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# Determination of Runoff from Rainfall on Punjab Torrents

BY

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## INTRODUCTION

The determination of the runoff from a catchment is a problem which is of considerable interest to Engineers in general. The problem has always been studied from two aspects, namely :—

(*i*) Determination of the total volume of runoff available within a specified period.

(*ii*) Determination of the intensity, duration, and the rise and fall of the maximum flood.

The determination of the total volume of runoff forms the basis of all storage projects, the supplies available deciding the capacity of the reservoir, the height of the dam, the power that can be generated and the supply that will be available for irrigation and drinking purposes.

Punjab Hill Torrents are not fed by glaciers. The winter runoff is very low. As such Storage Schemes are based on the supplies available during the monsoon season only, *i.e.*, June to September.

The determination of the maximum flood decides the design of various types of Engineering Structures and has, consequently, received greater attention in general than the former aspect. In the design of Storage Schemes the determination of the maximum flood is of paramount importance for the safety of the Structure, as adequate provision for the escapage of the surplus water has to be made.

This aspect of the problem plays an important role in the design of the low-head water power installations, road and railway bridges, storm water sewers, cross drainage works on canals and general flood control projects.

## PART I.

## DETERMINATION OF THE VOLUME OF RUNOFF

### 1. Previous Study

Previous study of the Subject has been made according to the three conceptions of the relation between rainfall and runoff.

(*a*) Runoff expressed as a percentage of rainfall.

(*b*) Runoff expressed as the residual of rainfall, after deducting losses due to evaporation and transpiration.

(*c*) Runoff expressed as a function of mean annual temperature and rainfall.

*1.1. Runoff Expressed as a Percentage of Rainfall.*

Sir Alexander Binnie (2) was probably the first Engineer in India to study the problem from this aspect. As a result of observations of rainfall and runoff for two years (1869) and (1872) of the Nag River at Ambajhari (4 miles from Nagpur, C. P. ) he evolved what have since become known as "Binnie Percentages." The results of his analysis, given in a tabular form below, were published in a paper before the Institute of Civil Engineers in November 1874. Fig. I shows the same in a graphical form.

TABLE 1.

| Year and Month. | Rainfall in inches. | Runoff in inches. | Total Rainfall since commencement of wet season. | Total Runoff since same date. | Total Runoff / Total Rainfall. | Remarks. |
|---|---|---|---|---|---|---|
| 1 | 2 | 3 | 4 | 5 | 6 | 7 |
| *Year 1869.* | | | | | | |
| June 17th July 31st ... | 12·76 | 1·25 | 12·76 | 1·25 | 0·098 | |
| August ... | 9·61 | 3·36 | 22·37 | 4·61 | 0·20 | |
| September ... | 7·41 | 3·26 | 29·79 | 7·87 | 0·268 | |
| *Year 1872.* | | | | | | |
| June ... | 6·77 | 0·32 | 6·77 | 0·32 | 0·047 | |
| July ... | 12·70 | 2·88 | 19·47 | 3·20 | 0·16 | |
| August ... | 11·82 | 6·59 | 31·29 | 9·79 | 0·31 | |
| September ... | 7·99 | 5·95 | 39·28 | 15·74 | 0·40 | |
| | | Break in the rains. | | | | |
| October ... | 4·37 | 1·72 | 43·65 | 17·46 | 0·40 | |

The earliest work on these lines in the United States of America was conducted by FitzGerald (in 1892) and Babb (in 1893) (11) and the results were published in the Transactions of the American Society of Civil Engineers Volumes 27 and 28 respectively.

W. L. Strange (30), another exponent of the percentage concept, divided catchments into (*a*) Good (*b*) Average (*c*) Bad Catchments.

(2) relates to reference in Bibliography.

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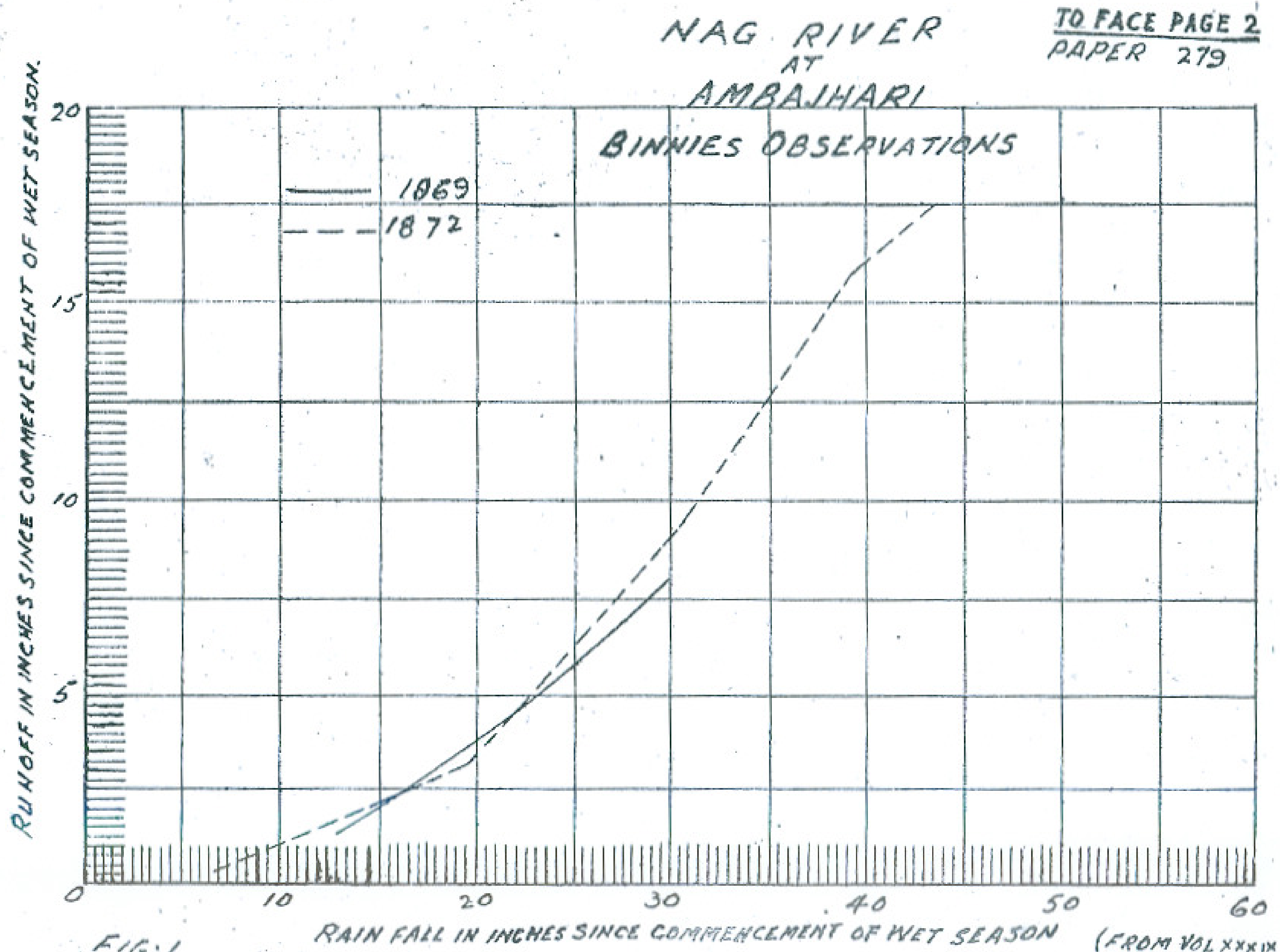


FIG:1

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## STRANGE AND INGLIS CURVES

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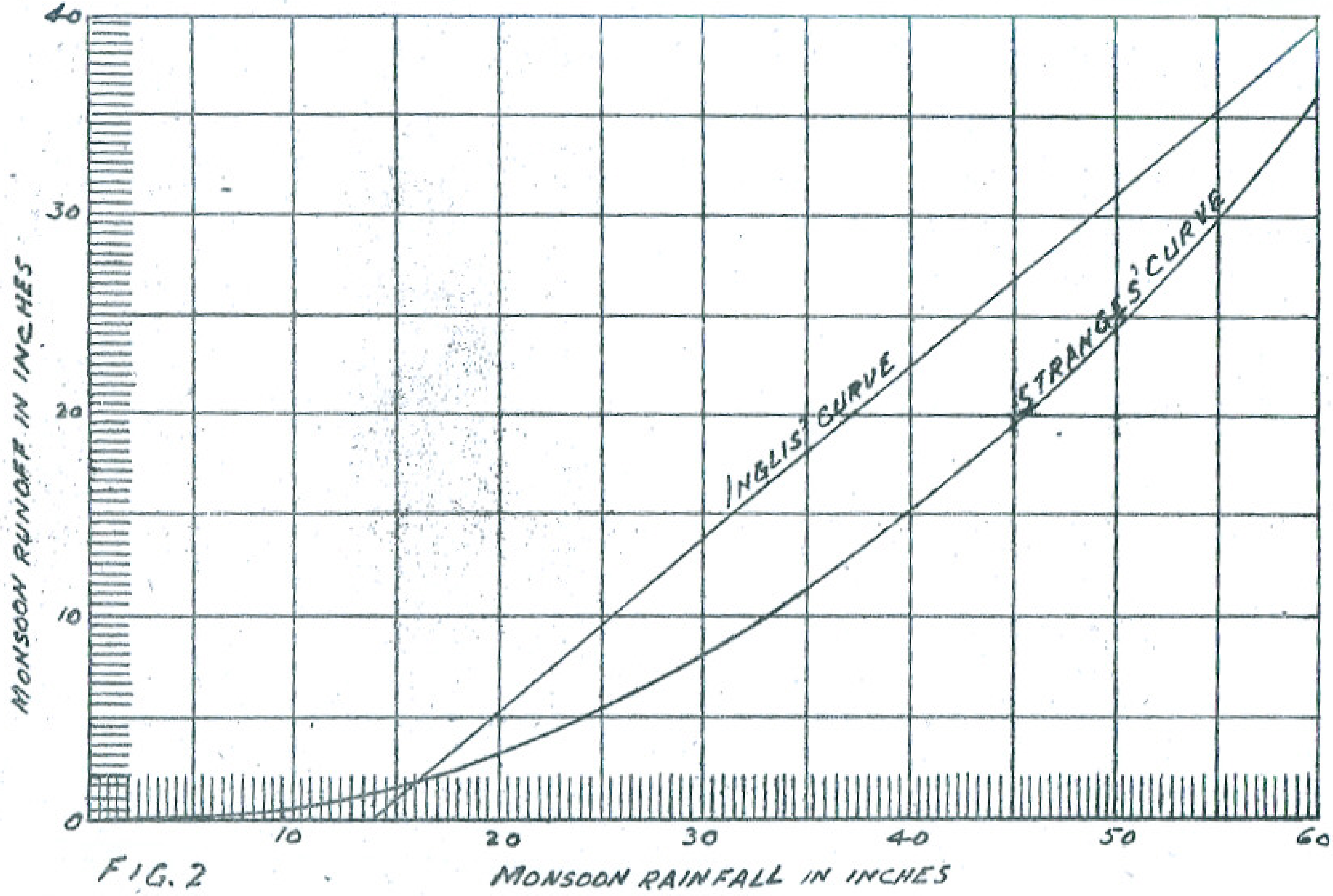


FIG. 2

According to him " The classification of catchments relates to their capabilities of producing runoffs, and figures for a good catchment approximate to those given for Ambajhari." He suggested percentages for a regularly ascending scale of rainfall for each type of catchment, with reference to Binnie's results of Ambajhari catchment and "......based on general ideas."

No other data was collected or analysed. Fig. 2.

Because of the very convenient form in which the table has been made available, these figures have become rather popular, especially in Northern India where Strange's figures form the basis of many forecasts.

### *1.2. Runoff Expressed as Rainfall Minus Losses.*

Expressed mathematically the relation is $R=(P-E)$. Early British Engineers decided a value for E arbitrarily, ranging from 12 inches to 18 inches (31). A later modification of this method lay in the subtraction of E from a percentage of the annual (or seasonal) rainfall.

$$R=xP-E$$

Parker in "Control of Water" (25) gives the runoff rainfall relation of the following catchments :—

(*i*) Catchments in the British Isles as $R=0.94P-14$

(*ii*) Catchments in Germany as $R=0.94P-16$

(*iii*) Catchments in the Eastern United States of America as $R=0.80P-16.5$

On his investigations in the Northern United States, Prof. A. F. Meyers presented a comprehensive paper entitled " Computing Runoff from Rainfall and other Physical Data " (24) in which he studied in great detail the effect of transpiration and evaporation on 15 catchments.

A detailed study of discharge and rainfall figures of thirty-seven catchments, both hilly and plain, in the Bombay Presidency, was made by C. C. Inglis and A. J. DeSouza in 1930. The results were published in the Technical Paper No. 30 of the Bombay P. W. D. (12). The conclusion arrived at was that the rainfall runoff relationship for hilly catchments is given by the equation :—

$$R=0.85P-12.$$

This is of the general form given before; and resembles greatly Parker's equations for the British Isles, Germany, and U. S. A,

As a result of observations on the Valley River (T. V. A.) Linsley and Ackermann (20) in 1941 suggested a method of determining rainfall losses, which were made up of (*a*) surface loss (*b*) field moisture loss and (*c*) ground water acretion. Their method involved the study and analysis of each individual storm and the estimation thereby of the total runoff. Commenting on the paper, B. S. Barnes (20) states :—

"The general applicability of a forecasting procedure developed on one type of stream can be established only by actual trial on other streams......It is the writer's belief, however, that the scheme calls for a more precise separation of the elements of flow, in which the personal judgment of the computer is not so important a factor."

*1.3. Runoff Expressed as a Function of Mean Annual Temperature.*

C. C. Vermeule, in 1894, put forward an original formula which expressed a relation between evaporation and mean annual temperature. He later modified the formula, which in its final form was (23)

$R = P - (11 + 0.29P)M$ where M is a factor varying with the mean annual temperature and for which he has prepared tables.

In 1914 J. D. Justin (23) expressed annual runoff in the form

$$R = 0.934\ S^{0.155}\ \frac{P^2}{T}$$

where S is the slope of the drainage found by dividing the maximum difference in elevation on the drainage by the square root of the drainage area and T is mean annual temperature in degrees Fahrenheit.

Another relation bringing in temperature was suggested by David Lloyd in 1936 (19)

$L = 0.57\ R^{0.87} + 1.10(T - 48) + 0.006(S - 1450 + G)$ where L = annual losses in inches, S = annual duration of sunshine in hours, G = loss due to percolation.

In a paper read before the Research Committee of the Central Board of Irrigation, R. B. A. N. Khosla (19) suspected a material contribution from Glaciers towards the annual runoff of streams. His formula

$$R = P - \frac{T}{2} + C$$

includes a constant C which allows for the characteristics of the catchment, humidity, and Glacier contribution.

## 2. Aims of Present Study

The present study is being made with special reference to Punjab catchments and only for non-glacier streams. Owing to the absence of Tank Irrigation and Storage Projects in the Punjab, the necessity for such investigations has not been felt until recently. Of late, however, with the possibilities of weir controlled Irrigation Schemes having been almost exhausted, the Province has launched an "all out" drive towards the investigation of Storage Schemes, with the object of storing as much water as possible during the monsoon season, to be utilized in the following Rabi Crop.

Great difficulty has been experienced in these investigations while estimating the supplies available for storage. The streams, on which these storages are proposed, have not been gauged for a sufficient period to facilitate accurate estimation. In the design of structures, therefore reliance has to be made on either Strange or Inglis curves, both of which have been derived from observations of catchments very different from those of the Punjab.

The aim in view has been to show to the Punjab Engineers the conditions existing in the Province, and to present a method whereby they may determine the supplies available for Storage Schemes.

## 3. Data Analysed.

### *3.1. Punjab Catchments.*

Discharge observations on a number of hill torrents have been maintained by the Discharge Division of the Irrigation Branch for a considerable period. The catchments selected for analysis are :—

(*i*) Gambhar Khad

(*ii*) Lunkhar Khad

(*iii*) Jabber Khad

(*iv*) Markanda Nadi.

Daily runoff records of the above streams are available for about 10 years.

Besides the torrents mentioned above there are a number of streams at present being gauged by the Staff of the Project Circle, Irrigation Branch, and the two years results of the Sirsa Nadi Catchment have been analysed.

In spite of the intention of treating only non-glacier streams, one river, Jumna at Tajewala, has also been included in the analysis. In a very recent paper for the Central Board of Irrigation, R. B. Kanwar Sain (16) has shown how to deduce the glacier contribution of the Jumna River. The runoff data utilized for the present analysis is the runoff due to rainfall, *i.e.*, total runoff less glacier contribution.

### *3.2. Alwar State Catchments.*

Information regarding these catchments has been obtained from the State Engineer of Alwar State. The climate in this locality is similar to the climate in the Gurgaon District.

### *3.3. American Catchments.*

The data for these catchments has been taken from (*a*) "Rainfall and Runoff of the Miami Valley" by Houk (10) and (*b*) Paper No. 80 of the U. S. Geological Survey by G. W. Rafter (26). They are :—

(*i*) Miami River

(*ii*) Muskingum River

(*iii*) Croton River

(*iv*) Lake Cochituate

(*v*) Upper Hudson River.

## 4. Method of Analysis.

The Punjab, and for the matter of that, India as a whole, receives most of the annual rainfall during the monsoon season. The analysis of the data of the Punjab and Alwar catchments has been made on the monsoon rainfall and runoff statistics. Normally in the Punjab this season lasts for four months, June to September.

The American rainfall year has been divided by G. W. Rafter (26) into three periods—(*i*) Storage period from January to April, (*ii*) Growing period from May to August, (*iii*) Replenishing period from September to December. There is no marked rainy season, but the storage period receives the most rainfall, and data for only this period has been analysed.

Binnie's Table (Table I, page 2) has formed the background of the analysis. For all catchments, where monthly rainfall and runoff figures were available, similar tables were prepared, Columns 4 and 5 of which give at a glance the total rainfall and runoff of, and up to end of, each month.

The advantage of tabulating observations in the manner mentioned above lies in the fact that, whereas each year would be expected to yield only one set of results, we have by this method four or more sets, depending on the number of months. "A little consideration will show that each of the entries in Columns 4 and 5 can be considered as giving runoff that would be produced by a 'Wet season' rainfall of the same magnitude as the rainfall that had occurred up to the end of the month considered." (25).

Where monthly rainfall and runoff figures have not been available, the total seasonal figures have served the purpose.

The figures in Column 4 and 5 have been plotted on separate sheets to facilitate analysis. For streams not tabulated in the above manner, the total season's rainfall and runoff figures have been plotted. The plots are shown on Figures 3 to 15 attached at end of the paper.

## 5. "Every Stream is a Law Unto Itself."

The plots mentioned above have shown a remarkable co-relation between rainfall and runoff. Except for the small scatter that is to be expected, the points for each stream without exception fall on a regular curve. The mean curve for each stream has been drawn.

Before we proceed to analyse the curves mentioned we would first of all like to draw attention to a quotation from Rafter (22). He had very ably expressed a great truth as early as 1904—a truth, which, in the last

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# COMPARISON OF CURVES

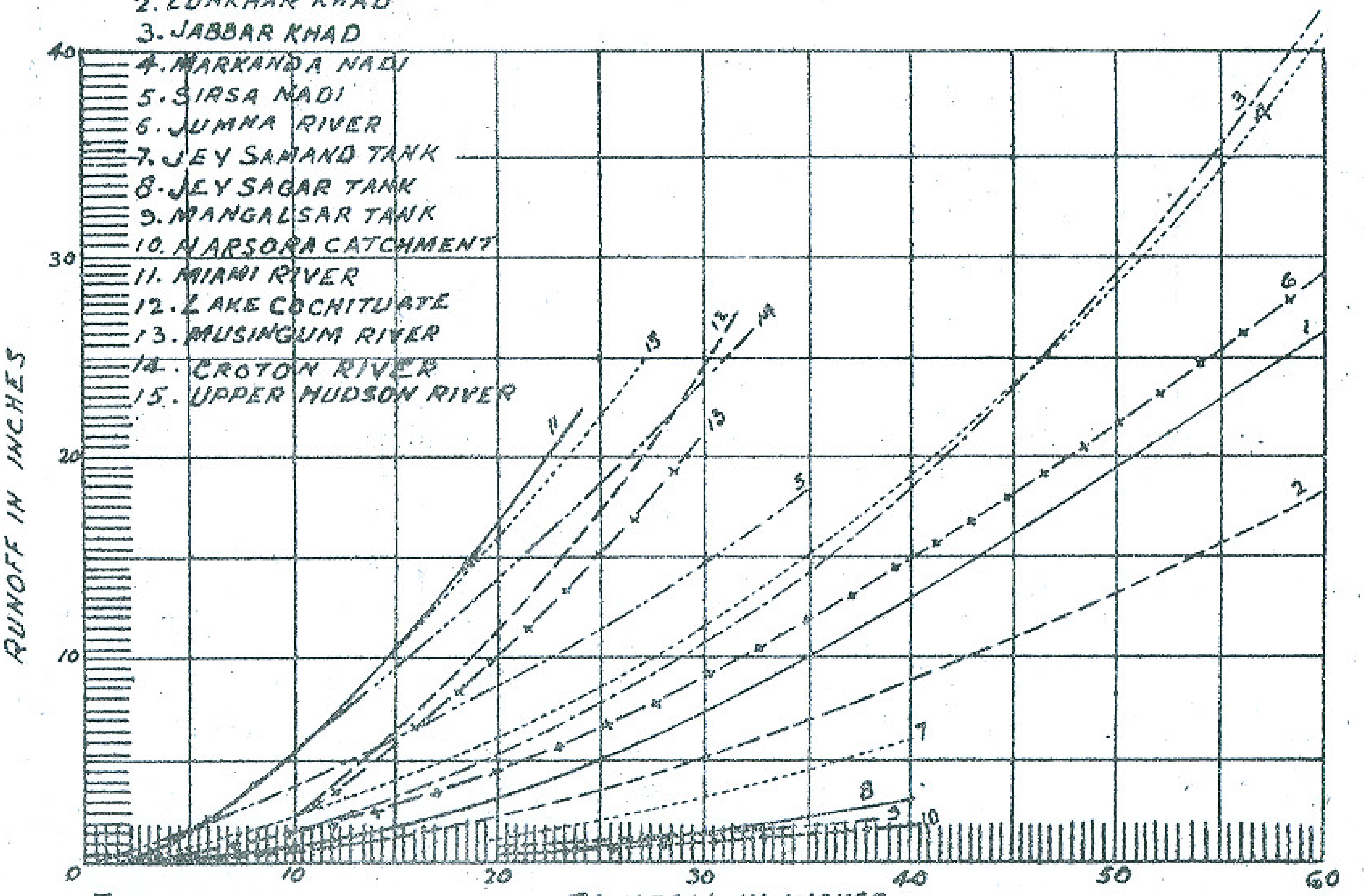


FIG. 16

forty years got burried under a mass of mathematical formulae. He stated :—

> "As a result of many years' study of the problem . . . . . the writer has come to the conclusion that no general formula is likely to be found expressing accurately the relation of rainfall and runoff, for streams vary widely in their behaviour, and when they do agree, the resemblance is usually accidental. As a general proposition we may say that every stream is a law unto itself."

The Authors would endeavour to establish the above truth denovo, and with this end in view each of the curves drawn separately (Fig. 3 to 15) has been reproduced on one sheet all drawn to the same scale. Fig. 16. The following table shows the catchment area of each of the streams, and the locality in which each is situated.

TABLE 2.

| No. | Stream. | Catchment Area in sq. miles | Locality | Remarks |
|---|---|---|---|---|
| 1 | 2 | 3 | 4 | 5 |
| 1 | Gambhar Khad at Jagat Khanna ... | 305 | Punjab | Tributary of Sutlej |
| 2 | Lunkhar Khad at Magra ... | 79 | Punjab | Tributary of Sutlej |
| 3 | Jabbar Khad of Nurpur ... | 35 | Punjab | Beas Tributary |
| 4 | Markanda Nadi at Kala Amb | 60 | Punjab-Nahan State | Adjoining Jumna |
| 5 | Sirsa Nadi at Dhang ... | 217 | Punjab-Nalagarh State | Tributary of Sutlej |
| 6 | Jumna River at Tajewala ... | 4,386 | Punjab-U.P. Boundary | Adjoining Gambhar Sirsa & Markanda |
| 7 | Jeysamand Tank ... | 70 | Alwar State | |
| 8 | Jey Sagar Tank ... | 27 | Alwar State | |
| 9 | Harsora Catchment ... | 43 | Alwar State | |
| 10 | Mangalsar Tank ... | 34 | Alwar State | |
| 11 | Miami River at Dayton ... | 2,525 | U.S.A. Ohio | |
| 12 | Muskingam River ... | 5,828 | Eastern United States | |
| 13 | Croton River ... | 339 | Eastern United States | |
| 14 | Lake Cochituate ... | 18·9 | Eastern United States | |
| 15 | Upper Hudson River ... | 4,500 | Eastern United States | |

A careful study of the curves on Fig. 16 in conjunction with the above table will reveal some very interesting facts.

The Gambhar Khad and the Sirsa Nadi have a common watershed. The former has a drainage of 305 square miles compared to that of 217 square miles of the latter. The curves show that, whereas the Gambhar will contribute 26 inches of the total wet season rainfall of 60 inches towards stream flow, the Sirsa may be expected to yield as much as 40 inches for the same rainfall.

The Lunkhar Khad, having a much smaller catchment area, and lying very close to the two mentioned, would manage only 18 inches.

The Jumna River has a large drainage and the 4,386 square miles include 133 square miles of glaciers. In arriving at the runoff figures the glacier contribution was determined by a method suggested in a paper for the Research Committee of the Central Board of Irrigation by R. B. Kanwar Sain. The total runoff at Tajewala less the glacier contribution would be runoff due to rainfall, and the curve has been plotted for the "rainfall" runoff figures. The catchment of the Jumna River adjoins those of the Gambhar Khad and Sirsa Nadi. The Jumna catchment being bigger than the Sirsa can yield only 28 inches towards stream-flow from a monsoon rainfall of 60 inches.

The Markanda Nadi and the Lunkhar Khad have drainages of almost the same size (60 square miles and 79 square miles) and both lie in the Punjab. There is a great difference, however, in the amount of runoff that each is capable of yielding. The Markanda Nadi can be expected to have a monsoon off-flow of 38 inches while the Lunkhar only 18 inches for a monsoon rainfall of 60 inches.

The Alwar State catchments appear to show some peculiarity in as much as the bigger drainages have a larger yield than the smaller ones. Thus while the Jeysamand Tank draining an area of 70 square miles has a monsoon yield of 6 inches for 40 inches rain, the Mangalsar (39 square miles) has only 3 inches, and Jeysagar (27 square miles) only 2·75 inches. But considering the fact that all these catchments lie in the same region the range of runoff from 2·75 inches to 6 inches for a monsoon rainfall of 40 inches appears to be too great.

The American catchments show a tendency towards very high runoff. Thus the Miami River curve shows a yield of 20 inches for a rainfall of 23 inches during the storage period.

It may be noticed that a larger catchment contributes less towards stream flow than a smaller catchment. The Upper Hudson River of drainage area 4,500 square miles yields much more than the Muskingum River with a catchment of 5,828 square miles.

In short we may conclude from the above observation that :

1. No similarity is evident in the rainfall runoff relation of streams lying side by side, or in the same locality.

2. Two catchments of almost the same area show a very great difference in the amounts of runoff produced from the same amount of rainfall even when the two lie in the same locality. Evidence of smaller catchment producing more runoff is also present.

3. In general we can conclude that there is little resemblance between the rainfall runoff relation of one stream to another. In short, to quote Rafter again, "Every stream is a law unto itself."

These conclusions lead to the rejection of the idea of a general formula by which accurate estimates of available supply may be made. In fact these conclusions go further to dispel ideas of having separate formulæ for separate localities (reference to which may be made for other streams in the same locality).

The comparison brings out rather strikingly the grave danger of resorting to curves and formulæ suggested by various Engineers for conditions very different from those of catchments under investigation. The two curves commonly used in the Punjab (or rather, commonly misused) are the Strange and Inglis curves. These were never intended by their Authors for universal application. As a matter of fact Strange has suggested that "It would be of great utility, were similar tables constructed by Engineers for different actual catchments."

To expect that these curves could be utilized with any degree of accuracy for Punjab conditions would be rather optimistic, and the Authors feel it their duty to warn against their use all those who will come across this problem.

## 6. How, then, to determine Runoff?

Due to lack of time, it has not been possible to work out the exact mathematical expression for the relation for each catchment. The mean curves have not been mathematically derived, and it may be possible to improve upon them. As they are, however, they show, to a reasonable extent, the relation of rainfall to runoff for each stream.

We have attempted to establish mathematical expressions for the mean curve of some of the streams. They are :—

(*i*) Gambhar Khad $R = \frac{P^2}{132}$ ... ... (Fig. 3)

(*ii*) Lunkhar Khad $R = \frac{P^2}{195}$ ... ... (Fig. 4)

(*iii*) Markanda Nadi $R = \frac{P^{1.8}}{39.5}$ ... ... (Fig. 6)

where R is Runoff in inches and P is the Rainfall in inches.

The similarity of the expression for these three streams and the similarity in the shape of all the curves leads us to expect that all streams will have a rainfall runoff ratio expressed in the general form

$$R = KP^n.$$

The conclusions arrived at in the previous paragraph are apt to be disturbing unless a method of the determination of runoff is suggested to replace the old ones. The evident similarity of shape of all the mean curves, and the general form of the curve shown above suggest a method whereby a fairly reliable estimate of runoff should be possible.

We have shown in the previous paragraphs that results of one stream cannot apply to that of another. It follows, therefore, that, before any estimate of supplies can be made, we must be in possession of sufficient data.

For those streams which have been gauged for a considerable period and for which sufficient data is available we can establish a relation in a manner similar to one adopted in this study.

The difficulty arises when it is proposed to investigate possibilities of storage on a stream which has never before been gauged. The immediate commencement of discharge observations of the stream, and the installation of as many rain gauges as possible in the catchment is extremely essential.

The period of observation would depend upon the magnitude of the project envisaged. Thus, for instance, daily observations have been made of the discharges of the Sutlej at Bhakra for over 30 years. For a smaller project like the Dhang Reservoir on the Sirsa Nadi, the estimate of supplies was made after two years observations. It is desirable that data for at least two, preferably three, seasons should be at hand for making any reasonable estimate, since the accuracy of the mean curve expressing the relation depends on the amount of data available.

Having established above, the fact that the form of the mean curve in all cases without exception will be

$$R = KP^n$$

we can proceed to tabulate our data as has been shown previously, and from it determine the value of K and n (constants which vary from catchment to catchment) for the stream in question.

The two year's results of the Sirsa Nadi are shown plotted on figure 7. The mean curve through the points has been drawn. The mathematical expression for this curve is

$$R = \frac{P^{1.35}}{6.7}$$

This relation can now be used in determining the runoff for those years for which we have only rainfall data.

## 7. Limitation of Data.

The reliability of any relation is necessarily governed by the accuracy of the observation of those factors expressed in the relation. The greater the accuracy attained, the greater is the approach of the expression proposed to the actual relation.

In this study we have had to observe both rainfall and the runoff from the catchment to arrive at a relation between the two.

To measure rainfall at one place is not a difficult problem. The complication arises, however, when we wish to know the rainfall over a large stretch of country, such as the catchment area of a stream.

The great difference in the elevations of points lying in the drainage area of a hill torrent suggests a great variation of rainfall from place to place in the catchment. To arrive at a figure, accurately representing the mean fall over the whole area, it would be necessary to have a detailed information of the rainfall at numerous places in the catchment.

We have been greatly handicapped by a lack of this detailed information at "numerous" places. Rain gauges are very scarce in the catchments of these Punjab Hill Torrents, and the actual state of affairs is shown in the following table that the Authors have prepared :—

TABLE 3.

| Name of stream. | Catchment area in square miles. | Rain gauges in catchment. | Rain gauges just outside water shed. | Total rain gauges used for computing rainfall. | Square miles per rain gauge. |
|---|---|---|---|---|---|
| 1 | 2 | 3 | 4 | 5 | 6 |
| | | | | | square miles. |
| Gambhar Khad at Jagat Khana | 305 | ... | 4 | 4 | 76 |
| Lukhar Khad at Magra | 79 | ... | 4 | 4 | 20 |
| Jabber Khad at Nurpur | 35 | 1 | ... | 1 | 35 |
| Markanda at Kala Amb | 60 | 1 | 2 | 3 | 20 |
| Sirsa Nadi at Dhang | 217 | 2 | ... | 2 | 108 |
| Jumna River at Tajewala | 4386 | 12 | 6 | 18 | 244 |

Out of six Punjab catchments considered in the present study we find two have no rain gauge in the catchment at all, and two catchments have only one rain gauge each inside the drainage area. The Jumna River has 12 rain gauges within the water shed, a figure which is very low considering the size of the drainage.

A number of streams for which discharge data was available had to be rejected for similar analysis owing to the non-existence of any rain-gauge either inside or just outside the water shed.

In the interest of future development of this subject and in the interest of the Province, it is very essential that the state of affairs exhibited by the above table should be improved and the Authors would recommend to the authorities concerned the fixing of as many rain gauges throughout this Mid-Himalayan belt as it will be practicable to maintain. The cost would be nominal, if local people can be encouraged to take up this honorary service, as is done in the United States of America.

### 8. Manual of Irrigation Practice.

While on the subject, it would not be out of place to refer to a recent publication of the Punjab P. W. D. namely "A Manual of Irrigation

Practice" (32). The subject of Hydrology has been referred to very briefly, and the method of determining Runoff Volume has been just touched (2.281 Runoff Volume).

Two formulæ have been mentioned, the Vermeule and Khosla, both of which express the evaporation losses as a function of temperature, and have been described in an earlier article of this paper.

Temperature recording stations in the Punjab are even more scarce than the rain-gauge stations. In all there are 10 temperature stations in the hilly catchments of the main Rivers, *viz.* Simla, Manali, Poo, Kailong, Mandi, Srinagar, Cherat, Murree, Drosh aud Parichinar. The stations are expected to be representative of a drainage of about 170,000 square miles, extending from the foot hills to the sources of the Rivers in the snowfields of the Himalayas.

Thus we see that the Province is not yet in a position to utilize any formula which involves temperature and early steps towards the extensive collection of such data are indicated. Even when we have a better knowledge of the temperature conditions in the Himalayas, we shall have to approach these formula with caution. Although R. B. A. N. Khosla has shown that his formula is better than the other two involving temperature by comparison of results on a large number of foreign catchments, it would have to be proved applicable to the Punjab conditions.

Pondering over the suitability of temperature formulæ, the Authors prepared a table which shows the losses for each month for the last 10 years on the Gambhar Khad and the Lunkhar Khad. Figures 17 and 18 show the results. Simla is the only temperature station in this area, and lies just outside the catchment area of the Gambhar Khad. The monthly temperatures are shown below :—

TABLE 4.

| Month | Temperature Mean | Max. | Min. | Remarks |
|---|---|---|---|---|
| 1 | 2 | 3 | 4 | 5 |
| June | 67.5°F | 73·0°F | 62·0°F | |
| July | 64·5 | 67·7 | 61·2 | |
| August | 62·9 | 66·4 | 59·4 | |
| September | 61·0 | 65·2 | 56·7 | |

Khosla's formula is $R = P - \frac{T}{2} + c$, where c is a constant which allows for "catchment characteristics, humidity, glacier contribution etc. but not for evaporation and transpiration, which are covered by the temperature factor $\frac{T}{2}$, T being the mean annual temperature.

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GAMBHAR KHAD AT JAGAT KHANA
MONTHLY LOSSES 1933-42

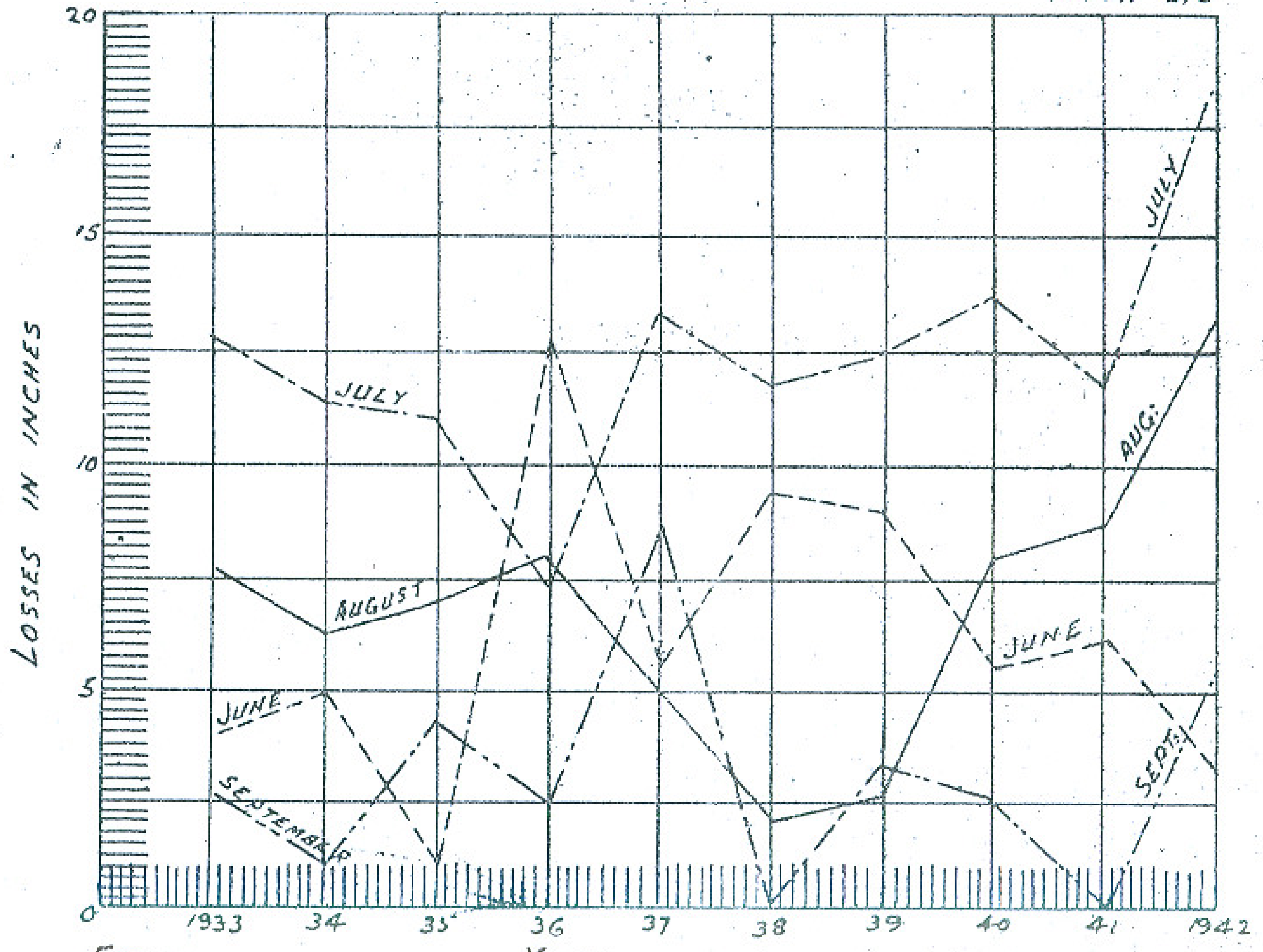


FIG. 17

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## LUNKHAR KHAD AT MAGRA
MONTHLY LOSSES 1933-41

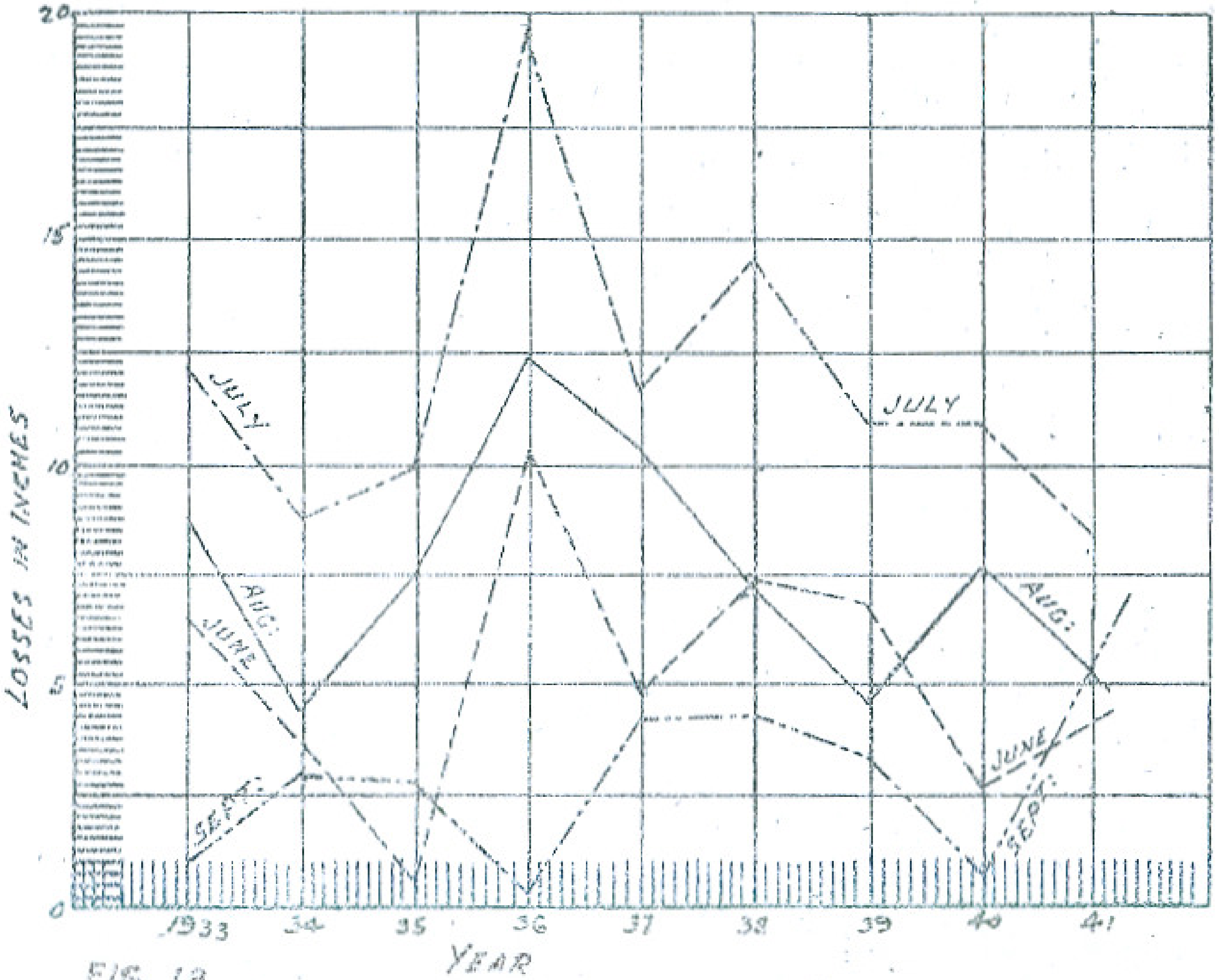


FIG. 18

For monthly figures the Author has suggested

$$R_m = P_m - \frac{t_m}{24} + C_m$$

The monthly losses from rainfall are given by $t_m$ which is the mean monthly temperature.

The total losses (P – R) are expressed by $\left(\frac{t_m}{24} - C_m\right)$

$C_m$ for non-glacier streams is a factor which allows for the characteristics of the catchment and humidity.

We see from figures 17 and 18 that the losses which are supposed to be " independent of rainfall," are highest for July, for both the streams. Besides being the month of most rainfall, and consequently the highest humidity, July is not the month of highest temperatures.

August, too, shows more losses than June in spite of the lower temperatures and higher humidity.

The Authors concede that it would be premature to draw any conclusions from the above observations until they are in possession of more extensive information, but wish to show the above results to stress the caution with which temperature formulae should be used in the future when better statistics are available.

It would add considerably to the value of the Manual ("an authoritative source from which the young officer may study the elements of his profession") if the present article is modified until such time as the reliability of the formulae mentioned is proved for conditions in the Punjab.

## 9. Summary of Part I.

The Authors have attempted to show in the preceding paragraphs by the collection, tabulation, plotting and comparison of the data of streams in the Punjab, in parts of India, and in America, the fact that no two streams can be expected to give the same results whether they lie side by side, or have the same size of drainage. By this, the Authors hope to discourage the use of curves and formulae suggested by other Engineers for catchments different to those under investigation.

The Authors have shown the similarity in the relation of rainfall to runoff for all streams investigated, expressed in a general form $R = K\ P^n$ where K and n are constants, and which can be determined from the available records of the streams. It has been recommended that, for new investigations, the data should be collected for at least two seasons, from which a curve of the form mentioned can be drawn, and utilized for estimating supplies for those years for which only rainfall data is available.

The need for more rain gauge stations and temperature recording stations has been brought into prominence.

Finally the Authors have shown the caution with which temperature formulae should be applied in the Punjab.

## PART II

## DETERMINATION OF THE INTENSITY OF FLOOD RUNOFF

### 1. Previous study.

This aspect of the rainfall runoff relation has been treated according to the nature of the Engineering problem. Thus Bridge Engineers have been interested only in the peak discharge to be expected during a flood to decide the water-way for the structure. The Storage Engineer, on the other hand, has to estimate the quantity of water coming into the reservoir during the flood, and to arrange for its disposal, if the inflow is more than can be accommodated.

Briefly, the methods employed in the different parts of the world may be classified as under :—

(*i*) Empirical Formulae
(*ii*) Probability Methods
(*iii*) Estimation based on Record floods in history
(*iv*) Rational Methods involving Intensity of Rainfall
(*v*) Unit Hydrograph Method.

### *1.1. Estimation by Empirical Formulae.*

Numerous formulae have been put forward from time to time for the estimation of the peak discharge. Included in these are formulae involving only catchment area; formulae involving catchment characteristics *e.g.* slope, shape, in addition to area; and formulae involving frequency of recurrence. A comprehensive list is available in "Flood Control by Marshall Ford Dam" (21)

The more popular formulae in use in India are :—

(*i*) Dickens' Formula $Q = 825\ A^{\frac{3}{4}}$ ... (Bengal)

(*ii*) Ryves' Formula $Q = C.\ A^{\frac{2}{3}}$ ... (Madras)

(*iii*) Inglis Formula $Q = \dfrac{7000\ A}{\sqrt{A + 4}}$ ... (Bombay)

(*iv*) Nawab Jang Bahadur's Formula $Q = C.\ A^{\left(0.92 - \frac{1}{14} \log A\right)}$ (Hyderabad)

(*v*) Khangar and Gulhati's Formula $Q = 645\ A\ \dfrac{Zmax - F}{T}\ \dfrac{(Ae)^m}{(Ao)}$

In the above formulæ

| | |
|---|---|
| Q | is maximum discharge from a catchment in cusecs |
| A | Total area of a catchment in square miles |
| Ae | Effective area of a catchment |
| Ao | That area for which dispersion is unity or that area which can be wholly covered by a storm and in which the intensity of storm does not vary. |
| Zmax | Maximum height of a theoretical hydrograph for a rainfall of maximum possible intensity in the catchment. |
| F | Reduction in inches due to rain initially held by trees, crops and undergrowth. |
| T | Inlet time. |
| m | Index of dispersion. |
| C | For Ryve's formula has a value 562.5 to 675 depending upon distance from sea As high a value of C as 2,000 has been used by Madras for the Thugbhadra River recently. In Nawab Jang Bahadur's formula value of C varies from 1,600 to 2,000. |

All these formulae involve constants 825, C, 7,000, which are based on the observations of the respective Authors in particular localities.

" It may be stated that at best a general formula is only a temporary substitute for observed or logically derived flood " information." (13)

*1.2. Probability Methods.*

These are based on long term records of high floods in the stream. A general idea is conveyed by the following abstract from " Flood Control by Marshall Ford Dam " (21) :—

" Two general methods of developing probability studies have been used in Engineering practice. These two differ only in the manner of selecting the data that are to be used. One is known as the " Annual flood method " wherein the maximum discharge recorded each year forms the basis, there being one event for each year of the record. The second method is known as the " Basic Stage " method, where in the data consists of all floods of record that are greater than some arbitrarily chosen minimum figure, regardless of the number or size of the floods that may occur in any one year."

The method is of " . . . . applying the principles of Probability (or Statistics) to available runoff data." Exponents of this method were Hazen, Whipple and Fuller, who designed a " probability paper " for plotting probability curves.

The long term data that is necessary for the use of this method is a great drawback, and limits it to only those streams which have sufficient record.

*1.3. Record Floods in History.*

A complete list of all the record floods in history on almost all streams and rivers in the United States, and on some of the larger rivers in other parts of the world is given in "Engineering for Dams" Vol. 1. (5). These maximum recorded discharges have been plotted against the respective catchment areas and curves enveloping the plots have been suggested. These curves can be used to estimate the maximum flood of a stream, catchment area being known.

Creager's equation for the enveloping curve is

$$Q = 46\, C\, A^{(0.894 \;-\; 0.048)}$$

Inglis has shown that his formula $Q = \dfrac{7000\,A}{\sqrt{(A+4)}}$ can cover almost all points of the plot mentioned.

This method is liable to give results, which are higher than the actuals that may occur.

By comparing the characteristics of the catchment in question with any one of those for which long term record is available, and selecting one which resembles most, it is possible to estimate the maximum flood, allowing for the difference in size of the two catchments.

The difficulty of the selection of a similar catchment is a very great drawback and for this reason the method is not extensively used.

The magnitude of the maximum flood can be worked out, if the water marks of the highest flood in the memory of the local inhabitants can be located. With the rise in water level there is an increase in the scour of the bed, and Karnail Singh and Gurdial Singh (17) have shown in a paper read before the Punjab Engineering Congress (1942) a method of calculating the amount of scour. Thus the area of cross section may be calculated and using Kutter's or Manning's formula the discharge of the stream for the given water surface can be known.

This method, however, cannot be applied in every case, and the tendency of the inhabitants of the locality to exaggerate the magnitude of the flood is often greatly misleading.

*1.4. Rational Method involving intensity of Rainfall.*

This method is based on the conception that the magnitude of a flood varies with the intensity of the storm causing it.

B. D. Richards, (27) in a recent publication (1944) dealing with the problem from this aspect, has deduced a number of equations in which he has expressed the average intensity of a storm in terms of the area of catchment and the period of concentration of the flood, and has in other equations introduced the catchment characteristics to reproduce the hydrograph of the flood.

Khangar and Gulhati (18), in a paper before the Punjab Engineering Congress (1941) have presented a method of flood estimation. They have shown a process whereby the flood hydrograph of runoff may be developed from a knowledge of the rainfall intensity. The formula evolved by them from rational basic considerations is given in para 1. 1.

*1.5. Unit Hydrograph Method.*

Although, strictly speaking, the Unit Hydrograph Method is a rational method, it has been mentioned separately because of its very great practical utility.

The Unit Hydrograph was first proposed in 1932 by L. K. Sherman (28), and is based on the fact that all floods caused by one day's rainfall will have the same time base for the hydrograph, the ordinates of the hydrographs varying with the intensity of the flood. As Sherman introduced it, the Unit Hydrograph is the hydrograph representing one inch runoff from the catchment. Thus a two inch runoff would according to Sherman's theory have ordinates twice as long as those of the Unit Graph.

In 1934 the Unit Hydrograph was slightly modified by M. M. Bernard (3) who introduced the "Distribution Graph." This is a graph showing the percentage of the total flood volume available at any stage of the flood period. He also presented the "Pulviagraph" which was the hydrograph showing one hundred per cent of the rainfall as runoff. By the application of "Regional Coefficients" C the Pulviagraph could be reduced to indicate the actual runoff to be expected.

Gerald T. McCarthy (22), in 1938, showed how it is possible to construct Unit Hydrographs and distribution graphs for streams without stream flow records. He states "The agreements between graphs developed from May and November storms substantiate the contention that primarily the unit hydrograph is a function not of surface cover, which may be subjected to seasonal change, but of the topographic features of the watershed." Based on this he has shown a method for the derivation of the Unit Hydrograph with a knowledge of topographic features.

The method has since been developed considerably and the present position is explained very clearly by the following, an extract from a chapter on the subject in "Hydrology" (29) :—

"The Unit Hydrograph is the hydrograph of surface runoff (not including groundwater runoff) on a given basin due to an effective rain falling for a unit time. The term "effective rain" means rain producing surface runoff. The unit of time may be one day, or preferably a fraction of a day. It must be less than the time of concentration.

"The Unit Hydrograph takes cognizance of the facts

(*a*) That peak and other runoff rates are materially affected by variations of intensity of rainfall during a storm, that the single average rate of rainfall for the period of a storm, (as commonly used) is not in accordance with the varying rain pattern that takes place in nature.

(*b*) That, from a given basin the observed hydrograph of runoff due to a given period of rainfall reflects all the combined physical characteristics of the drainage basin, including infiltration, surface detention and storage. It has further been found that, within close approximate limits.

(*c*) The ordinates of a Unit Hydrograph are proportional to the total volume of surface runoff from such unit time rains irrespective of the amount or depth of such unit rainfalls.

(*d*) The base or time duration of the hydrograph of surface runoff, due to an effective rain in a unit of time, is practically constant.

(*e*) The distribution of runoff represented by the ratios of volume of runoff during a particular unit of time to the total runoff is a constant for all Unit Hydrographs of runoff derived from the same basin. This holds true for all storms on the basin, without regard to their intensity. These percentages represent what is called the distribution graph.

(*f*) The complete hydrograph of runoff due to a storm is composed of the summation of a series of unit graphs, each representing the distributed runoff due to a rate of rainfall for a unit of time. The proportionality of ordinates (*c*) does not hold for the hydrograph composed of a series of Unit Graphs.

" The Unit Hydrograph method does not apply to runoff from snow or ice."

The application of the Unit Hydrograph lies in (*a*) Estimating the maximum storm (either of one day, or several days duration) that is likely to occur and (*b*) The determination of " rainfall excess " from the storm. Rainfall-excess is that portion of the rain which finds its way into the stream, *i.e.*, surface runoff.

The latter is of very great importance for on its accurate estimation lies the reliability of the application of the distribution graph. Based on the rainfall data recorded by automatic rain gauges, and taking into account the infiltration capacity of soils (with due consideration to preceding precipitation) the "Infiltration Theory," introduced by American Engineers goes a long way towards the accurate estimation of rainfall excess.

It is not possible to apply the Infiltration Theory when only daily rainfall figures, without any indication of the hourly distribution or intensity, are available. For such records Sherman has suggested the drawing of a diagram of runoff (fig. 19) for each month, which will indicate the ratio of runoff to rainfall for storms of various magnitudes.

Sherman has not lost sight of the effect of preceding rains and the following table (28) gives his idea of what percentage of the previous rain should be added for determining the amount of runoff.

**Table 5.**

| No. of days elapsed since previous rain. | Proportion of previous rain to be added. |
|---|---|
| 0 | 1.0 |
| 1 | 0.8 |
| 2 | 0 6 |
| 3 | 0.5 |
| 4 | 0.4 |
| 5 | 0.3 |
| 6 | 0.2 |
| 7 | 0.2 |
| 8 | 0.1 |
| 9 | 0.1 |
| 10 | $\frac{1}{11}$ |
| 11 | $\frac{1}{12}$ |

The application of Table 5 is best explained by a small example. A rain of 4.0 inches is preceded by a rain of 2.0 inches two days before. The percentage of the earlier rain to be added is (from Table 5) 60 per cent *i.e.* 1.2 inches. The total rain therefore is 4.0 inches plus 1.2 inches = 5.2 inches. From the diagram the rainfall runoff ratio for 5.2 inches for July is 32 per cent. The runoff from the 4.0 inches rain is therefore $4.0 \times \frac{32}{100} = 1.28$ inches.

The maximum storm is divided into a number of smaller storms each of unit duration. The amount of runoff due to each smaller storm is calculated, and distributed according to the distribution graph. The hydrographs thus obtained are added to give the summated graph of the expected flood. The summated hydrograph thus has a time base much greater than that of the Unit Hydrograph.

Unlike the other methods of flood estimation, the Unit Hydrograph method enables the Engineer to reproduce the entire hydrograph of runoff. This, coupled with the fact that it is based on a rational treatment, makes the Unit Hydrograph a very useful and accurate instrument in the hands of those engaged on flood control problems.

## 2. Data available in the Punjab.

It has been attempted to show briefly in the previous article the great utility of the Unit Graph method for flood estimation. The data of Punjab hill torrents is extremely limited and we are deprived of the benefit we may have derived by the application of the Unit Graph in its advanced stage. The limiting data is rainfall. The rain-gauges in the Punjab record only the total rainfall, measured every morning at 8 o'clock. They give no idea of the intensity and duration of a storm. Thus a two inch rain which commenced at 7 a.m., and continued till 9 a.m., would be shown in the records as a two-day rainfall, instead of a two-hour rainfall. For the purpose of rational analysis it is very essential that we should be in possession of complete information regarding rainfall, as it is the cause of runoff and the cause of destructive floods. It should be possible to arrange this by the installation of automatic rain-gauges in place of the present recording system.

Of late a move has been made to improve the stream-flow records of a few of the Punjab Torrents. With the object of securing accurate knowledge regarding the rise and fall of floods, the streams are under constant observation, and we are thus in possession of hourly gauges (over the entire monsoon season) of a few of them.

### 3. Application of the Unit Hydrograph in the Punjab.

The Sirsa Nadi, a tributary of the River Sutlej, is one of the few streams for which information as mentioned above is available. The discharge site is at village Dhang, in the Nalagarh State, below the confluence of the Sirsa Nadi with its main tributary, the Chikni torrent. The catchment area is 217 square miles.

The Sirsa Nadi has been gauged for two seasons, 1944 and 1945. There are two rain gauge station in the catchment of the nadi, and the straight average of the recordings at the two places is taken as the mean over the drainage.

The two years data was analysed and it was possible to locate only one isolated rainy day, runoff from which was not affected by that from another rain. This was a rain 2.5 inches measured on 1st August, 1944, causing a runoff with a peak of 36,923 cusecs at 8 o'clock on 1st August, 1945.

The Hydrograph, Fig. 20, shows that the nadi does not run dry after rains, a small seepage flow persisting. Deduction for this has to be made. Table 6 accounts for it in determining surface runoff. The distribution graph is shown on Fig. 21.

It has been rather fortunate that in the selection of the Unit storm for the above example we have been in a position to fulfil one of the main requirements of the Unit Hydrograph, namely that the duration of rainfall must not exceed the period of concentration. The rain was measured at 8 a.m. on 1st August, 1944, at the same time as the hydrograph attained its peak. With only daily rainfall data available this condition is seldom fulfilled, and an assumption to that effect has to be made. It is desirable that a number of such storms be selected (where records allow), and the average of the distribution graphs due to each storm be accepted for further application.

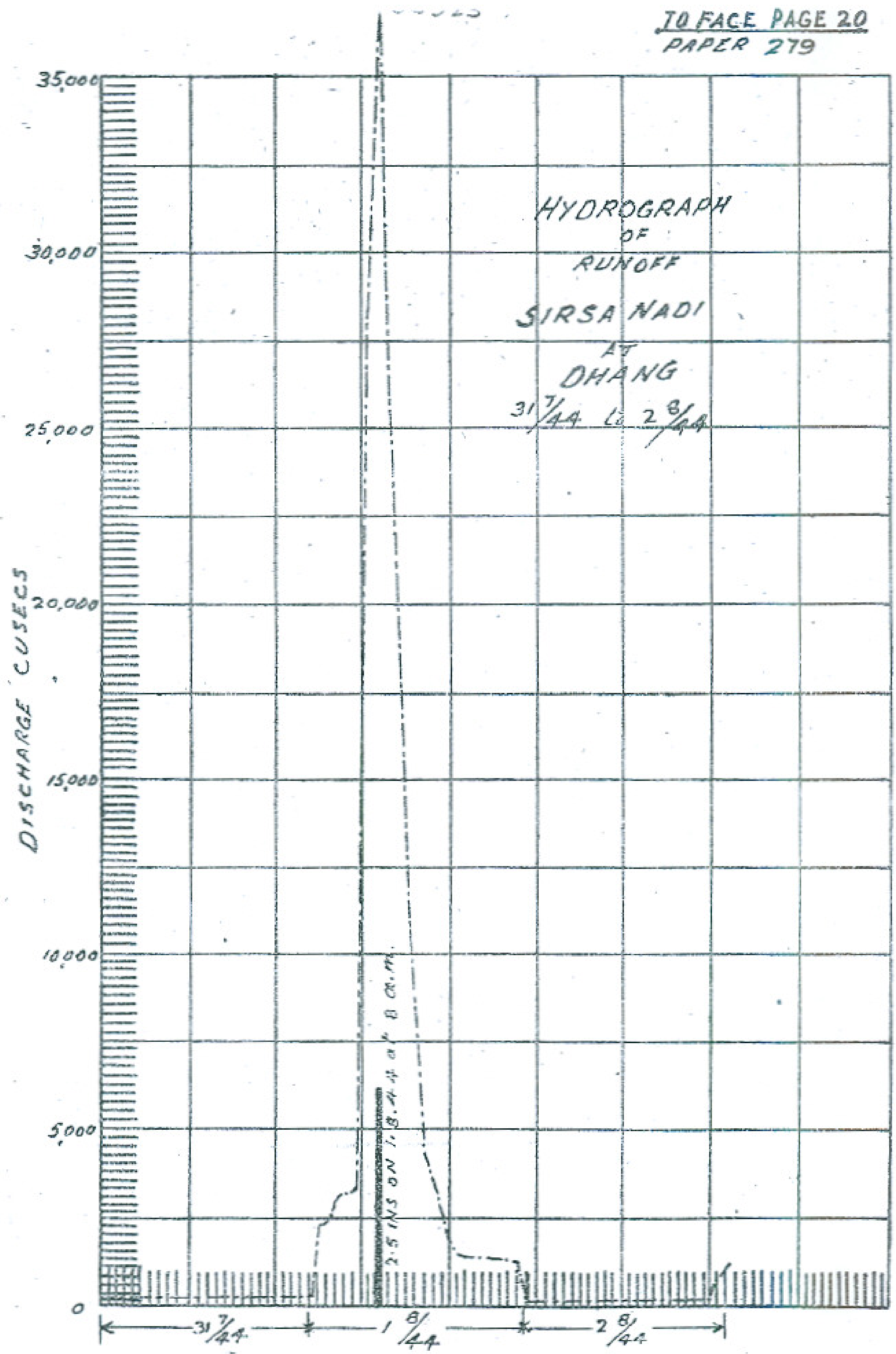
HYDROGRAPH
OF
RUNOFF
SIRSA NADI
AT
DHANG
31/7/44 to 2/8/44
35,000
30,000
25,000
20,000
15,000
10,000
5,000
0
DISCHARGE CUSECS
2.5 INS ON 1.8.44 at 8 A.M.
31/7/44
1/8/44
2/8/44

FIG. 20

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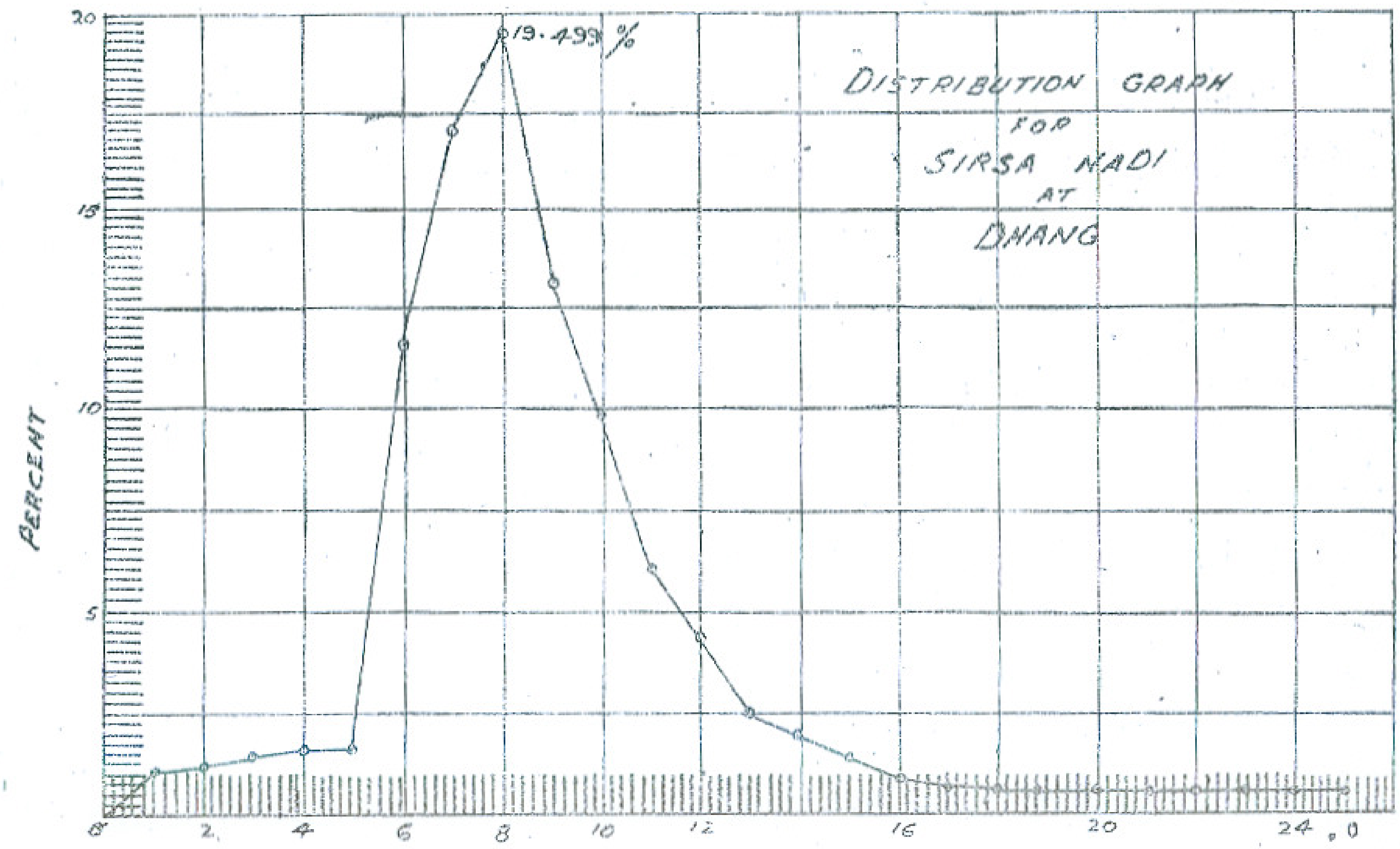
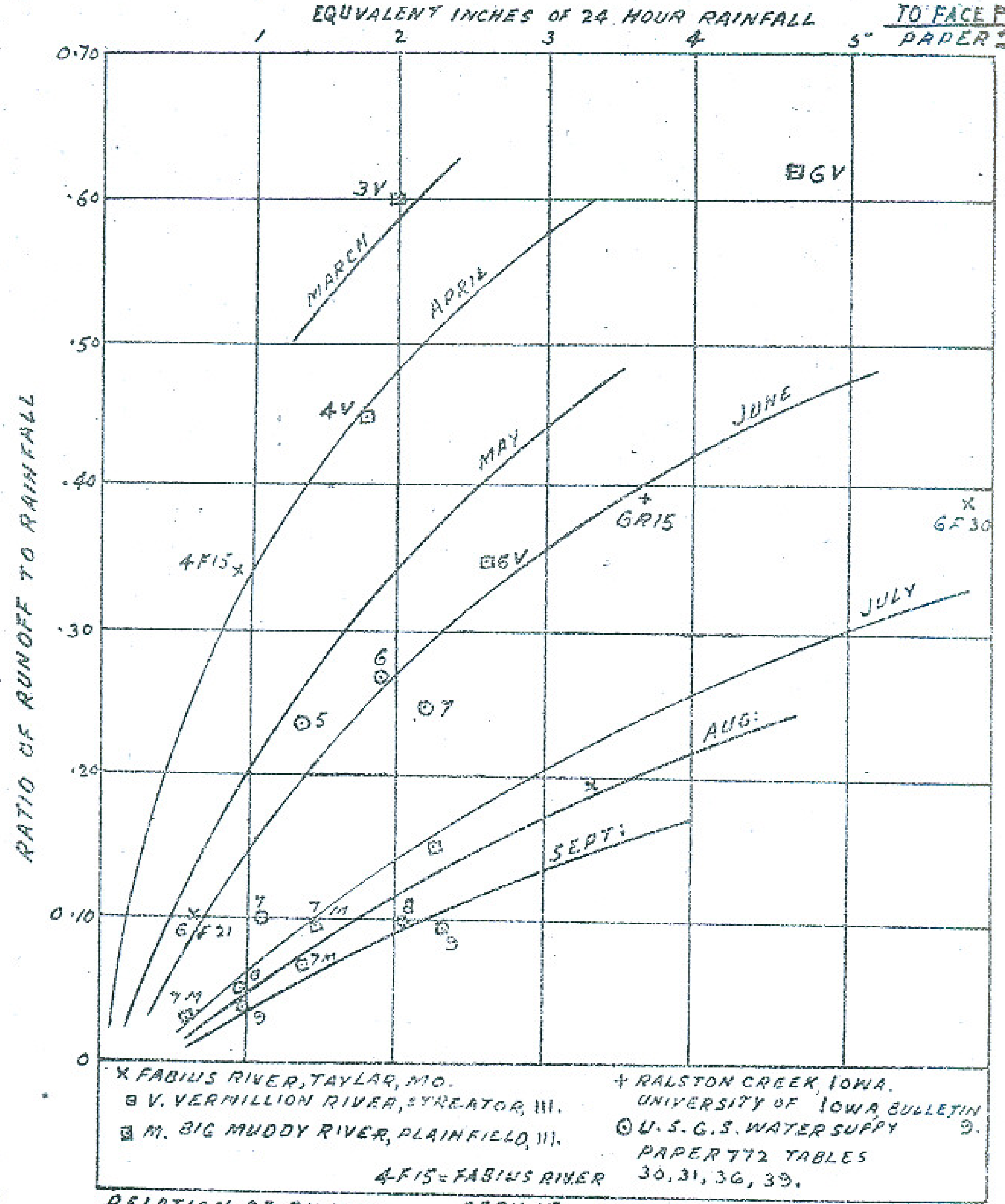



FIG. 21




RELATION OF RUNOFF TO RAINFALL.

FIG. 19

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TABLE 6.

| Date and time in hours | | Observed flow c. f. s. | Base flows c. f. s. | Surface Runoff c. f. s. | Distribution Graph (Per cent) |
|---|---|---|---|---|---|
| 1 | | 2 | 3 | 4 | 5 |
| 31-7-44 | | | | | |
| | 24 | 291 | 291 | 0 | 0·000 |
| 1-8-44 | | | | | |
| | 1 | 2232 | 281 | 1951 | 1·036 |
| | 2 | 2398 | 272 | 2126 | 1·130 |
| | 3 | 2975 | 263 | 2712 | 1·440 |
| | 4 | 3129 | 254 | 2875 | 1·527 |
| | 5 | 3210 | 245 | 2965 | 1·575 |
| | 6 | 22056 | 236 | 21820 | 11·600 |
| | 7 | 32174 | 227 | 31947 | 16·971 |
| | 8 | 36923 | 218 | 36605 | 19·499 |
| | 9 | 25004 | 209 | 24795 | 13·173 |
| | 10 | 18568 | 200 | 18368 | 9·758 |
| | 11 | 11629 | 191 | 11438 | 6·076 |
| | 12 | 8314 | 182 | 8132 | 4·320 |
| | 13 | 4975 | 173 | 4802 | 2·551 |
| | 14 | 3805 | 164 | 3641 | 1·934 |
| | 15 | 2924 | 155 | 2769 | 1·471 |
| | 16 | 1795 | 146 | 1649 | 0·876 |
| | 17 | 1468 | 137 | 1331 | 0·707 |
| | 18 | 1370 | 128 | 1242 | 0·660 |
| | 19 | 1290 | 119 | 1171 | 0·622 |
| | 20 | 1252 | 110 | 1142 | 0·607 |
| | 21 | 1252 | 101 | 1151 | 0·611 |
| | 22 | 1252 | 92 | 1160 | 0·616 |
| | 23 | 1252 | 83 | 1169 | 0·621 |
| | 24 | 1252 | 74 | 1178 | 0·626 |
| 2-8-44 | | | | | |
| | 1 | 65 | 65 | 0 | 0·000 |
| Total | | 192855 cusec hours | 4616 cusec hours | 188239 cusec hours =1-43 ins. | 100·007 |

The daily rainfall data does not permit the application of the Infiltration Theory. We have attempted to draw a rainfall runoff diagram to determine the "rainfall excess" in the way Sherman has suggested in Figure 19. A number of storms of various durations were selected, and the amount of runoff due to each was calculated. A graph was then plotted Fig. 22, which shows the rainfall runoff relation for such storms. This graph shows that the percentage of off-flow increases with the magnitude of the storm, but at a decreasing rate. The percentage has a limiting value, which varies with the type of soil, vegetable cover, the topographic characteristics of the catchment, and the season of the year. Figure 22 shows that, for the Sirsa Nadi, the limiting value of the percentage of runoff is 82 per cent.

The heaviest rainfall ever recorded for this catchment was as follows :—

| Date. | Rainfall in inches. | | Average for catchment. |
|---|---|---|---|
| | Nalagarh. | Kasauli. | |
| 4-7-30 | 2.73 | ... | 1.37 |
| 5-7-30 | 5.71 | ... | 2.85 |
| 27-7-30 | ... | 11.75 | 5.88 |
| 28-7-30 | ... | 10.63 | 5.31 |

It has to be assumed, that the average for the two stations represents the rainfall for the entire catchment. The time base for the Unit Hydrograph of the Sirsa Nadi is 26 hours. Hence the rainfall of 27-7-30 would not affect the surface runoff of 28-7-30 and consequently the peak flood would occur on 27-7-30 when there was heavier rainfall.

The preceding rainfall of 5-7-30 would not affect percentage runoff for 27-7-30.

From Fig. 22 percentage runoff for a rainfall of 5.88 inches comes to 78 per cent.

Runoff in inches from a rain of 5.88 inches would therefore be $5.88 \times \frac{78}{100} = 4.58$ inches.

Based on the proportionality of the ordinates of the hydrograph of runoff for 1-8-1944, the hydrograph for the flood on 27th July, 1930 can now be drawn. The peak discharge expected would be

$$\frac{4.58 \times 36{,}605}{1.43} = 1{,}17{,}136 \text{ cusecs.}$$

The Sirsa Nadi is a tributary of the Sutlej River and joins it about 7 miles above Rupar Weir. The discharge of the Sutlej at Rupar is measured accurately owing to the existence of the weir. The maximum discharge ever observe was 3,15,500 cusecs on 7th August, 1913. The discharge of the river during July 1930 was

| | | |
|---|---|---|
| 27-7-30 | ... | 1,80,000 cusecs. |
| 28-7-30 | ... | 1,09,200 cusecs. |
| 29-7-30 | ... | 88,731 cusecs. |

The peak of 1,17,136 cusecs in the Sirsa would thus appear to be reasonable.

An actual rainfall of 2.47 inches at Nalagarh and 4 inches at Kasauli on 5-8-43 caused a peak flood of 96,000 cusecs at Dhang. From the Unit Hydrograph method peak discharge for 5-8-43 after correcting it for the preceding rainfall of 4-8-43 comes to 62,230 cusecs. Either the actual observation of peak discharge on 5-8-43 was erroneous, or the average

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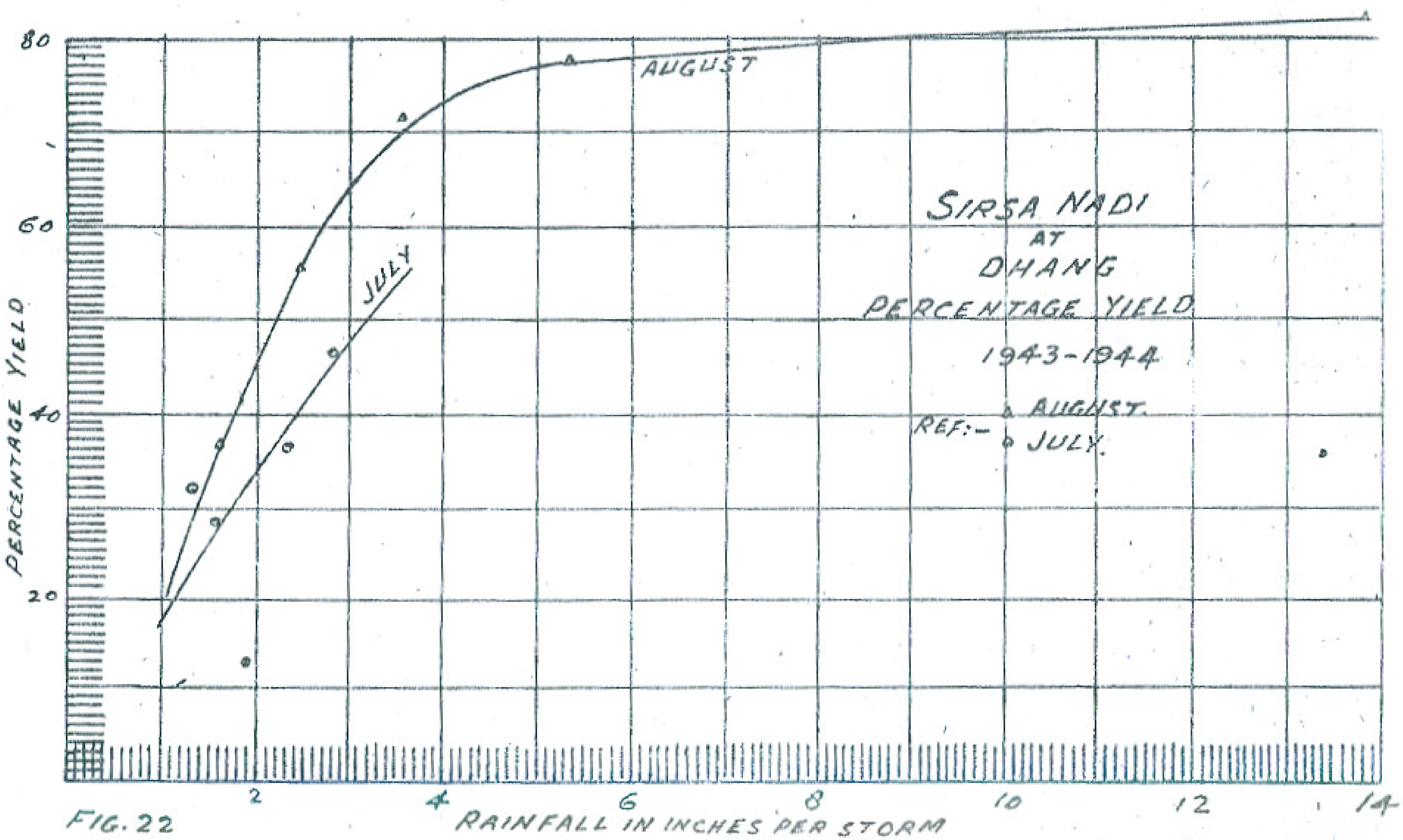


FIG. 22

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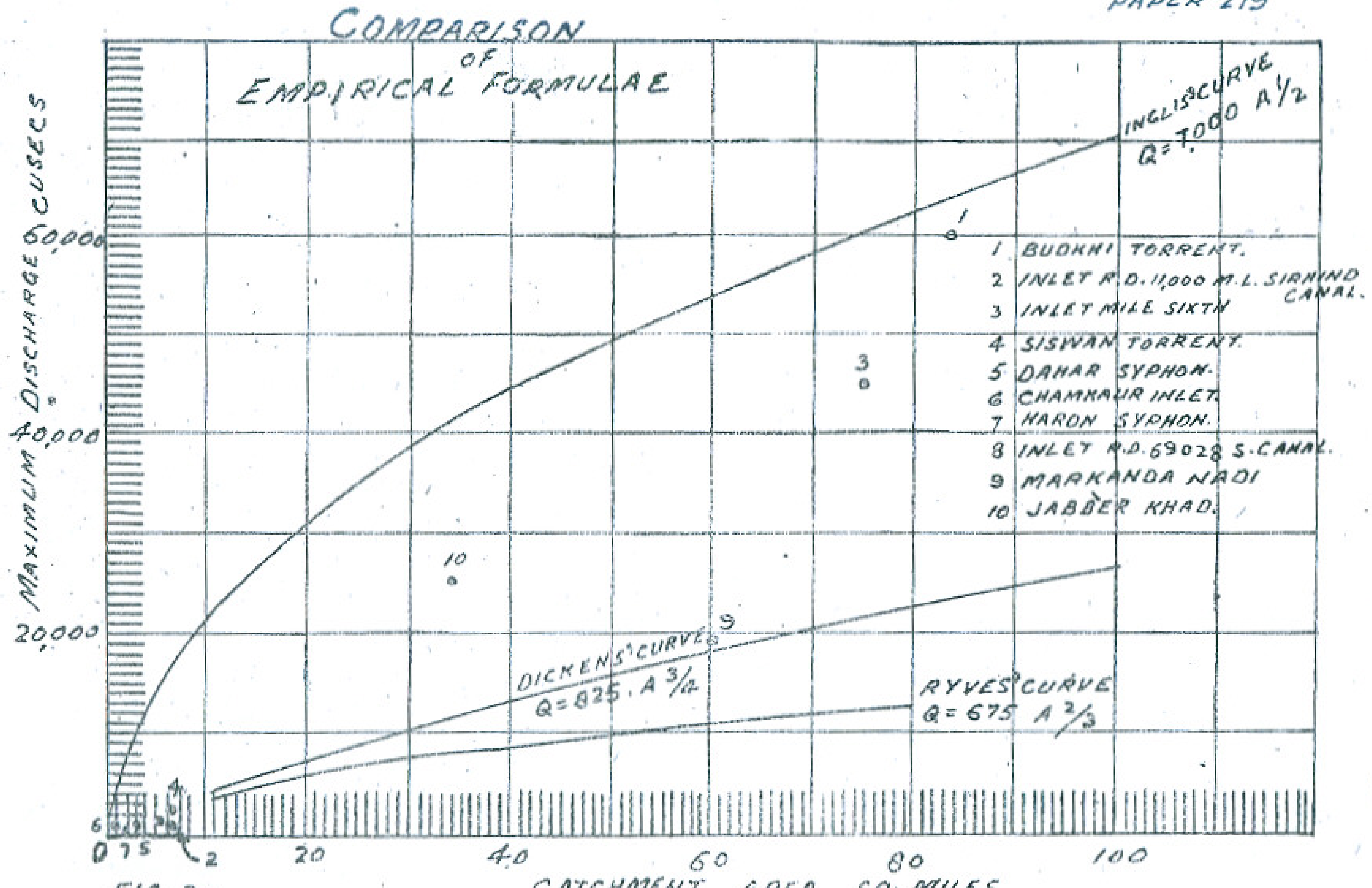


FIG. 23

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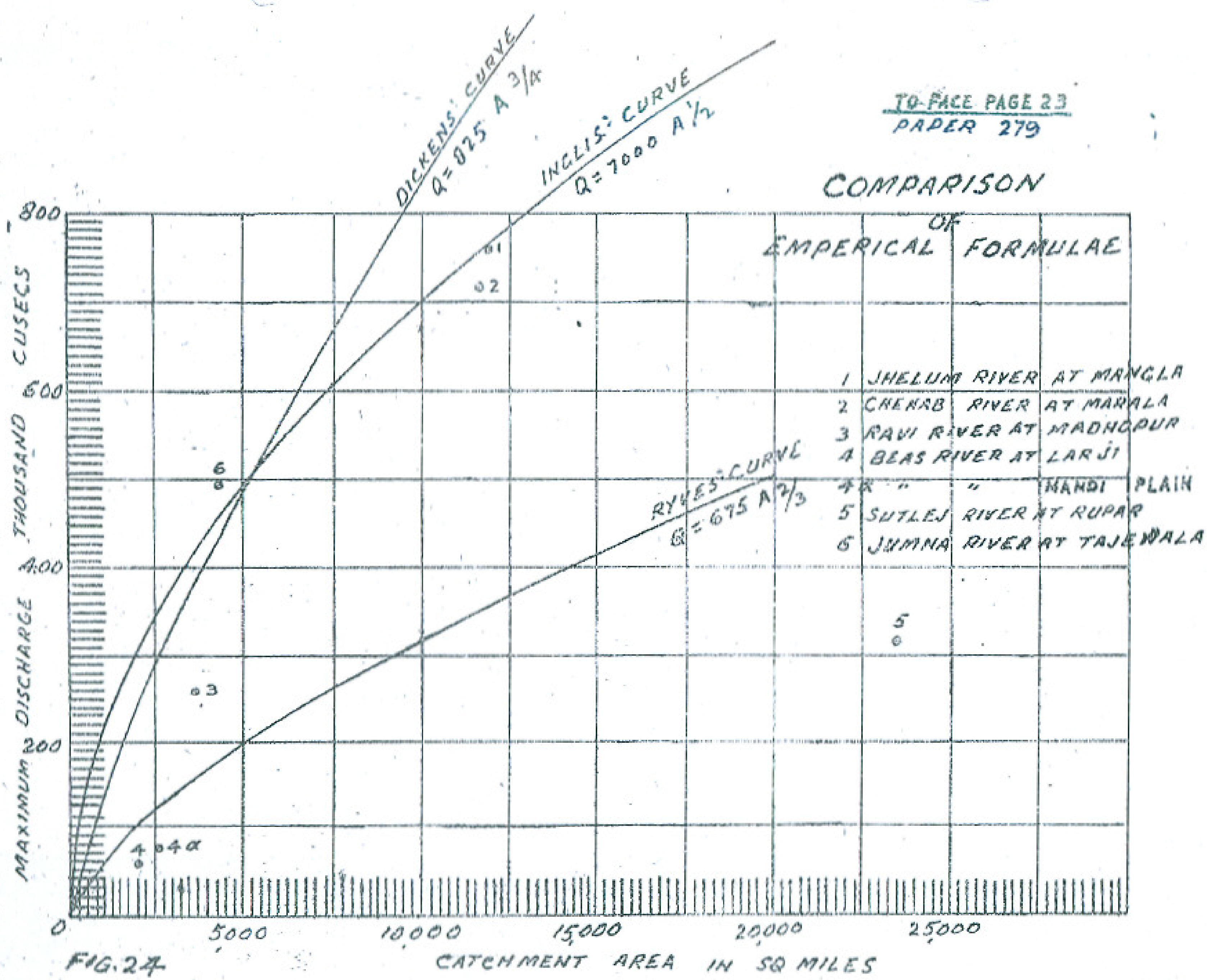


FIG. 24

rainfall over the catchment was higher than the average of the two stations. Maximum peak discharge at this site may be even higher than 1,17,136 cusecs, as the average rainfall in the catchment might have been greater than that assumed for the 27th July, 1930.

### 4. Disadvantages of Empirical Formulae.

Engineers are inclined to use empirical formulæ for flood estimation. These formulæ are apt to be misleading, and it would not be out of place to question their suitability. With this end in view we have on Fig. 23 and Fig. 24 shown three curves represented by the empirical formulæ :—

(*i*) $Q = 7{,}000 \ A^{\frac{1}{2}}$ Inglis' Formula

(*ii*) $Q = 825 \ A^{\frac{3}{4}}$ Dickens' Formula

(*iii*) $Q = 675 \ A^{\frac{2}{3}}$ Ryves' Formula.

On Fig. 23 are plotted the maximum-observed discharges against the respective catchment areas of ten torrents of the Punjab. On Fig. 24 are shown, in a similar manner, the maximum discharges of the Rivers of the Punjab at the foot hills (although strictly speaking these are beyond the scope of this paper).

These plots show the great variation that exists between the actual observed values and those according to each of these curves. There appears to be no law connecting the maximum discharge with catchment area.

Floods are the direct outcome of rainfall and it is only reasonable that rainfall data should feature prominently in the determination of the maximum flood. The empirical formulæ mentioned above would give the same value of Q for two streams of equal drainage, irrespective o the intensities of rain to which either is subject. Other characteristics of the catchment area are not given the due importance they deserve, being accounted for jointly under a constant C which may or may not be modified from catchment to catchment.

The Empirical formulæ do not furnish comprehensive information of the flood. Knowledge of only the peak discharge may be sufficient for a bridge engineer, but it would serve little purpose in the design of the spillway of a storage scheme.

### 5. Manual of Irrigation Practice.

The above manual gives only Inglis' and Khangar-and-Gulhati's formulæ for the determination of maximum discharge from a catchment. The Inglis formula gives results which are appreciably different from the actuals that occur in the Punjab. Khangar and Gulhati's formula is a valuable deduction from basic considerations. It, however, involves a a number of assumptions about which information is rarely available for any catchment. Their formula is, therefore, in the opinion of the Authors, of little practical help to the engineer in his projects.

The young engineer joining the Punjab Irrigation Department is, consequently, likely to be misled by the selective information given in the Manual on this subject.

### 6. Summary of Part II.

The Unit Hydrograph-method is one of the very rational methods of flood estimation. The Punjab Engineers have not yet used this method and in the previous paragraphs it has been attempted to show the great utility of the method, and the advantage it has over others that have from time to time been suggested. The limitations of rainfall data in the Punjab are an hindrance in the accurate estimation of floods by this method. The application of the method, with what data we have, has been shown for the Sirsa Nadi. It is hoped that this will stimulate further investigation on the subject.

The unsuitability of empirical formulæ to Punjab conditions has been shown.

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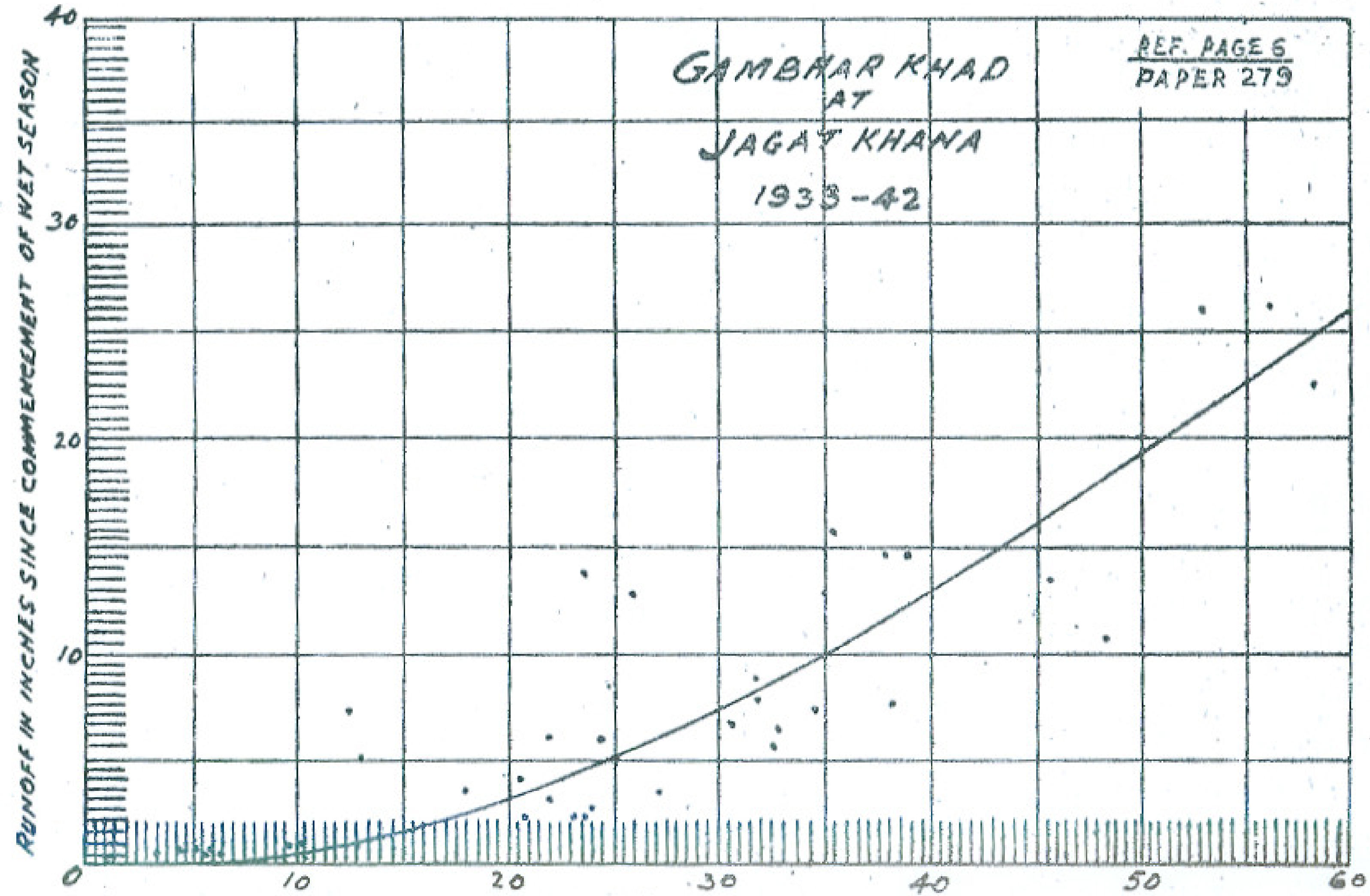
GAMBHAR KHAD
AT
JAGAT KHANA
1933-42
REF. PAGE 6
PAPER 279
RUNOFF IN INCHES SINCE COMMENCEMENT OF WET SEASON
RAINFALL IN INCHES SINCE COMMENCEMENT OF WET SEASON
0
10
20
30
40
50
60

FIG. 3

REF. PAGE 8
PAPER 279

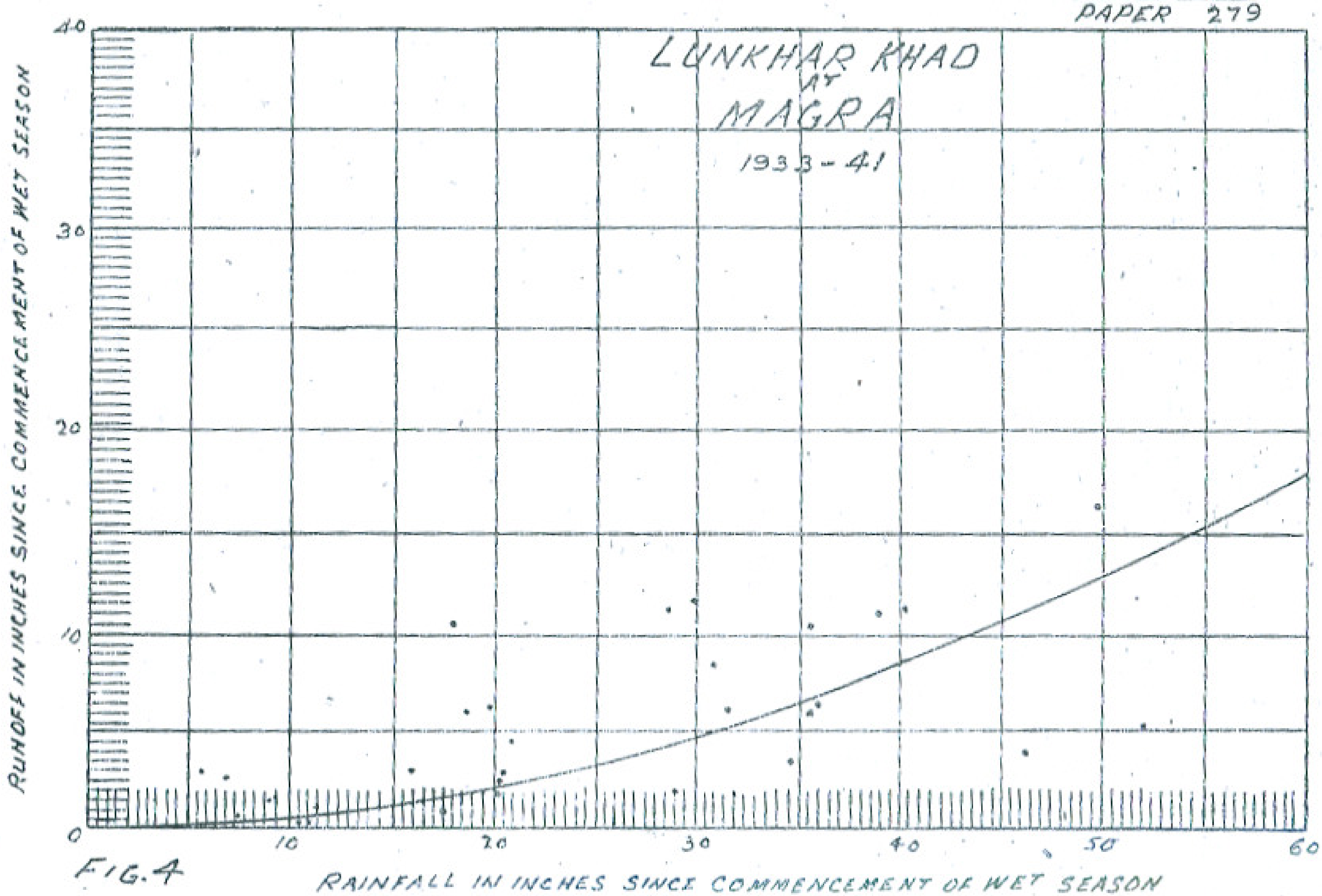


FIG. 4

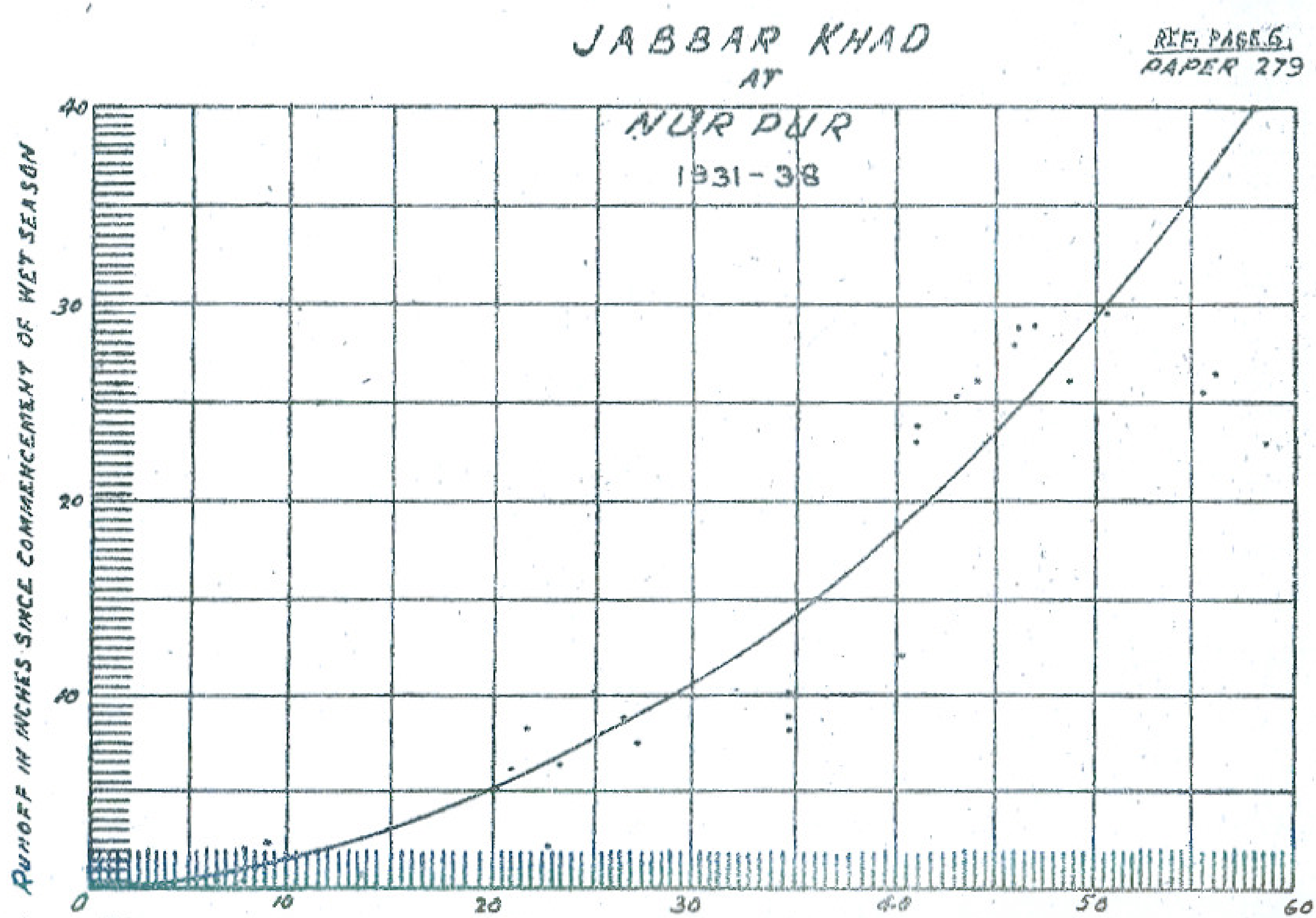
JABBAR KHAD
AT
NUR PUR
1931-38
RUNOFF IN INCHES SINCE COMMENCEMENT OF WET SEASON
RAINFALL IN INCHES SINCE COMMENCEMENT OF WET SEASON
0
10
20
30
40
50
60

FIG. 5

REF. PAGE 6
PAPER 273

# MARKANDA NADI
AT
KALAAMB
1930 – 39

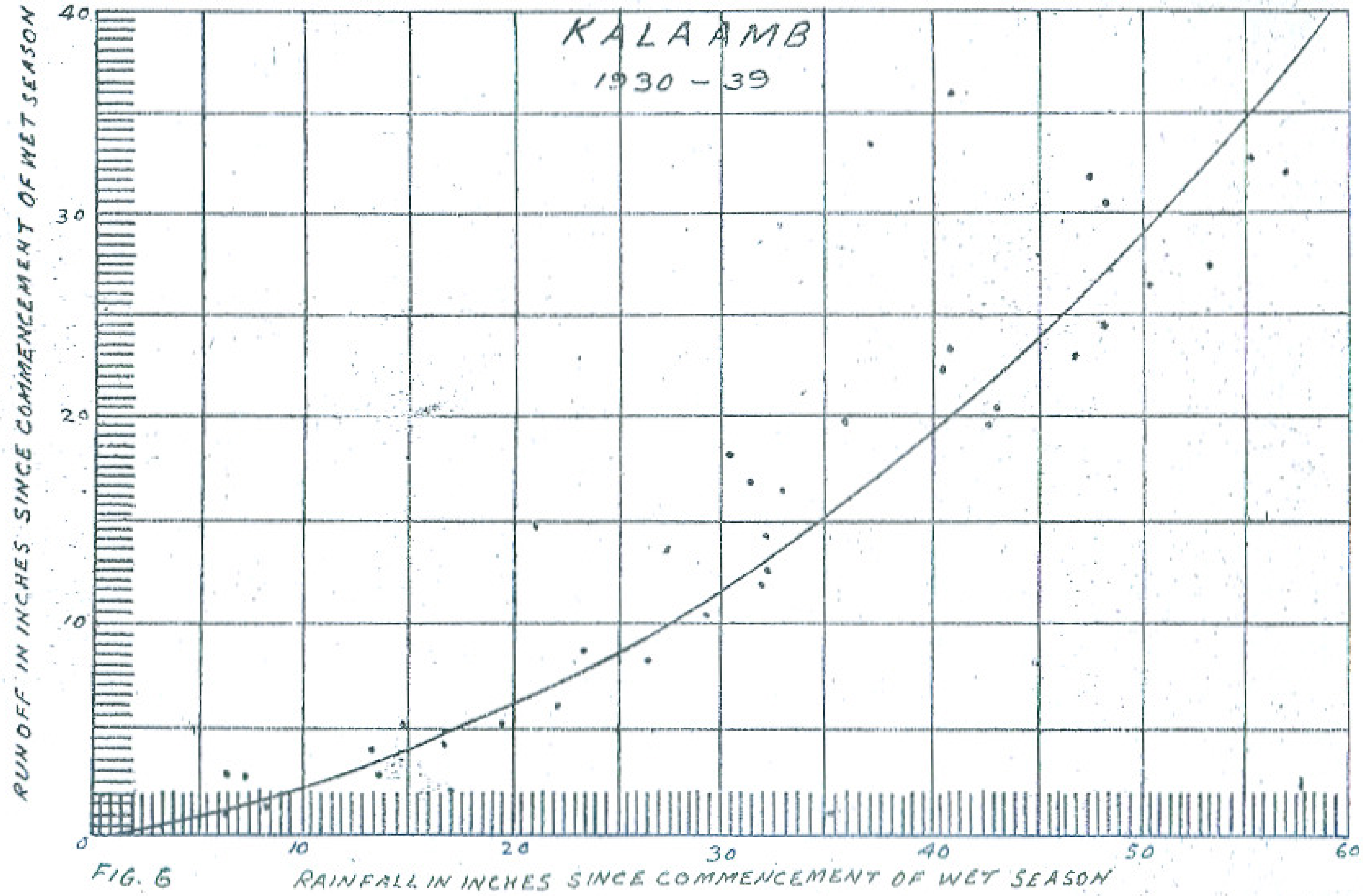


FIG. 6

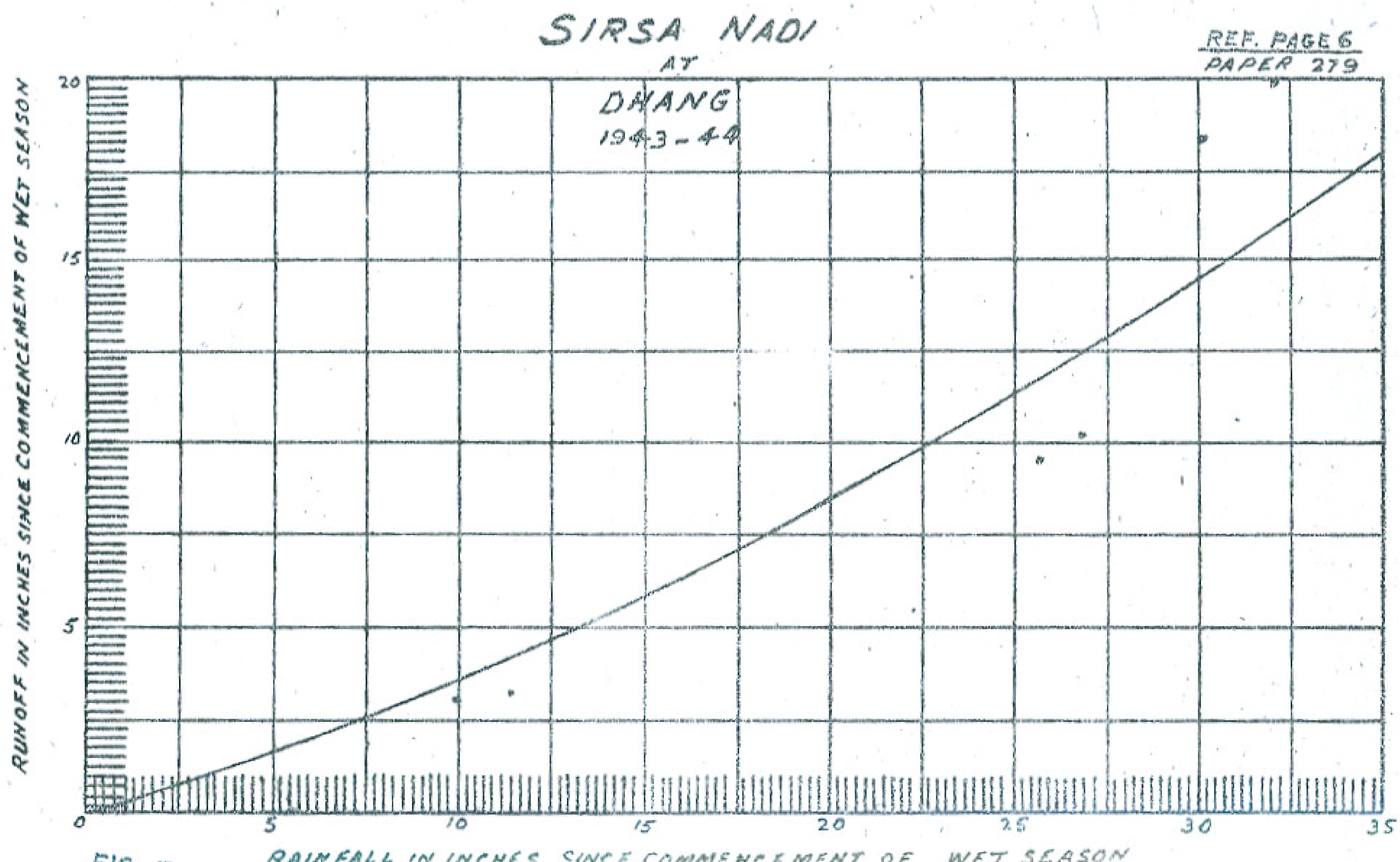
SIRSA NADI
AT
DHANG
1943-44
REF. PAGE 6
PAPER 279
RUNOFF IN INCHES SINCE COMMENCEMENT OF WET SEASON
0
5
10
15
20
25
30
35
RAINFALL IN INCHES SINCE COMMENCEMENT OF WET SEASON

FIG. 7.

# JUMNA RIVER AT TAJEWALA 1934-43

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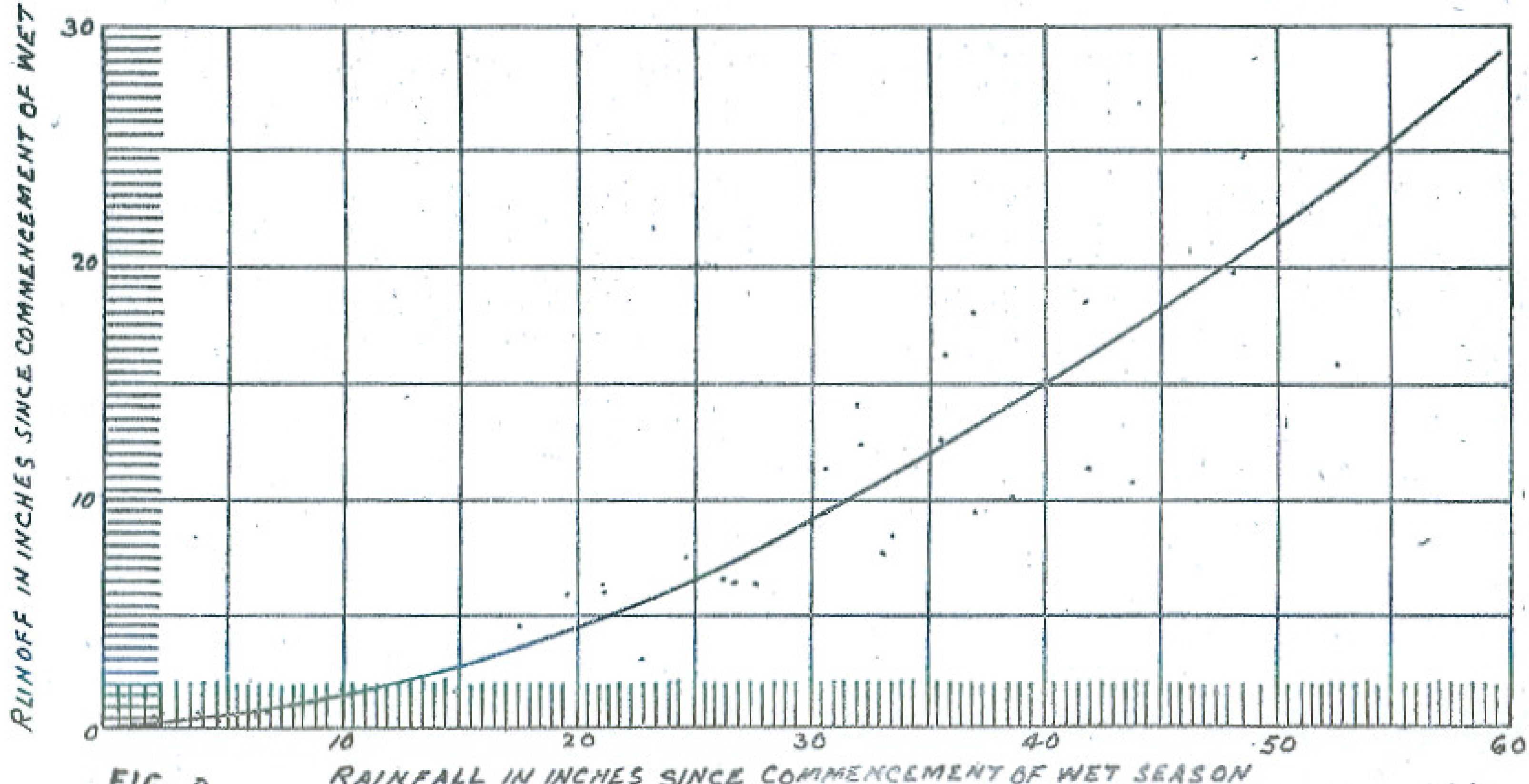



FIG. 8

ALWAR STATE
JEY SAMAND TANK

REF. PAGE 6
PAPER 279

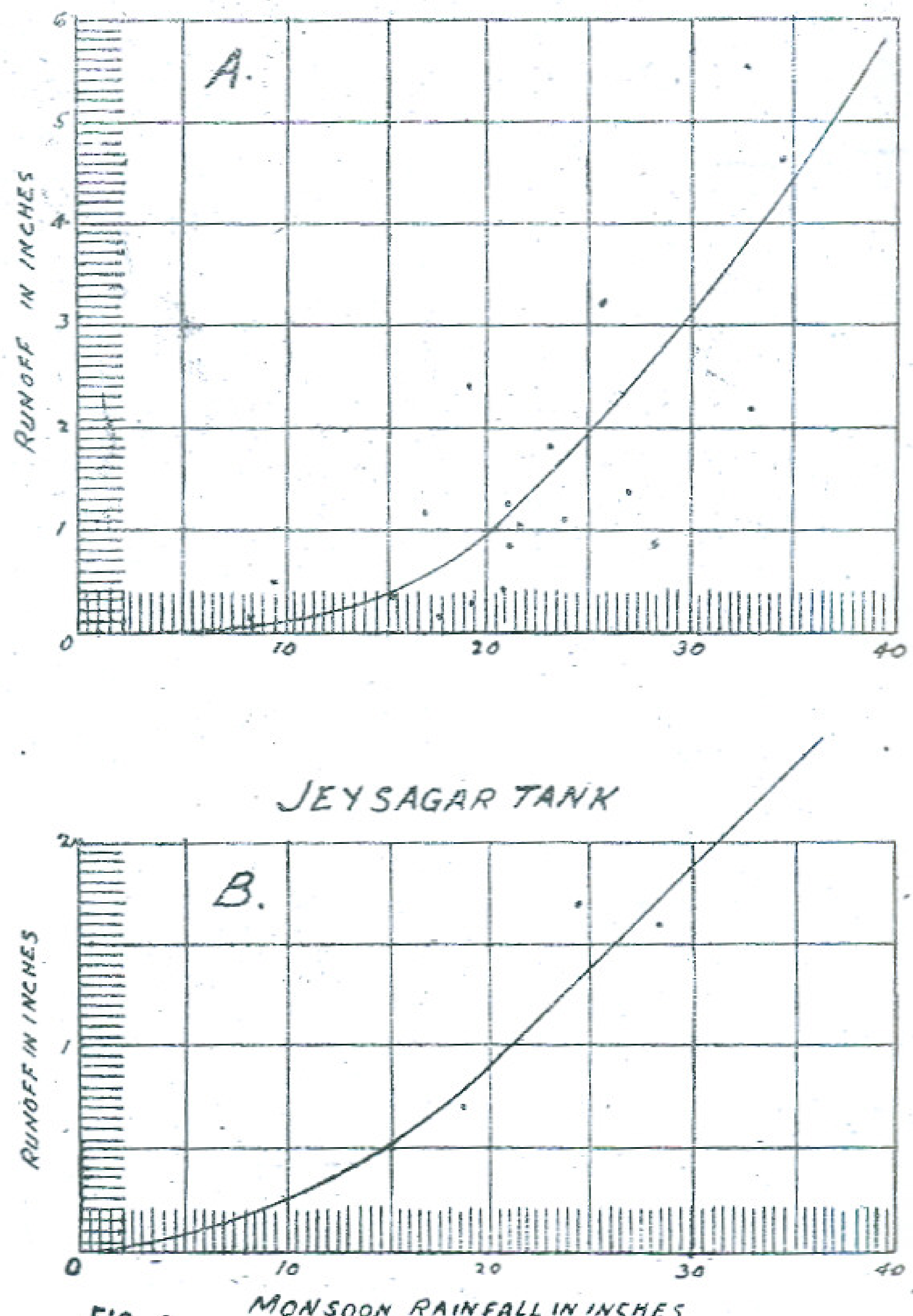



FIG. 9

## ALWAR STATE

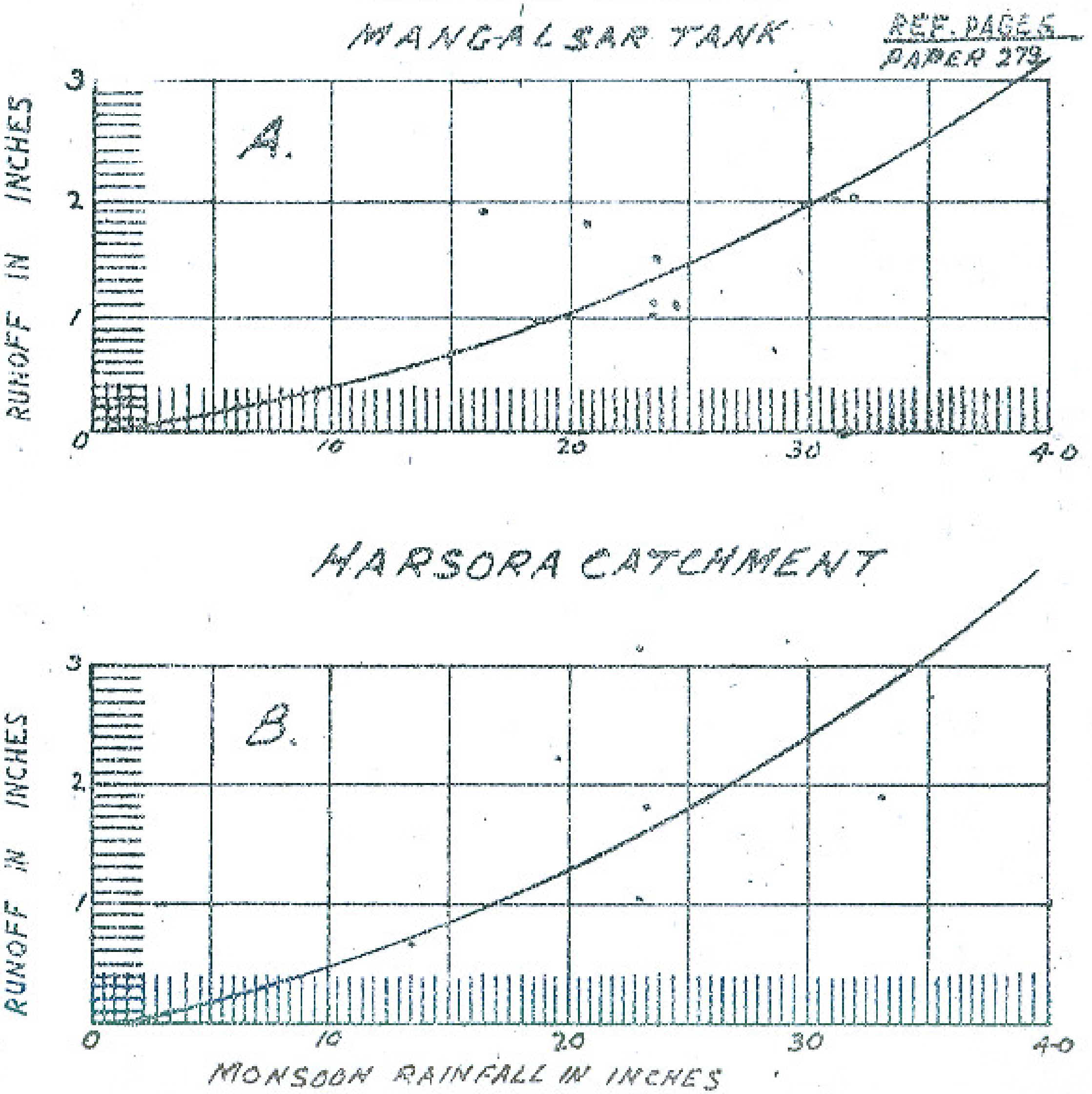



FIG. 10

MIAMI RIVER ABOVE DAYTON REF. PAGE 6 PAPER 279

1894 - 1918

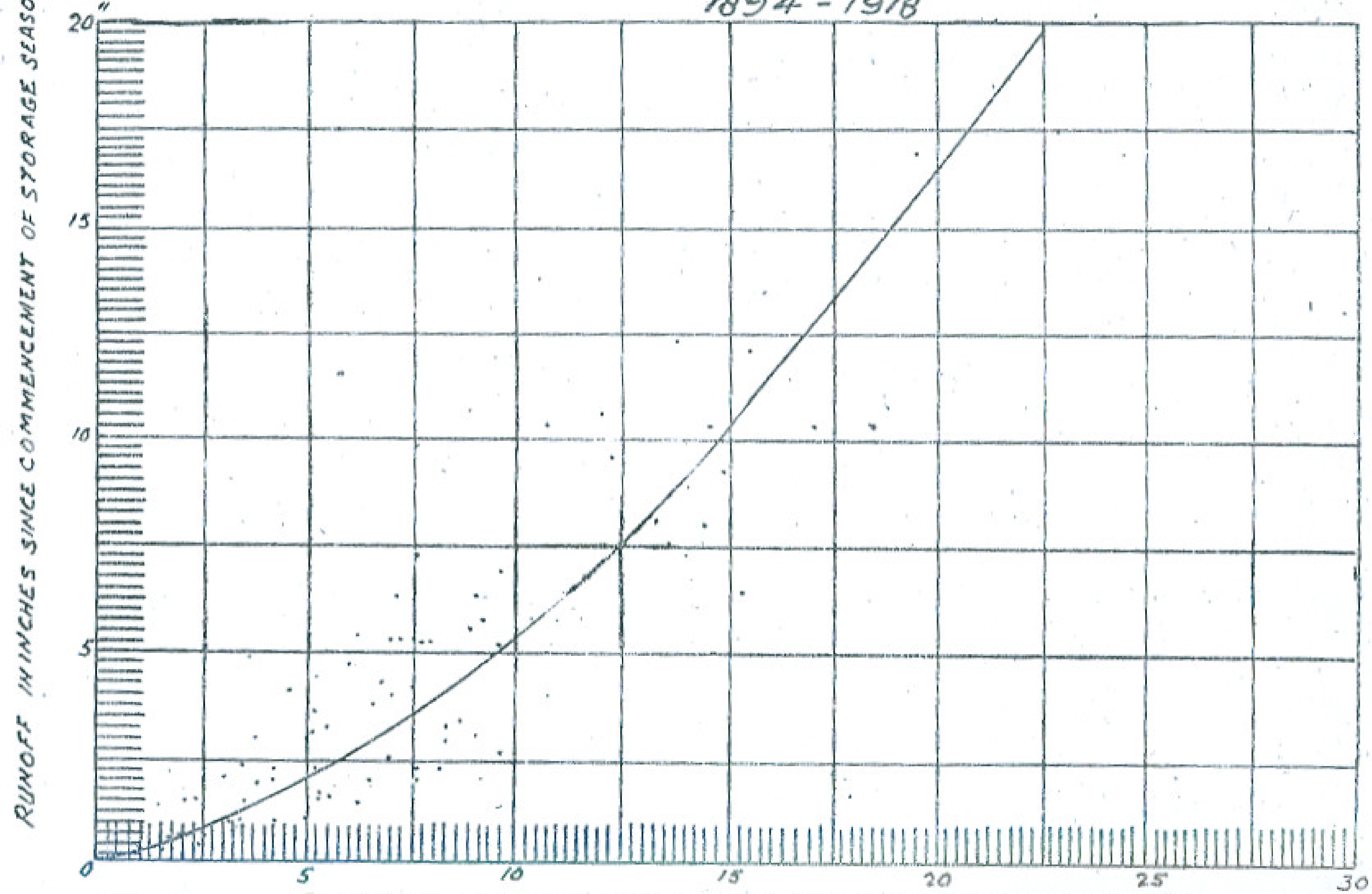
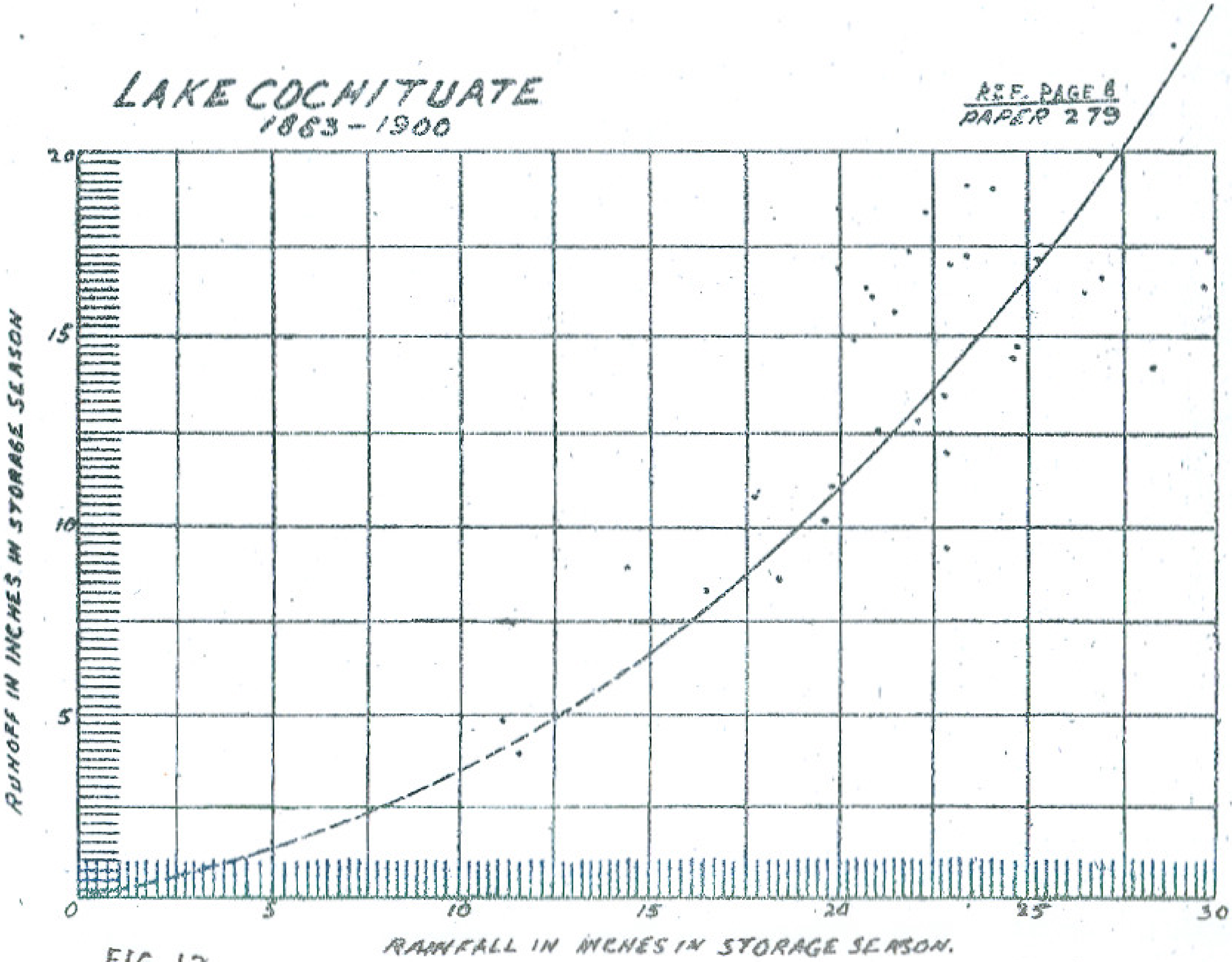



FIG. 11



LAKE COCHITUATE
1863 – 1900
REF. PAGE 8
PAPER 279
RUNOFF IN INCHES IN STORAGE SEASON
RAINFALL IN INCHES IN STORAGE SEASON.
0
5
10
15
20
25
30


FIG. 12

# MUSKINGUM RIVER

1888 – 1895

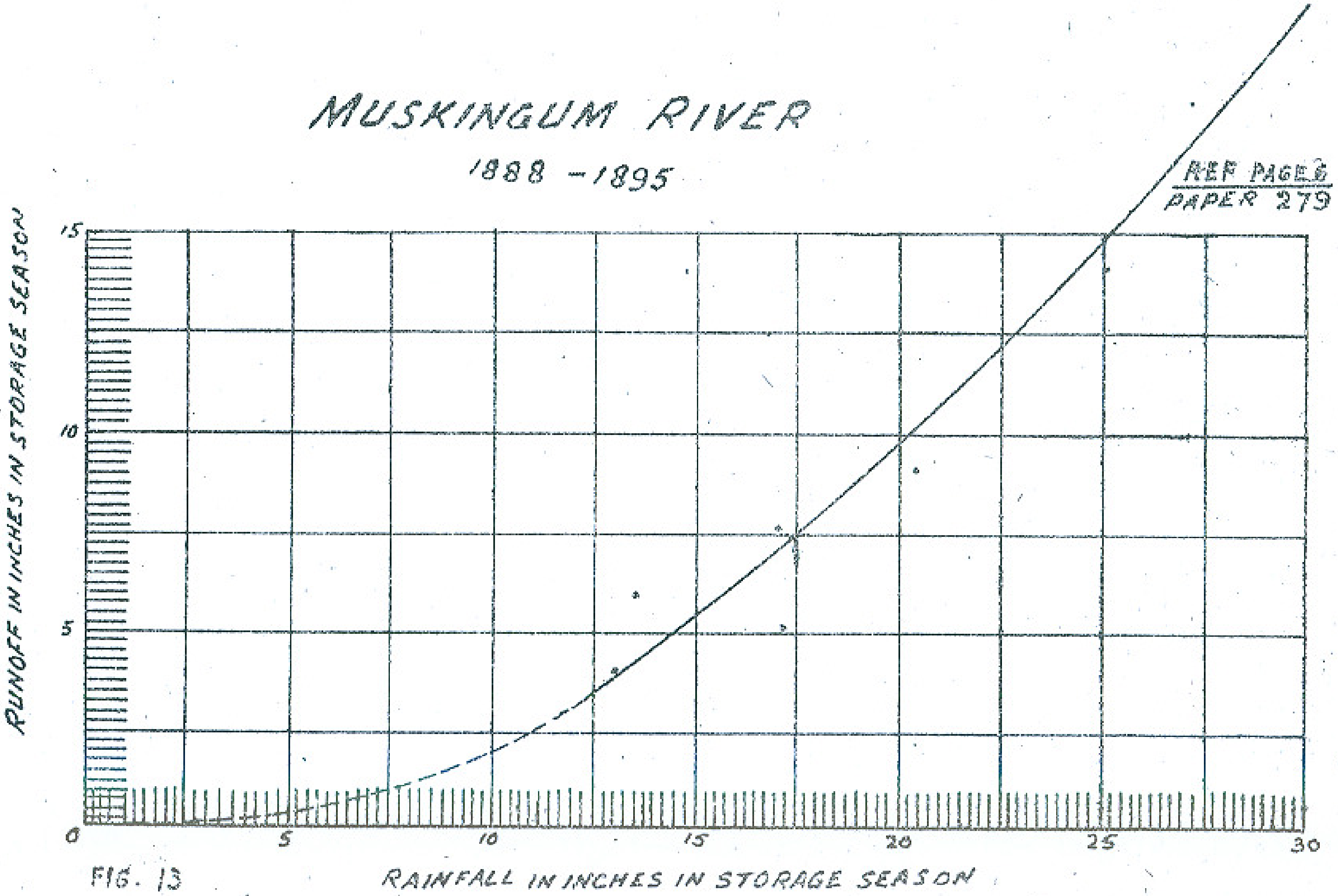



FIG. 13

# CROTON RIVER

1868 – 1899

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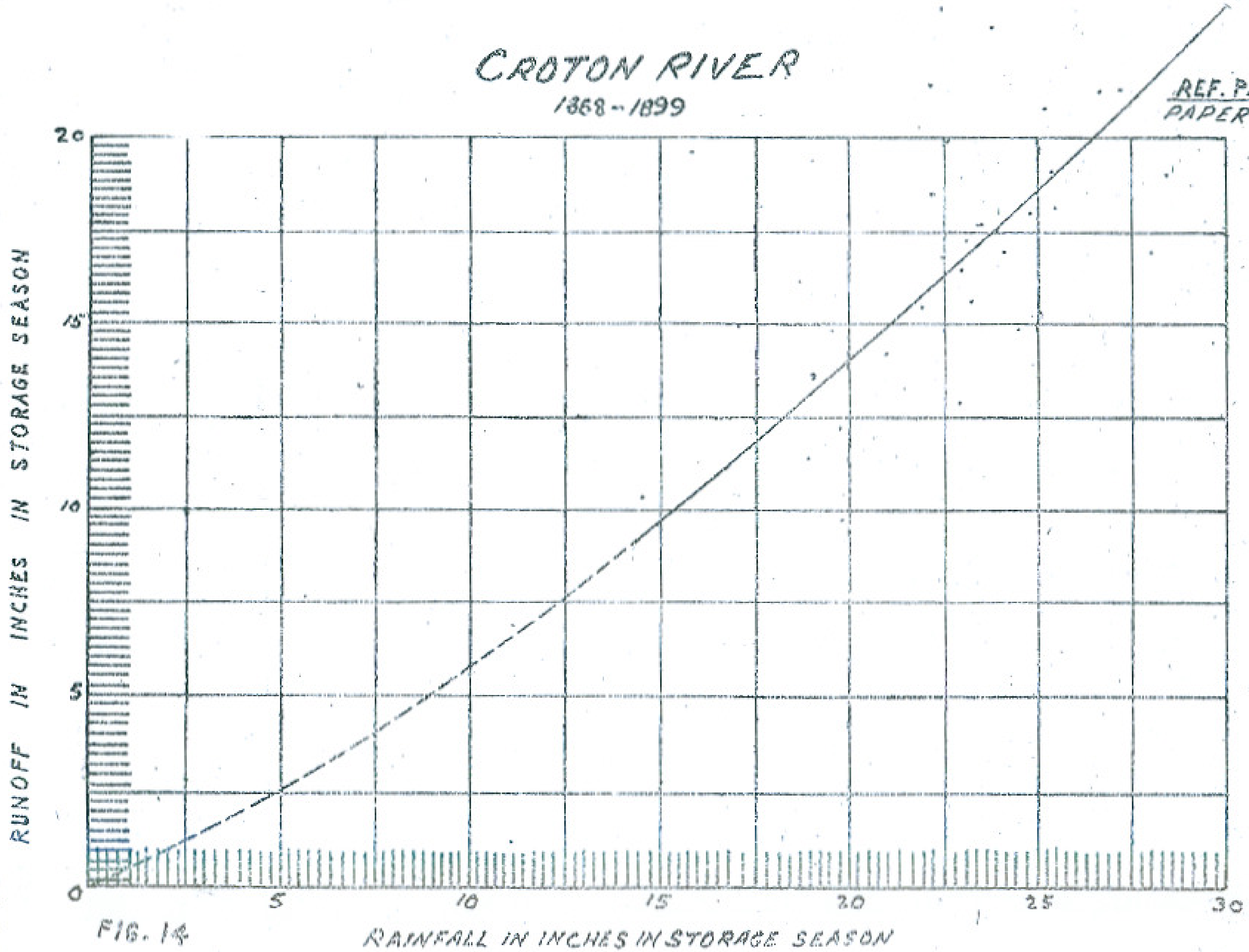


FIG. 14

# UPPER HUDSON RIVER

1888 – 1901

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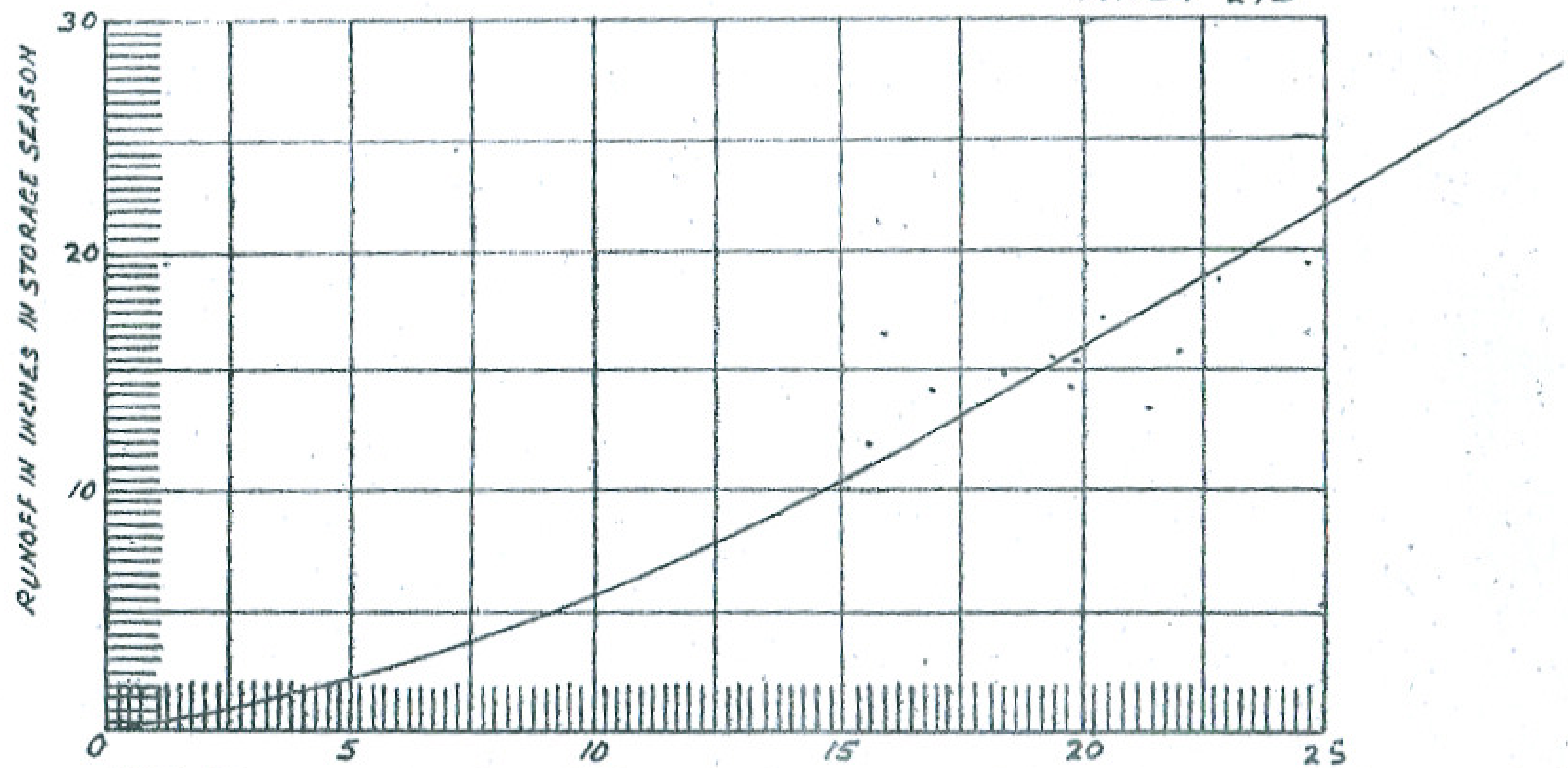


FIG. 15