that during the midsummer months the infiltration-capacity is likely to be either close to the minimum or close to the maximum for the given area. Intermediate values occur, but less frequently than the maximum and minimum values. The minimum infiltration-capacity is a more definite quantity than the maximum. The latter is affected by sun-checking of the soil-surface, presence or absence of earthworm-perforations, and the effect of recent cultivation.

One important use of infiltration-capacity is in the estimation of maximum flood-intensities to be expected on a given area. For this purpose the minimum infiltration-capacity should in general be assumed.

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Voorheesville, New York

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# THE VALUE OF GEOPHYSICAL METHODS IN GROUND-WATER STUDIES

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(Published with the approval of the Director, U. S. Geological Survey)

Two meanings are unfortunately given to the term geophysics. In the broad sense, based on the etymology of the term, geophysics means the physics of the Earth. This is its significance in the names "Geophysical Laboratory of the Carnegie Institution of Washington," "International Union of Geodesy and Geophysics," and "American Geophysical Union." In this sense the sciences of geology and hydrology are largely geophysics, although in part they are geochemistry or biology. Geologists and hydraulic engineers who are elected to membership in the American Geophysical Union are, however, often surprised to find that they are regarded as "geophysicists." I hope that when the Union establishes a journal, its name will include the expression "Earth physics" or "Physics of the Earth," in order that there will be no misunderstanding as to its scope.

The popular use of the term geophysics is very restricted. It does not even include nearly all the instrumental methods of investigating the physics of the Earth. Thus, most of the instrumental methods developed for ground-water investigations are not commonly regarded as geophysical methods although they are based strictly on physics. Instruments used in applying these methods are water-level and pressure recorders, current-meters, and other devices for measuring the discharge of springs and wells, deep-well current-meters, salinity-apparatus and samplers, laboratory-apparatus for determining mechanical composition, porosity, moisture-equivalent, and permeability, instruments used in tests of underflow and permeability by the Slichter, Thiem, Theis, and dye methods, leveling and measuring equipment used in making contour-maps of the water-table or the piezometric surfaces of confined aquifers, lysimeters and boring, measuring, weighing, and drying equipment used in recharge-studies, and tanks and accessory apparatus used in determining specific yield and ground-water discharge by evaporation and transpiration. None of these is ordinarily considered as a "geophysical instrument," except that the Slichter apparatus and the deep-well salinity-apparatus have been partially adopted under that term. "Geophysical instruments," as popularly understood, are essentially those used in determining gravimetric and magnetic variations, electric conductivity, and artificial seismic effects in the Earth.

The automatic water-stage recorders are among the most valuable instruments of precision used in the study of ground-water. They are comparable to the seismic instruments in that they record natural variations of pressure-effects within the Earth and also artificial variations--produced not by explosions but by pumping or artesian flow from wells, often at considerable distances from the recording instrument. Indeed, water-stage recorders of a certain type have been adopted by the seismologists for recording pressure-effects of natural earthquakes, whereas water-stage recorders of various types are used by hydrologists, chiefly to record pressure-effects produced by several other agencies, both natural and artificial. It may be predicted that water-stage recorders will eventually come to have greater value in the study of the physics