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HYDROLOGY AND ITS APPLICATIONS IN ENGINEERING [1]

(With particular reference to Civil Engineering Problems)

by

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(With particular reference to Civil Engineering Problems)

Civil Engineers are concerned with the design and construction of structures for flood control, drainage, water power and water supply. Their interest is to make certain that the structure willwork, that it cannot be destroyed by action of ice or water, and that the project is completed as economically as possible. Inherently the hydrologic problems arising in these designs fall into two broad catagories.

1. Estimating the size of the flood hydrograph which may occur at infrequent intervals--or never. This governs the design of all flood controlworks and is important in all other problems.

2. Estimating the extent to which river flow may drop during the summer, and the extent that this may be regulated by storage.

In each case the study makes use of basic measurements of stream flow, of precipitation, temperature etc. Invariably all of these studies require an appreciation of the phases of the hydrologic cycle, although it is becoming only too obvious that the study of hydrology is a full time job in itself. In all cases the Civil Engineer is interested in the end result of the hydrologic cycle namely "runoff". To him the water going to evaporation, to ground infiltration and plants, are "losses" whereas they may be thought of as "gains" by an irrigation engineer.

Runoff and the Hydrologic Cycle

Picture if you will the occasion of a single storm period consisting of substantially continuous rainfall. The rate of rainfall will be found to vary from place to place within the storm area, and will vary from minute to minute at any particular observation station. When the storm begins, water immediately begins to fill surface depressions and to penetrate the pores of the soil. Depending upon antecedent weather conditions, the nature of the soil, and the intensity of the rain, water may accumulate faster than it can soak away. If this happens the excess rain fills surface depressions before it spills over to join other excess rainfall on its way toward the stream. Water which does penetrate the soil joins the ground water and is available for evaporation, transpiration (plants), and for sustaining the flow of our streams during the greatest portion of the year. In this climate a considerable amount of surface storage as snow in the winter season results in a characteristic variation in stream flow peculiar to our streams. The resulting diagram illustrating the flow rate or discharge in the stream at any time throughout the year is known as a hydrograph (Fig. 1). With this great uneveness in discharge we find ourselves faced with the two problems mentioned previously of predicting the characteristics of the flood hydrograph and the extent to which this excess water can be stored for subsequent river regulation.

The Hydrograph

On many natural streams the Dominion Government maintains gauging stations for the purpose of securing daily or continuous records of stream discharge. The Water and Power Bureau of the Department of Mines and Resources is responsible for this work and publishes the results of these measurements bi-annually.

Essentially the method of determining stream discharge depends upon the fact that natural weirs or control sections exist in our rivers. These sections restrict the flow of the stream and fix the elevation of its water surface for some distance upstream from the control. By means of current meter measurements of the velocity of the water, the Water and Power Bureau experts are able to relate the actual discharge to the elevation of the water surface at some convenient point above the contorl. In general a rock ledge at the head of a rapids will make a suitable control. Thereafter the determination of discharge is effected from an observation of water surface elevation at the gauge. (see Figure 2) Daily observations of this type form the basis for the construction of the hydrograph shown in Figure 1.

These records are useful for statistical studies of flood magnitude, and for the planning of river regulation. Without this information the planning of major projects would be an impossible task. Figure 3 shows a frequency plot of the maximum annual floods on the Moira River near Belleville, Ontario. For confident predictions of future flood possibilities it is impoıtant that the sample of annual floods be what statisticians call "normal" or representative of the range of all floods. It is in this lack of normality that the weakness of the method lies, for it is known that invariably weather conditions could easily have produced worse floods than those experienced with or without heavy rainfall.

For the multitude of small projects for which gaugings are not available it is necessary to predict the extent of the hydrograph from rainfall. Whereas this technique is probably better from a fundamental point of view than predictions based directly on the hydrograph it is much more difficult to employ. The reason for this is obvious when it is re-called that runoff is the residual of rainfall after interception, evaporation, transpiration, ground storage and surface storage have all taken their share of rainfall.

The shape of the hydrograph is different for each drainage basin, but the hydrographs for any one drainage area are of essentially the same shape. This similarity in shape has been employed by LeRoy K. Sherman and others since 1938 under the name of the "Unit Hydrograph Method". Obviously its use is restricted to basins for which stream gauging records exist. In fact the basis for the unit hydrograph has been tacidly accepted ever since Emile Kuichling proposed the "Rational Method" for determining runoff from small areas about the turn of the century. Perhaps the greatest similarity between the two methods is that both recognized that the shape of the hydrograph is a fundamental characteristic of the drainage basin, although the details of the methods differ widely.

The Unit Hydrograph Method makes use of the fact that the hydrographs are similar, and that the peak flow reached is directly proportional to the area of the hydrograph. In use it is necessary to divide the flow into two components, seepage or ground flow, and surface runoff. With basins like that the Moira River there is very little soil cover on the rock so that there is relatively little stream flow resulting from seepage except after heavy rains in the spring and in late fall when the ground is saturated. The effect of a heavy rain on saturated ground is shown in Figure 1, in which the ground flow and the surface flow have been separated out in an approximate manner. In fact the practical determination of excess rainfall is necessarily done using coefficients which depend upon antecedent weather conditions.

Sometimes a mathematical analysis of actual hydrographs can be quite helpful in answering some of these questions which arise concerning its shape. The recession curve has the form

$$q_2 = q_1 e^{-Kt}$$

where q_1 and q_2 are successive flows and this the interval of time in days between these flows. K. is a coefficient which depends upon the flow in the river to some extent. For the Moira River flood peaks K = 0.072 so that essentially the discharge is halved every ten days. The area under this part of the curve as the discharge decreases is $\frac{q_1}{K}$, so that the peak flow is proportional to the area under the curve. The fact that K varies slightly as the flow decreases does not detract from the practical value of this statement. The rising part of the hydrograph is not so easily dealt with as it is almost always affected by continuing rainfall and/or snow-melt, which for larger basins usually terminates before the peak flow is reached. Various investigators have used an equation of e^{kt} for this. In any case it can be shown (Figure 4) that the peak flow is directly proportional to the area of the hydrograph, and where data are not available a triangle will serve for the shape of the hydrograph very well.

The problems arising in connection with the construction of a hydrograph are:

1. To determine the magnitude of the rain which should be considered.

2. To determine the amount of total rain which will actually runoff.

3. To estimate the amount of ground flow before and after the rain in order to establish what Sherman calls "base flow".

4. To apply each unit of net rainfall to form a single hydrograph which can be summed with adjacent hydrographs including base flow.

Rainfall Analysis

After Kuichling proposed the Rational Method for Determining Runoff from small areas, much attention was focused on the variability of storm rainfall. This interest has continued on an expanding scale, with the work of the Miami Conservancy District in Ohio being one of the most outstanding studies in this field. The use of the unit hydrograph, and a clearer and more widespread understanding of the mechanism of runoff has added to this interest.

Runoff is expressed as a residual or fraction of the rainfall. Since rainfall records are available over long periods engineers have attempted to make use of statistical analysis in an attempt to guarantee the safety of a structure, or to determine an economic period for design. The records from both automatic or standard gauges are tabulated in order of magnitude, and their frequency of occurrence determined. In general Hortons recurrence interval is used in which the frequency is given by the period in years, times number of samples equal to, or larger than the oneconsidered, divided by the total number of observations. In the Ottawa record, (Figure 5) 120 observations were made in the 16 year period. Thus the apparent frequency of the largest observation of 1.05 inches of rain falling in 15 minutes is taken as 16 years whereas the next smaller one has a frequency of 8 years since it was equalled once and exceeded once. This method of calculating frequency is not quite correct statistically but is practical and easy to apply. The results from an analysis of this kind are commonly plotted on logarithmic paper since it is felt that the same relationship exists between rate of rainfall and frequency of occurrence for all durations and the large frequencies are modified by the relatively greater accuracy of the lower frequency. This method has been successfully employed by Merril Bernard and forms the basis for his "Modified Rational Method of Estimating Flood Flows" (Low Dams, Supt. of Documents, Washington, D.C.). Another method of presenting the same results isshown in Figure 6.

For climates such as Ontario it has been found that the worst floods in municipalities generally occur as a result of intense summer storms of short duration. For our main rivers this is almost never the case, since the runoff from melting snows contributes much more water, and only in the spring is the ground sufficiently saturated to allow very much runoff. In fact it may be said that after the first of June all rainfall is absorbed by the ground and evaporated, unless of course the amount of rain is very great.

With the major flows of our main streams resulting from melting snow and ice, and with the understanding that more favorable (or unfavorable) weather conditions could almost always have resulted in a higher flood crest it would seem logical that we should begin to approach the problem of runoff of our big rivers from a study of the amount of water stored on the ground prior to the spring break-up. This has not been done in the past largely because of the difficulties of providing a check on the calculations. Now with a better understanding of many basic problems of hydrology the method may develop into a useful tool. (We will consider this later along with a discussion of storage, evaporation and transpiration.) Power companies such as the Hydro Electric Power Commission of Ontario make extensive use of snow surveys as a practical method of forecasting where the expense is warranted.

With the smaller areas it seems probable that the design will continue to rest on the use of the rainfall intensity curves discussed previously. It is perhaps well to emphasize that the interest of the engineer is to secure optimum safety in design for the greatest economy of construction. Thus where lack of a adequate hydraulic capacity endangers life great care is taken to ensure safety. Alternatively if only inconvenience and economic loss results from an infrequent and random occurrence of a flood it may be possible to balance the cost of repairing the damage against the added cost for greater safety. The results shown in Figure 5 are useful to illustrate the influence of increased hydraulic capacity on the safety of a structure since the amount of rainfall varies with the frequency to the 0.3 power. Thus it may be shown that a 33% increase in capacity results in a 100% decrease in frequency of recurrence of the structure being loaded to design capacity. This means that a structure with a safety factor of 1 1/3 hydraulically designed on the basis of a 25 year flood, actually would only be taxed to capacity by a storm with a 50 year recurrence interval (or greater).

Evaporation, Transpiration and Storage

With the realization that better flow predictions stem from a direct analysis of rainfall, more attention has been given to the other phases of the hydrologic cycle in recent years. From an engineering point of view interest lies in determining the amount of infiltration which may be expected during and following any storm period. Also a reliable method of calculating the amount of precipitation stored in the form of snow would be of immense value for water power and for flood peak estimates. Attempts at evaluating all of the losses - evaporation, transpiration, infiltration, surface storage have received much study in past years.

Unfortunately it is impossible to determine any of these separately from the records of stream flow, temperature and rainfall that are commonly available to us. Engineers concerned with water power development have in the past done the next best thing in running snow surveys to determine the amount of storage available in the spring. These surveys will probably be continued for a long time to come. Adolph Meyer in his book "Hydrology" describes methods of evaluating the loss-components but the procedure has not been widely adopted because of its complexity. C. W. Thornthwaite (1948) has proposed a convenient shortcut to the balancing of the hydrologic cycle, although it appears very much like the method proposed by Vermeule in 1894 in that both make use of the annual and monthly temperatures. Thornthwaite has made his method work with obvious success although his treatment of storage and winter evaporation seem inadequate. From any point of view the method is interesting because it is simple and rapid to apply, and perhaps the main contribution is in the claim that there is a upper limit to the amount of water which can be lost by evaporation and transpiration, either from storage or from rainfall. This amount is called the potential evapotranspiration and varies with the length of day, monthly temperature and annual temperature. The treatment of data by Thornthwaites' method required the use of tables and charts which makes the calculations time consuming particularly when the equations are in terms of temperature in centigrade scale and are of dimensional character. It would appear that a method whose difficulty is more in keeping with the possible accuracy of the results is more desirable. This can be achieved by taking average potential evapo-transpiration results and representing the relationship between experimentally determined potential evapo-transpiration and monthly mean temperature in the form of

$$e = 0.29\,(T-32)$$

where e = inches potential evapo-transpiration

T = mean monthly temperature $^{\circ}F$.

which gives results very similar to Thornthwaites method.

Unfortunately any method which attempts to deal with the balancing of the hydrologic cycle deals with one very difficult fact-- there are two unknowns and only one equation. This equation is

Rainfall = Runoff + evapo-transpiration ∓ storage. Never the less certain facts are known which enable us to use the method with some confidence. These are:

1. That the storage or field moisture is almost zero at the end of the water year.

2. That a relationship exists between the amount of storage--and type--and the flow in the stream.

3. In any water year the estimated losses should check with the known difference between rainfall and runoff.

4. That potential evapo-transpiration exists as a simple function of temperature, and length of day for each drainage area.

5. That over a long period of time the errors in estimated storage, and in evaporation and transpiration, must equal zero.

Before learning of Thornthwaites work I had an occasion to apply this equation in balancing the hydrologic cycle using a modification of the curve presented by Adolph Meyer as a result of his studies on Lake of the Woods. Observed losses in evaporation from snow made by Houk and Horton supplemented this information. The results of the calculations checked very well, and agree with Thornthwaite in aggregate but not in detail. Unfortunately these studies never were completed sufficiently for a statement of the results (about 19 years consecutive record were used) from an scientific point of view but they proved to be good enough for the purpose for which they were intended. Among other things this study convinced me of the following:

(1) Of the need for a theoretically correct curve indicating the relation between evapo-transpiration and temperature. Almost any curve can be sketched in and will give a reasonable check using the rules available.

(2) That practically no runoff occurs after the first of June, and from studying actual records there would seem to be no limit to the amount of water plants can use. Perhaps it is better to say that nature does not exceed the limit very often.

Temperature

Before closing this brief treatment of hydrologic problems it might be in order to mention another use to which meteorological data are put. On the Moira River, among many others, trouble arises in winter and spring from the frazil and sheet ice formed in the river. This ice jams and causes floods. Figure 7 shows how Weather Bureau Data can be employed to indicate the probability of floods occurring from a record of temperature alone. The two values which did not agree (1922 and 1923) may be explained in terms of temperature and precipitation, but otherwise floods may be expected when the sum of monthly mean temperatures for November, December, January, February and March is lower than 120.

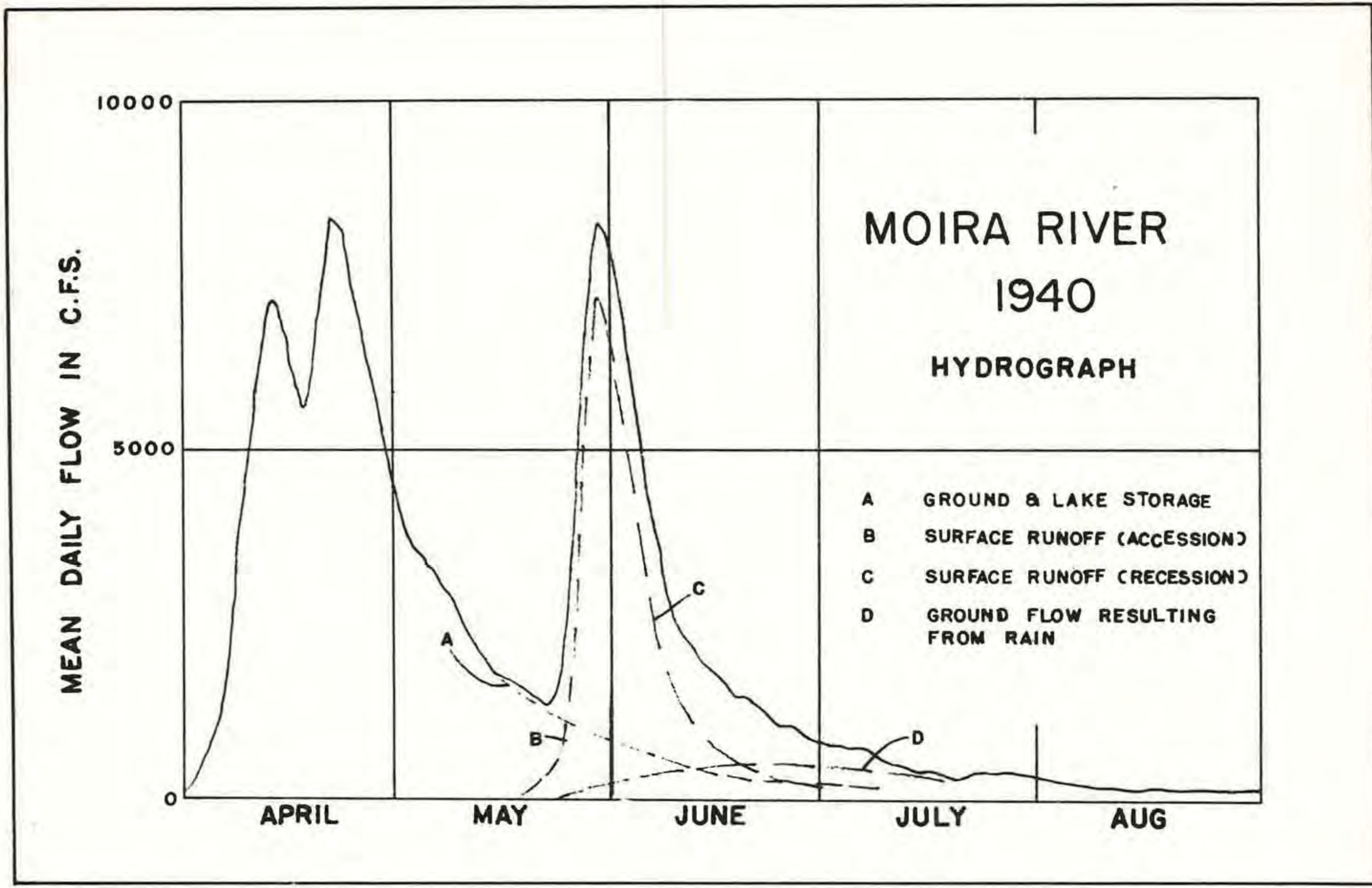
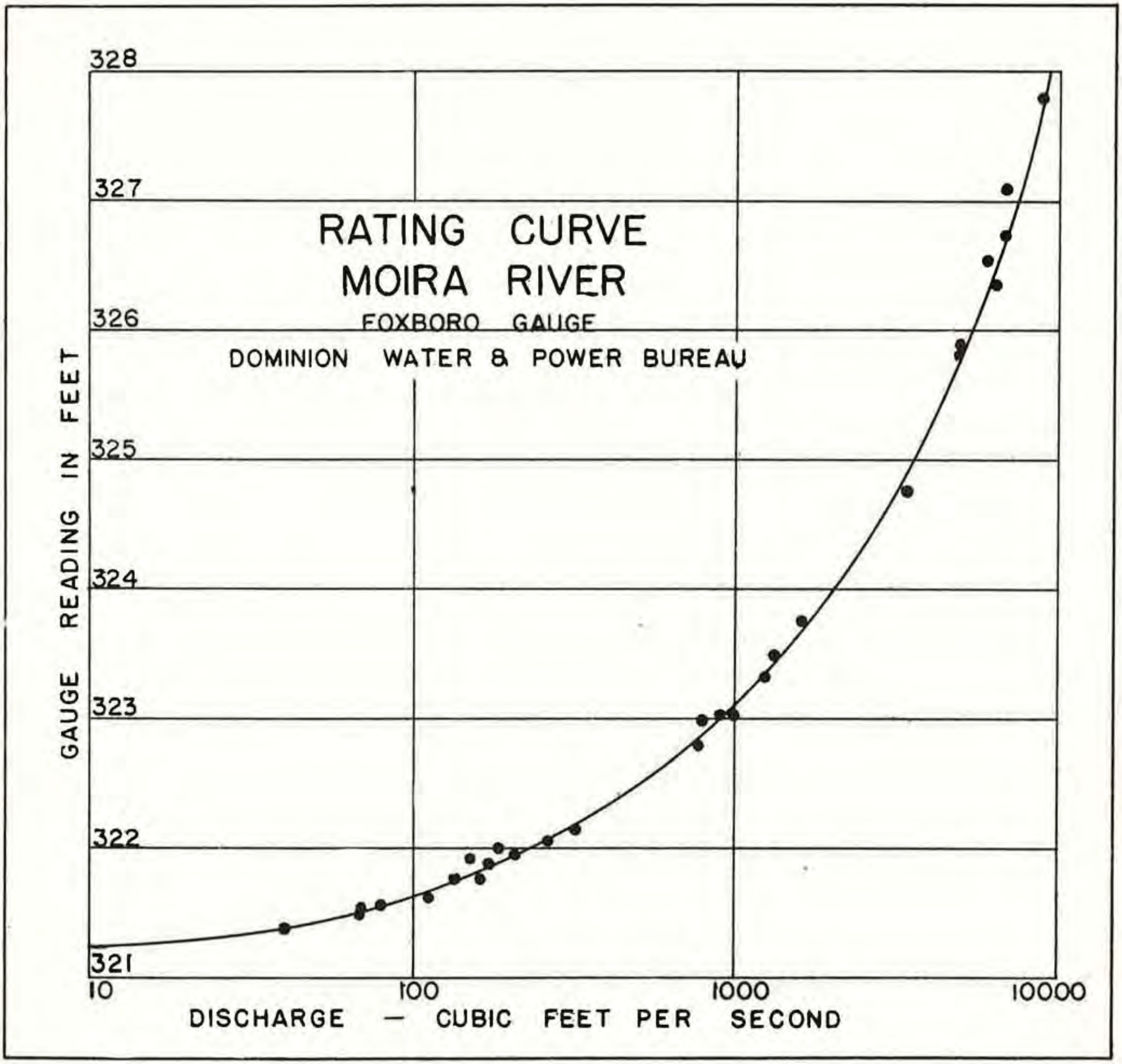

MOIRA RIVER
1940
HYDROGRAPH
A GROUND & LAKE STORAGE
B SURFACE RUNOFF (ACCESSION)
C SURFACE RUNOFF (RECESSION)
D GROUND FLOW RESULTING FROM RAIN
MEAN DAILY FLOW IN C.F.S.
10000
5000
0
APRIL
MAY
JUNE
JULY
AUG
A
B
C
D

Figure 1



RATING CURVE
MOIRA RIVER
FOXBORO GAUGE
DOMINION WATER & POWER BUREAU
328
327
326
325
324
323
322
321
GAUGE READING IN FEET
10
100
1000
10000
DISCHARGE — CUBIC FEET PER SECOND

Figure 2

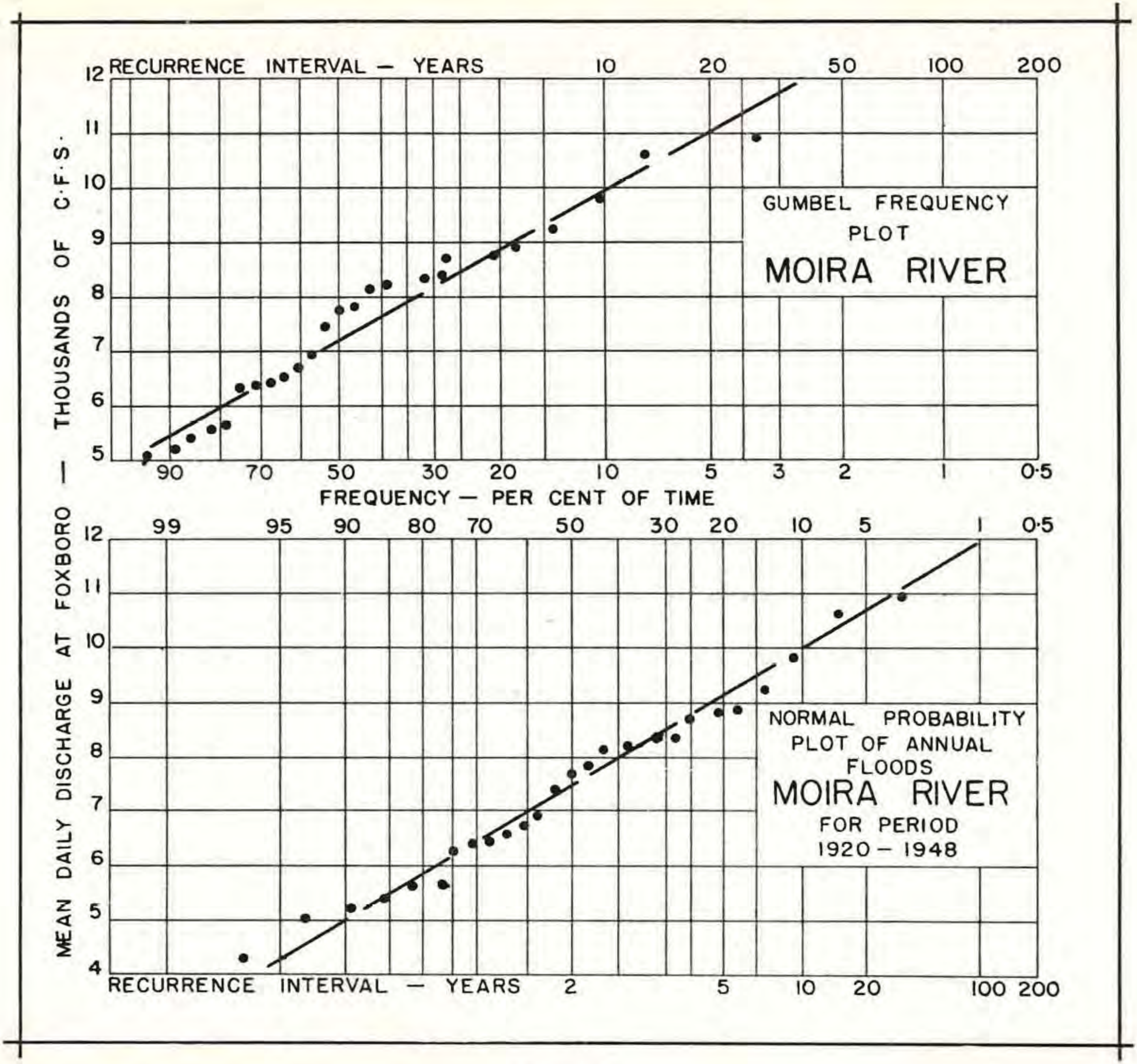
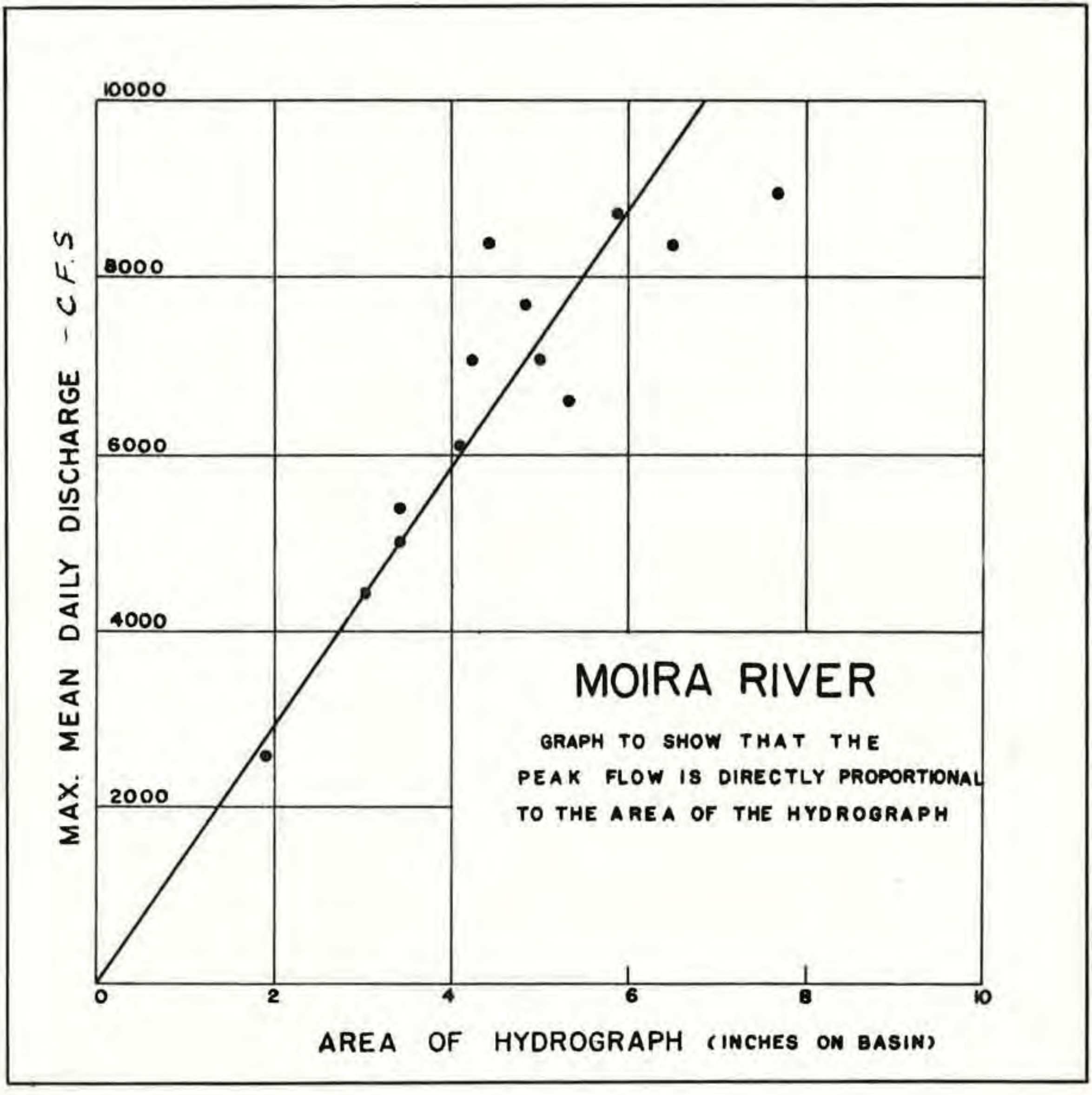

RECURRENCE INTERVAL — YEARS
10
20
50
100
200
GUMBEL FREQUENCY PLOT
MOIRA RIVER
FREQUENCY — PER CENT OF TIME
90
70
50
30
20
10
5
3
2
1
0·5
MEAN DAILY DISCHARGE AT FOXBORO — THOUSANDS OF C·F·S·
12
11
10
9
8
7
6
5
4
99
95
90
80
70
50
30
20
10
5
1
0·5
NORMAL PROBABILITY PLOT OF ANNUAL FLOODS
MOIRA RIVER
FOR PERIOD 1920 – 1948
RECURRENCE INTERVAL — YEARS
2
5
10
20
100
200

Figure 3



10000
8000
6000
4000
2000
MAX. MEAN DAILY DISCHARGE - C.F.S
0
2
4
6
8
10
AREA OF HYDROGRAPH (INCHES ON BASIN)
MOIRA RIVER
GRAPH TO SHOW THAT THE
PEAK FLOW IS DIRECTLY PROPORTIONAL
TO THE AREA OF THE HYDROGRAPH

Figure 4

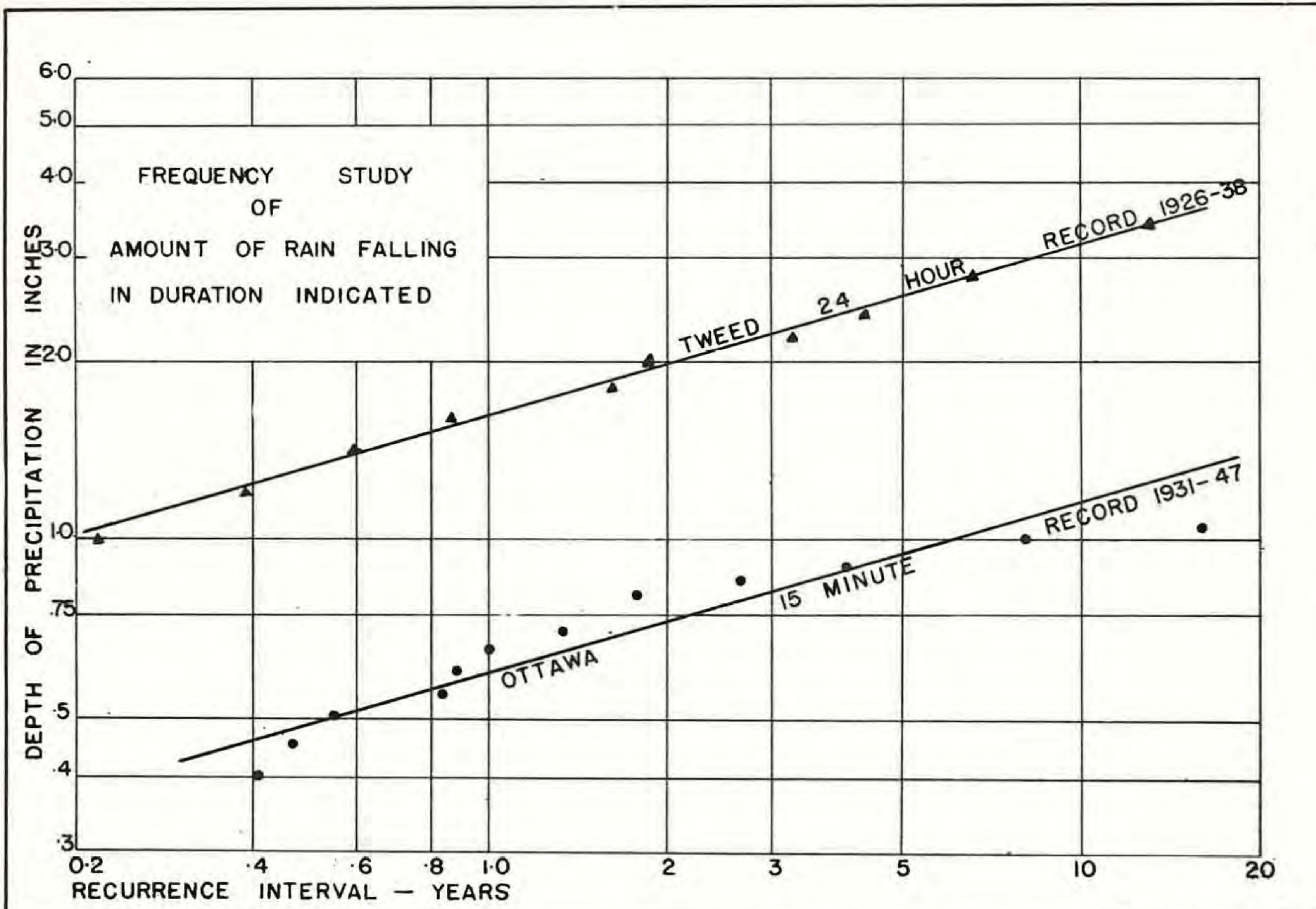

FREQUENCY STUDY
OF
AMOUNT OF RAIN FALLING
IN DURATION INDICATED
TWEED 24 HOUR RECORD 1926-38
OTTAWA 15 MINUTE RECORD 1931-47
DEPTH OF PRECIPITATION IN INCHES
6·0
5·0
4·0
3·0
2·0
1·0
.75
·5
·4
·3
0·2
·4
·6
·8
1·0
2
3
5
10
20
RECURRENCE INTERVAL — YEARS

Figure 5

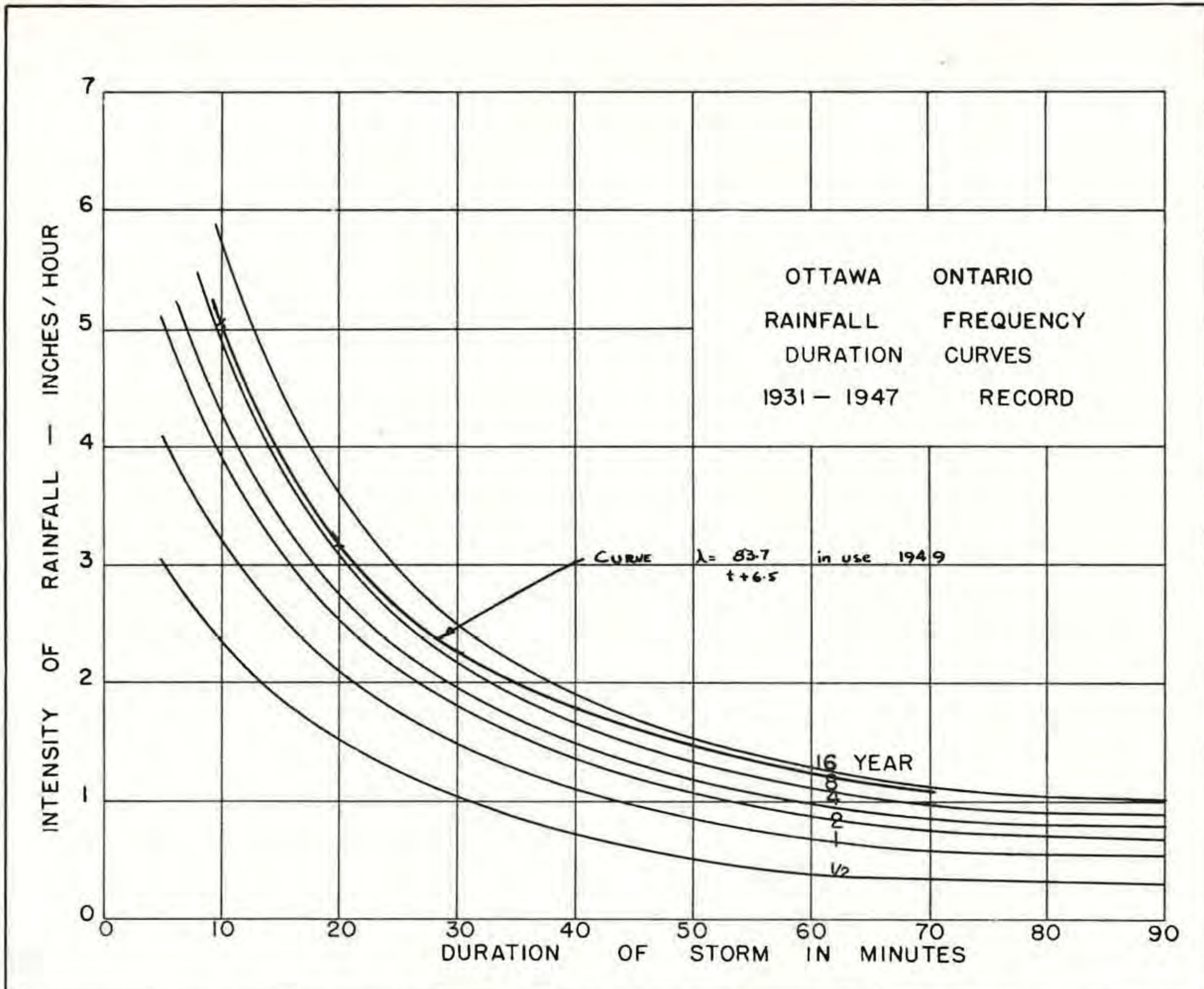

OTTAWA ONTARIO
RAINFALL FREQUENCY
DURATION CURVES
1931 – 1947 RECORD
CURVE λ= 83.7 / t+6.5 in use 1949
16 YEAR
8
4
2
1
1/2
INTENSITY OF RAINFALL — INCHES / HOUR
DURATION OF STORM IN MINUTES
0
1
2
3
4
5
6
7
10
20
30
40
50
60
70
80
90

Figure 6

PREDICTION OF ICE JAMS ON MOIRA RIVER

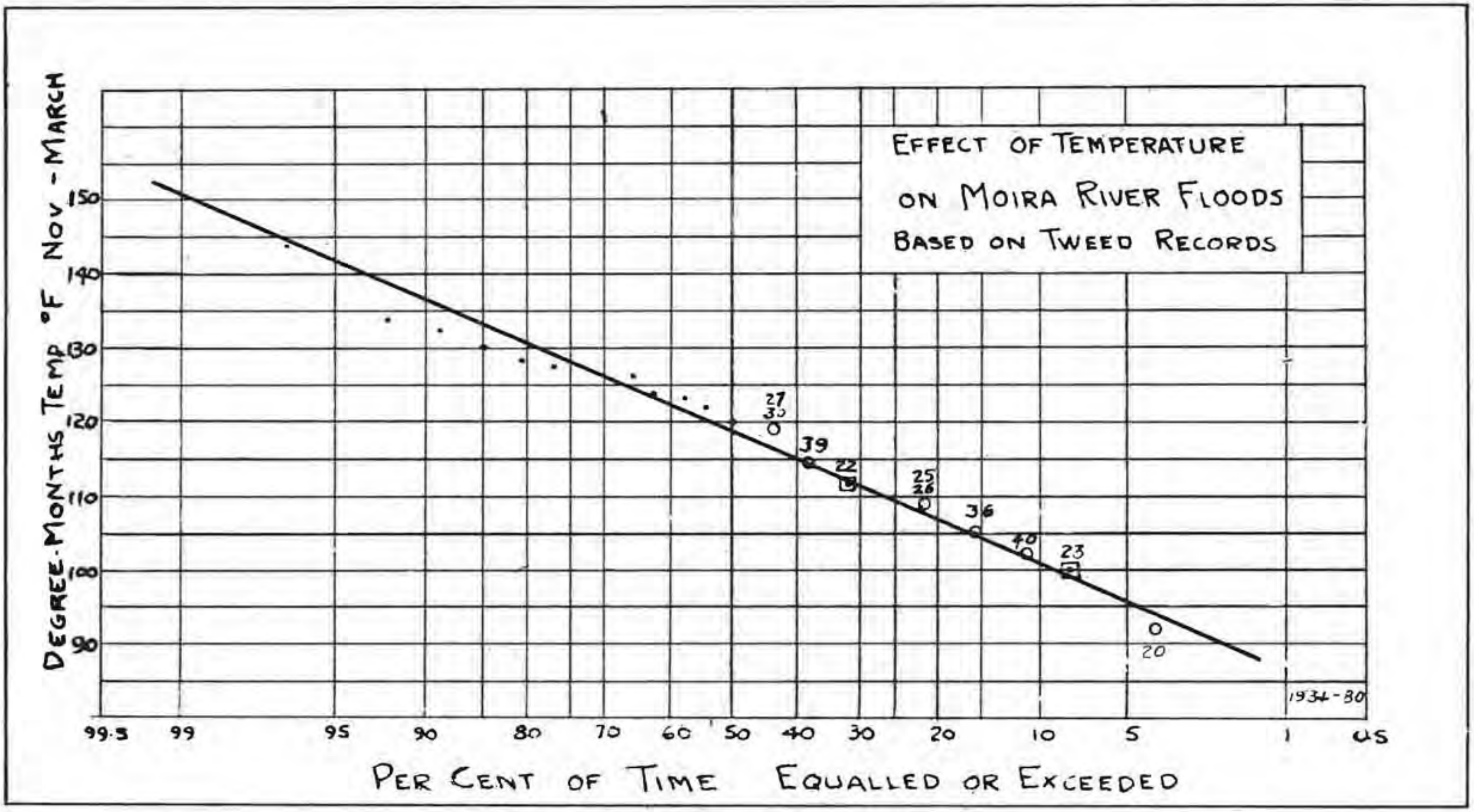


Figure 7