PAPER NO. 245

RAINFALL RUNOFF

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CHAPTER I

INTRODUCTORY

1. Importance of the Problem

The problem of Rainfall Runoff is of interest to more than one branch of the engineering profession. For every storage scheme, whether for water supply, or for hydro-electric generation, or for irrigation, it is most important to know the quantity of water that can be had, the time at, and the manner in which, the same is available. To the town engineer, it is important to be able to know how much storm water his sewers will have to carry and what will be the intensity and duration of floods. To the railway and irrigation engineers the problem has always been of importance for the determination of waterways for drainage crossings to be provided under railways and irrigation channels.

As early as 1885, when the Lower Chenab Canal was under construction, this problem was studied with a view to find the capacity for which inlets into the canal and syphons under it should be designed. As a result of the observations then made, it was decided* to construct syphons and inlets capable of passing discharges equivalent to 31 cusecs† per square mile of catchment area. Discharges of this order were actually attained on these works on more than one occasion; but there has been for some time now a distinct tendency towards a fall in the intensity of floods reaching these sites.

In recent years a very large number of storm-water drains have been constructed in the Punjab, most of which had their designed capacities fixed in an arbitrary fashion. It is high time that the problem is studied in all its different aspects to arrive at some definite basis for the future calculation of required capacities of drains.

2. Phenomena of Rainfall Runoff

As rain falls, part of it is held by leaves and foliage of trees and crops. The rest falls on to the surface of earth and may be called

*Revised Chenab Canal Project—1888.

†Based on a maximum rainfall of 7-inches in 24 hours and half of it to be drained off in three days.

ground rainfall. If the ground is dry and parched, a light shower would be entirely spent up in saturating the thin crust of the earth's surface. Any water surplus to it would begin to collect and flow over the ground. From this flow there is a continuous absorption into the soil. The equation of runoff in volumetric units may thus be written as:

Runoff = ground rainfall—absorption and evaporation.

This runoff first goes to fill in small and large cavities and irregularities in the surface of the earth; and, when all such depressions fill up and start to overflow, active runoff begins. It is this active runoff which it is desired to determine.

3. Scope of the Paper

In this paper the problem of rainfall runoff is first treated in a general way. A study is made of the various factors that have a bearing on the subject. A method is then described of determining the runoff that is obtained from a particular rainstorm. Subsequent discussion is confined to the problem of determining runoff that should be expected from cultivated and barren lands in flat catchment areas as exist in the Punjab plains and to the fixing of capacities of drains in such areas.

4. Acknowledgments

All sources of information have been acknowledged in the text. A complete bibliography is given at the end. The authors are particularly indebted to Mr. E. S. Crump, C.I.E., for his valuable and exhaustive criticism on the rough draft of this paper, which has enabled the authors to considerably improve upon it.

5. Notations

The various symbols used in the paper are:

A	.. Effective area of catchment in square miles.
a	.. Area of strip in square miles.
n	.. Number of strips into which area A is subdivided. $A = n \cdot a$
L	.. Distance in feet of water shed from the drain along the line of flow.
T	.. Inlet time in hours.
t	.. Time in hours taken by water in travelling from one strip to another. $T = n \cdot t$

$r_1, r_2 \ldots . r_s$	.. Rainfall in inches during successive time intervals.
R_s	.. Total rainfall in inches to end of storm.
R_1, R_2, R_3	.. Total rainfall in inches to end of time intervals t, 2t, 3t........
st	.. Duration of storm.
D	.. Absorption including evaporation in inches of depth per hour.
V	.. Average velocity of runoff in feet per second over the catchment.
S	.. Average slope of the catchment.
Q	.. Maximum discharge in cusecs.
q_1, q_2, q_3	.. Discharge in cusecs reaching the Drain in time intervals t, 2t, 3t......
Z	.. Mean height of the hydrograph for a rainfall of maximum intensity.
δ	.. Average depth of sheet flow in feet.
F	.. Reduction in inches due to rain initially held by trees, crops and undergrowth.
m	.. Index of dispersion.
A_o	.. That area in square miles 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.
Q_o	.. Discharge from area A_o.

CHAPTER II

RAINFALL

1. Causes of Rainfall

Rain is condensed moisture in the atmosphere falling on the surface of the earth after becoming too heavy for the atmosphere to support. Various causes operate in the production of rainfall. The major portion of the precipitation is, however, caused by the expansive cooling of air as it ascends.

"As a result of a long study of the rainfall of India (and perhaps no country affords greater advantages for the purpose) I have become convinced that dynamic cooling, if not the sole cause of rain, is at all events the only cause of importance, and that all of the other causes so frequently appealed to in popular literature on the subject, such as intermingling of warm and cold air, contact with cold mountain slopes, etc., are either inoperative or relatively insignificant."*

The ascensional movement of moist air which results in dynamic cooling and consequently in precipitation is brought about in one of the three different ways :†

(*i*) By convective currents (convective rainfall) ;

(*ii*) By hills and mountains (orographic) ; and

(*iii*) By cyclonic circulation (cyclonic).

2. Instruments for the Measurement of Rainfall

There are two kinds of instruments for measuring rainfall. The type most commonly used is Symon's Rain Gauge which can measure only the total rainfall that occurs in a known period. The other is an integrating type which records automatically the total rainfall at any time from the beginning of the storm.

3. Rainfall Records in India

In India the rainfall records are maintained by the Meteorological Department. Observations are made generally at tehsil and district headquarters by means of a Symon's Rain Gauge. The observer seldom lives at the premises and observations are made once in 24 hours at 8 A.M. every morning. Thus the rainfall recorded on any date represents the total rainfall during 24 hours ending 8 A.M. that day. This rainfall may have occurred in one or more sharp showers, or may have fallen steadily for a number of hours during that period.

**Nature*, Vol. XXXIX, page 583—Blanford.

†D. W. Mead, "Hydrology," page 160.

In the Punjab, the Irrigation Department also maintains a number of Rain Gauge Stations which are spaced nearer to each other than those of the Meteorological Department. These Rain Gauges are generally 10 to 15 miles apart, and are located mostly in Rest House compounds, so that no special establishment is necessary to read them. The observations are made once in 24 hours. The time of observations varies at different places but is generally between 6 and 8 A.M. every day.

The records thus available, whether with the Meteorological Department or with the Irrigation Branch, can supply only the total daily rainfall, but give no information of its duration or intensity.

4. General Nature of Rainstorms

Since 1930 an Integrating Rain Gauge has been installed at Lahore. On Plate I are shown the graphs* of eight different storms recorded at the Lahore Meteorological Station from 1930 to 1933. The abscissæ show the time in hours and the ordinate at any instant shows the total rainfall in inches from the beginning of a storm.

It will be seen from the graph of Storm No. 1 that rainfall started at 4-30 in the morning and up to 5·45 the total rainfall was equal to $\frac{1}{10}$th of an inch. Then the intensity increased and by about 9 hours a rainfall of 1.8-inches had been recorded. The graph of Storm No. 2 represents a shower of high and almost uniform intensity. Storm No. 4 is a type in itself. Rain started with a high intensity and maintained this high intensity for about an hour during which period more than two inches of rain was recorded. After that it continued to drizzle and, during the subsequent period of four hours, hardly half an inch was added to the total rainfall. Storm No. 7 is another type. Rain started with more or less a uniform and moderate intensity. In about one-and-a-half hours about $\frac{3}{4}$-inch of rain fell. Subsequent to that, during a period of about five hours, the addition was only about $\frac{1}{3}$rd of an inch.

From the above, it will be seen that the total daily rainfall as recorded by most Indian Stations does not give any idea of how the rain has fallen—whether the total rain fell in one hour or in five. Again, it may happen that rainfall starts half an hour before the scheduled time for reading the gauge and continues until half an hour after this scheduled time. The rain which has actually fallen during a period of one hour will be shown in the records as having fallen during a period of 48 hours.

*Indian Meteorological Department—Self-recording Rain Gauge Charts—Lahore, 1930—34 (not published).

5. Necessity for Measuring the Intensity and Duration of Rainfall

A little consideration will show that a mere record of total daily rainfall without a knowledge of duration and time cannot be of much use in the determination of probable runoff. A total daily rainfall of, say, two inches may have fallen in 12 hours, in which case the entire rain would have soaked into the ground. On the other hand the same rain of two inches may have fallen in two hours, when a part of the rain must have produced surface flow over the catchment. When dealing with very large catchment areas and for storms lasting two to three days, some use may be made of these records in the way shown in the author's previous paper* on this subject. But for small catchment areas and for short drains, the record of total daily rainfall alone is not of much use.

Information regarding the intensity and duration of storms can easily be obtained from Integrating Rain Gauges but there are very few gauges of this type installed in India. In the Punjab perhaps the only Integrating Rain Gauge installed is at Lahore which is working since 1930. Until such time that more of these Integrating Rain Gauges are installed in India and records are collected for a large number of years, no progress can be made on proper lines. For the time being, one can only resort to indirect methods for obtaining the probable form of rainfall curves.

6. Shape of Rainfall Curve of Maximum Intensity

Some observations are available of the intensities of rainfall observed for different periods of time in the area served by the Lower Jhelum Canal. These observations have been plotted on Plate II and a curve has been drawn connecting the highest intensities observed for different intervals of time. Similar curves could be drawn for other localities where such information has been collected, but a comparison of the graph on Plate II with similar graphs obtained for other countries shows that there is little likelihood of such graphs showing any marked variation in the various districts of the Punjab.

From the maximum intensities obtained from the graph on Plate II, a summation curve or a graph of rainfall of maximum intensity has been drawn on Plate III. The ordinates of this graph for any time represent the total rainfall up to that time. Such a graph would be recorded by an Integrating Rain Gauge, if rain fell with the maximum possible intensity for a period of 24 hours. A little consideration will show that all rainfall curves for any total rainfall will generally fall below the graph of the most intense rainfall shown on Plate III. In other words, the graph on Plate III is an enveloping curve for rainfall graphs of all storms that are likely to occur in this area.

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*Punjab Engineering Congress Proceedings, 1935, Paper No. 178, Sillanwali Drain.

The graph of the heaviest storm obtained by the Integrating Rain Gauge at Lahore, Storm No. 4 of Plate I, has been superimposed on Plate III. It will be seen that it very well conforms with the graph obtained analytically for the most intense rainfall.

7. Variation in the Intensity and Distribution of Rainfall

Anyone acquainted with the monsoon rainfall in India can very readily appreciate the variation in the intensity of rainfall from place to place. While one portion of a village may receive a good shower, the other end might have remained quite dry. It is proposed to examine below how far the records obtained from Rain Gauge Stations as existing at present represent the actual rainfall that occurs over a defined area.

On July 16, 1914,* a storm chanced to centre over the U. S. Weather Bureau Station at Cambridge, Ohio. In 90 minutes a rainfall of over 7-inches was recorded by the observer. Soon after the storm was over, the County Surveyor traced its outline upon the topographical map. In drawing the map (Fig. 1) it was assumed that the outline traced represented a rainfall of $\frac{1}{2}$-inch. Lines of equal rainfall—hyetographs—were proportioned between this outline and the station.

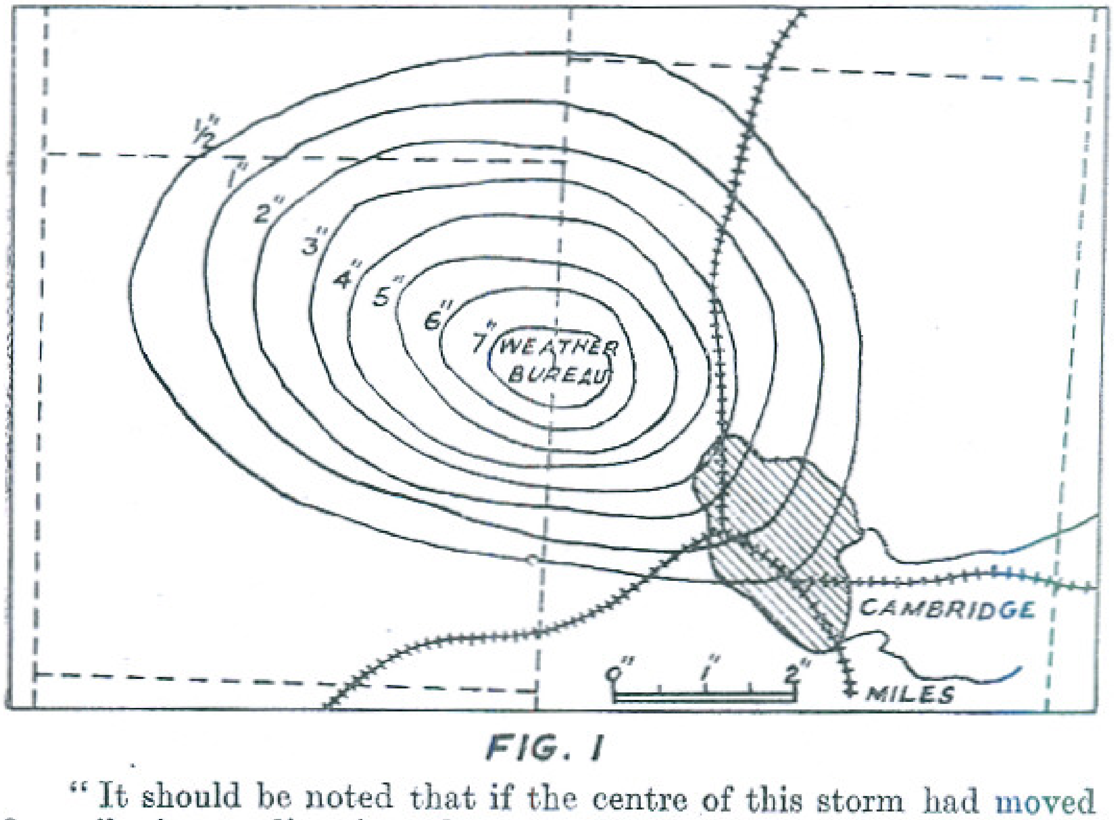

FIG. 1

" It should be noted that if the centre of this storm had moved five miles in any direction, there would have been no adequate record to give any idea of the intensity, and if the centre had moved two

*D. W. Mead, "Hydrology," page 246.

miles, its maximum intensity would not have been recorded within 25 per cent. or more."

The sketch in Fig. 1 is a very good illustration of the variation in the intensity of rainstorms. The fact that a certain rain gauge has recorded two inches of rainfall does not necessarily mean that all the area represented by this station has received a rainfall of that amount.

Even when Rain Gauge Stations have been spaced a short distance apart they have recorded very different rainfalls for the same storm. At Cherapunji there are two Rain Gauges, one at the Police Station and the other at the Welsh Mission Hospital. The following statement* shows some of the rainfall recorded at the two gauges :

Date	Welsh Mission Hospital Gauge	Police Station Gauge
June 30, 1913 ..	22.10	17.61
June 13,1923 ..	30.67	10.85
June 14, 1923 ..	11.76	28.15
July 17, 1926 ..	13.50	10.30
October 8, 1926 ..	19.25	14.60

Consider now a large area (Fig. 2) with Rain Gauges installed at G_1, G_2, G_3 .... G_7.

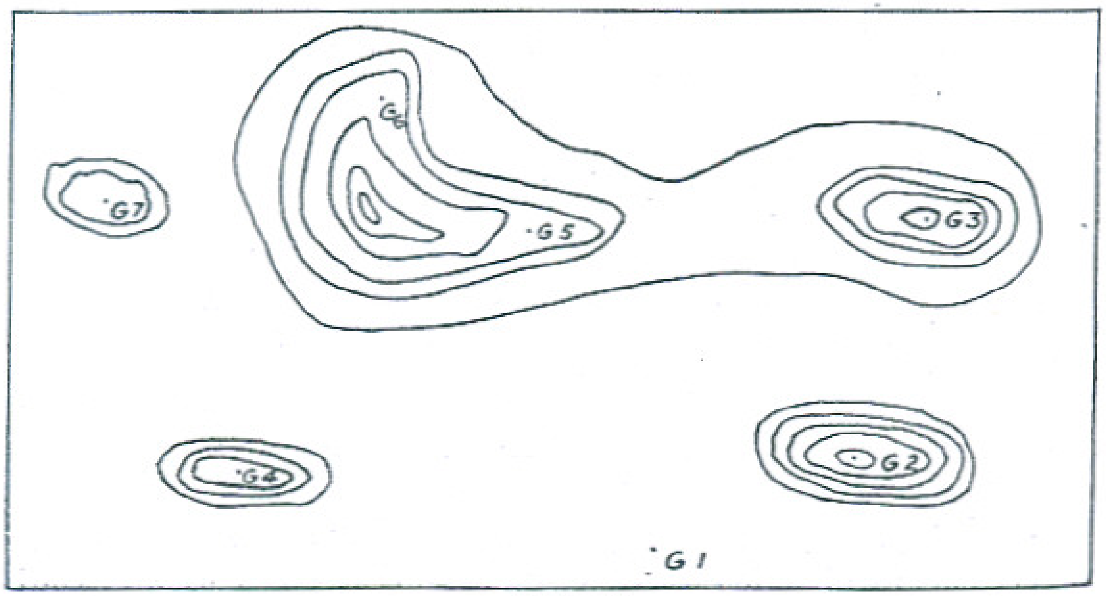

FIG. 2

*Memoirs of the Indian Meteorological Department—Volume XXV, Part III.

If hyetographs for a particular storm were drawn in the way shown in Fig. 1, the resulting sketch would take the form shown in Fig. 2. The following facts seem to emerge :

(1) That the rainfall recorded at any rain gauge is a true index of the intensity of the storm for only a limited area around it and

(2) That there may be areas between neighbouring rain gauge stations that may either receive no rainfall at all, or very much in excess of, or less than that recorded by any of those stations.

Apart from the above, the time at which rain falls at different rain gauge stations may not be the same.

Various investigations* have been made in the U. S. A. and other countries for co-relating the variation in the intensity of rainfall with area, but except for illustrating the great disparity in the phenomenon these have not led to any definite results. The problem is made all the more complicated when the movement of a storm along or across a basin is also to be taken into account.

8. Spacing of Rain Gauge Stations

In view of what has been said above, it is obvious that the closer the rain gauge stations and the more uniform their spacing in a catchment the more accurate will be the estimate of total rainfall over it. In this connection the following quotations are relevant :

" Not a few reservoirs have been constructed which have never filled to more than a fraction of their capacity, and not unfrequently the error has been caused by accepting the rainfall data of one or two stations, as a true gauge of the fall over the entire catchment area of the reservoir. Too much care can hardly be taken to get as many observations as possible in different sites in the catchment area."†

" In the British Isles, waterworks engineers prefer to have one rain gauge to about every 1,000 acres of gathering ground ; but it must be remembered that the rainfall of the British Isles (and more especially that of England), varies from place to place far more rapidly, and more patchily, than is the case in countries possessing topographical features on a larger scale.

" In plains, variation in rainfall from place to place is generally accidental, due to summer thunderstorms of small extent in respect to area," which produce short but heavy and very local falls of rain over comparatively small areas.

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*F. A. Marston—American Society of Civil Engineers—Transactions, Vol. LXXXVII, 1924, page 535.

†R. B. Buckley, C.S.I.—" Irrigation Works of India." 2nd Edition, page 50.

‡Parker—" Control of Water," page 181.

In a note* dated 1906 Mr. Benton, Inspector-General of Irrigation, wrote: "It appears to me that the least number of rainfall stations inside the boundaries of a catchment area which will afford a reasonably safe estimate of the rainfall may be assumed to be as follows:

Area in square miles	*Number of stations*
0 to 50	1
50 to 100	2
100 to 200	3
200 to 350	4
350 to 500	5
500 to 700	6"

The gross area on the Lower Chenab Canal is 5,721 square miles and there are 47 rain gauge stations in it—an average of 122 square miles per rain gauge station. The existing number is very inadequate, particularly when there are a large number of drains with catchment areas of less than 50 square miles.

It is recommended that rain gauge stations in the irrigated areas of the Punjab should be spaced generally not more than seven miles apart in either direction, and that in fixing their sites due regard should be paid to their positions with regard to the catchments of the existing or proposed drains. The number of rain gauge stations in the area of the Lower Chenab Canal on this basis would be 115, and at least 10 per cent. of these should be of the integrating type.

9. Frequency of Heavy Rainfall

It is sometimes necessary to determine the frequency with which a rainfall of, say, 3 inches in 24 hours, would occur. Such information is necessary to determine the volume of runoff for storage schemes.

The Meteorological Department of India has published figures giving the frequency of heavy rainfall in this country. As an illustration the data available for the Gujranwala District are reproduced on the next page from their publication. †

*Report of the Committee on the Probable Effects of the Bhakra Dam Scheme, Appendix 3, page 45.

† "Memoirs of the Indian Meteorological Department," Vol. XXIII, Part VIII—Frequency of Heavy Rainfall in India, page 461.

TABLE I

Station.	Number of years for which record is available	NUMBER OF STORMS WITH TOTAL DAILY RAINFALL FROM—											
		3″ to 4″	4″ to 5″	5″ to 6″	6″ to 7″	7″ to 8″	8″ to 9″	9″ to 10″	10″ to 11″	11″ to 12″	12″ to 13″	13″ to 14″	14″ to 15″
Ramnagar	30	19	5	4	1	1	..	..	..	..	..	..	..
Wazirabad	30	17	7	2	..	..	..	..	..	..	..	..	..
Gujranwala (Sadar Kacheri)	30	14	6	2	2	..	..	..	..	1	..	..	..
Hafizabad	30	7	4	1	3	..	..	..	..	..	..	..	..
Shahjamal	23	7	2	..	..	1	1	..	..	..	..	..	..

The data tabulated above are for only five stations and the observations do not last for more than 30 years. It is realized that the data, as they stand, are not enough to draw any conclusions therefrom. But to overcome this defect for statistical treatment, it is usual to combine the records of several stations. This method is now well recognized and has been used by various eminent Hydraulicians like Mr. W. E. Fuller and A. F. Mayer. In the words of A. J. Schafmayer and B. E. Grant,* this method may be described as follows :

> "If there are 10 stations with a 30 years' record for each station, there are 300 station years. A record that occurs three times in the entire 30 years has a probable frequency of 100 years for any one station, or the chance of such a storm occurring at a given station in any year is 1 in 100. In the same manner, a record that occurs thirty times has an average frequency of 10 years and a record that occurs sixty times has a frequency of five years. If the distribution were uniform and if each station showed that a certain record occurred six times in the 30 years, the five years' frequency would be apparent and the record of one station, in so far as this record was concerned, would be as good as the record of 10 stations, but the distribution is not uniform, and an average frequency is sought. The use of several raingauges distributed throughout the area considered is a reasonable method of accumulating the needed data if the record extends over a considerable number of years."

*Proceedings, American Society of Civil Engineers, Vol. 63, No. 2, February 1937—Rainfall Intensities and Frequencies, page 231.

The following table has been prepared on the basis of the above method from the data in Table I:

TABLE II

Name of Station	Number of years for which record is available	Number of Storms with 24 Hours Intensity more than—					
		3″	4″	5″	6″	7″	8″
Ramnagar ..	30	30	11	6	2	1	..
Wazirabad ..	30	26	9	2	..	..	..
Gujranwala ..	30	25	11	5	3	1	1
Hafizabad ..	30	15	8	4	3	..	..
Shahjamal ..	23	11	4	2	2	2	1
Total ..	143	107	43	19	10	4	2
Frequency once in :—		1.3 years	3.3 years	7.5 years	14.3 years	35.8 years	71.5 years

From the frequencies obtained above, a rainfall frequency curve has been drawn on Plate IV. From this curve it is now easy to find the frequency of storms of any magnitude or the magnitude of a storm for a particular frequency. For the Gujranwala District, it is clear from this curve that a daily rainfall of:

2.5 inches occurs once every year.

3.5 inches occurs once in two years.

3.9 inches occurs once in three years.

4.2 inches occurs once in four years.

7.4 inches occurs once in fifty years.

Curves similar to that on Plate IV can be drawn for any district by the method explained above from the data published by the Meteorological Department of India.

CHAPTER III

OTHER FACTORS THAT INFLUENCE RUNOFF

1. Vegetation

Rain gauges are always installed in the open. However, when actually dealing with runoffs, it is not the rain that falls on the ground in the open that matters, but one should take into account that part of the rain that is initially held by trees, plants and other vegetable cover on the ground. The rain so held may fall to the ground by wind action during or after the currency of a storm, or it may be directly re-evaporated from the surface of leaves, etc. The rain that actually falls on the ground and can produce runoff is thus always less than that recorded by a rain gauge.

No accurate estimates exist of the quantity which should be deducted on the above account. From observations* made in America of rainfall under shelter of trees it was concluded that rainfall reaching the ground was on an average about 70 per cent. of that caught in the open. It has also been estimated† that the wedge-like capillary spaces between grass blades may hold at least ¼-inch depth of water. These figures cannot, of course, be applied in a general way. The amount of water held by foliage, crops and undergrowth will vary with :

(*i*) The intensity of rainfall ;

(*ii*) Wind action during and after the storm ;

(*iii*) Thickness and nature of foliage, kind of crop and nature of undergrowth ; and

(*iv*) Dry or wet state of plants prior to commencement of the rain.

It will be appreciated that the deduction from the total rainfall for the effect of vegetable cover will vary even for the same area from time to time on account of the action of wind. If wind is blowing, there will be hardly any rain held by the foliage of trees and thus the figure of 30 per cent. obtained in certain experiments mentioned above may be too high for many other cases. Until some experiments have been conducted on a large scale, it is difficult to evaluate correctly

*D. W. Mead—" Hydrology," page 147.
†R. E. Horton—" Surface Runoff Phenomena," page 14.

the amount of this deduction. The following figures are proposed to be adopted tentatively:

TABLE III

Serial No.	Kind of catchment	Deduction from total recorded rainfall for amount initially held by vegetable cover
1	For area under trees ..	$\frac{1}{4}$ inch.
2	For area under crops ..	$\frac{3}{8}$ inch.
3	For area with thick undergrowth	$\frac{3}{8}$ inch.
4	For area with light undergrowth	$\frac{1}{4}$ inch.
5	*Banjar* lands with no undergrowth ..	Nil.

2. Absorption Losses

These losses consist of:

(*a*) Evaporation;

(*b*) Transpiration by plants; and

(*c*) Absorption into subsoil.

*Buckley's experiments showed that evaporation losses in India were of the order of $^1/_{100}$-inch per hour.

The total monthly evaporation (average of 16 stations in U. S. A.) observed† during 1887-88 was 5.5 inches during June and 6.7 inches in July. This works to about $^1/_{120}$-inch per hour.

Mr. W. Harrington‡ made an estimate of transpiration losses. At the locality in which the investigation was made, the transpiration was concluded to be 6.5 inches. During the same period the evaporation from free water surface was 8·39 inches. The transpiration was, therefore, 77 per cent. of the open water evaporation in this case, or say, $^1/_{130}$-inch per hour.

*Irrigation Pocket Book of Mr. Buckley.
†D. W. Mead, "Hydrology," page 127.
‡D. W. Mead, "Hydrology," page 147.

Dr. McKenzie Taylor* has estimated the water transpired by *kharif* crops in the Punjab.

TABLE IV

Crops	Water transpired expressed as inches of rainfall or irrigation
Cotton ..	12
Sugarcane ..	38
Rice ..	22
Maize ..	9
Millet ..	8
Fodder ..	14

Assuming an average of 13 inches during the crop, say, six months, the transpiration loss works to $^1/_{330}$-inch per hour.

The loss due to infiltration into the subsoil is the principal loss. The writers referred in paper No. 178 of the Punjab Engineering Congress to the experiments carried out by Kennedy in this connection on forest land. In the introduction of that paper they described some experiments conducted by them on good soil. Since then they have made some further investigations to determine this loss for other kinds of soil. The result of these further experiments is given below :

Kind of Soil	*Kalrathi* Soil		
	Cropped land	Fallow land	Banjar
Area in square feet ..	13,401	10,898	8,093
Date of 1st filling ..	7-7-35	7-7-35	7-7-35
Days of filling ..	*Absorption in inches per hour*		
1st day of filling ..	0·35″	0·47″	0·25″
2nd day of filling ..	0·18″	0·32″	0·22″
3rd day of filling ..	0·14″	0·13″	0·12″
4th day of filling ..	0·07″	0·09″	0·08″
5th day of filling ..	0·07″	0·09″	0·06″
6th day of filling ..	0·06″	0·09″	0·06″
7th day of filling ..	0·06″	..	0·06″
8th day of filling ..	..	..	0·06″
9th day of filling ..	..	..	0·05″
10th day of filling ..	..	..	0·06″

*An investigation of the rise of water table in Upper Chenab Canal Area.

Kind of Soil	HIGH* SPRING LEVEL SOIL		
	Fallow land	Cropped land (Rice)	*Banjar*
Area in square feet ..	10,201	10,428	10,371
Date of 1st filling ..	12-8-35	12-8-35	12-8-35
Days of filling ..	Absorption in inches per hour.		
1st day of filling ..	0·46″	0·07″	0·52″
2nd day of filling ..	0·37″	0·08″	0·39″
3rd day of filling ..	0·27″	0·04″	0·31″
4th day of filling ..	0·19″	0·04″	0·23″
5th day of filling ..	0·16″	0·04″	0·18″
6th day of filling ..	0·16″	0·04″	..

Kind of Soil	SANDY SOIL		
	Fallow land	Cropped land (Cotton)	*Banjar* Land
Area in square feet ..	9,951	10,273	9,116
Date of 1st filling ..	11-10-35	7-10-35	7-10-35
Days of filling ..	*Absorption in inches per hour*		
1st day of filling ..	2·64″	1·15″	2·29″
2nd day of filling ..	1·69″	1·33″	1·88″
3rd day of filling ..	2·03″	1·04″	1·73″

*NOTE.—Spring Level 5.08 feet below ground level.

From the above it is seen that absorption losses vary considerably for different kinds of soil. For paved areas these losses may be considered as nil. It is also clear from the results obtained that in every case the absorption decreases with the duration of flooding, except in one or two cases, where there was either an error in observation, or there were some other causes that the authors are unable to explain. It is considered that if, instead of keeping the plots continuously under water, they were allowed to dry up and the experiment repeated, the absorption losses for a new flooding would be as high as those on the first or second day of flooding, or even higher.

In general the absorption losses depend* on :

(*i*) Temperature changes ;
(*ii*) Packing of the soil surface and in-washing of fine material to pores and openings in the soil surface by rain ;
(*iii*) Soil moisture content ;
(*iv*) Cultivation ;
(*v*) Earthworm and insect perforation of the surface soil and subsoil and perforations left as the result of the decay of plant roots ;
(*vi*) Shrinking and swelling of surface soils which contain colloid material, particularly sun-checking of the soil surface during dry periods.

The experiments carried out by the authors are not considered to be sufficiently comprehensive, and further work in this direction would supply data which has a very important bearing on the problem of runoff. Meanwhile the losses for various soils based on the second day's observations may be taken as shown in Table V.

TABLE V

Kind of soil	Absorption loss in inches per hour		
	Fallow land	Land with crop	Banjar
Good soil ..	0·49	0·50	0·57
Kalrathi soil ..	0·32	0·18	0·22
Sandy soil ..	1·69	1·33	1·88
High spring level ..	0·37	0·08	0·39

*R. E. Horton—" Surface Runoff Phenomena", page 11.

3. Topography of the Catchment

The next factor affecting runoff is the topography of the catchment and under this head the following considerations arise :

(*a*) *Shape of the Catchment and the Distance from the Watershed to the Drain.*—When the width of catchment measured from the drain to the watershed is narrow, the time taken for removal of rainwater is comparatively short and one can expect quicker drainage resulting in higher intensity of runoff than if the catchment had been wider.

(*b*) *The Slope of the Country from the Watershed to the Drain.*—A steep slope has the same effect as a narrow width, *viz.*, water takes a comparatively short time to be drained off.

(*c*) *Natural or Artificial Pondage in the Area.*—The effect of natural storage provided by a catchment is considerable. Apart from big ponds or natural reservoirs, the effect of each of which must be considered separately, all surfaces, even the paved ones in urban areas, contain depressions which must fill up and overflow before active runoff can begin. These depressions are of all kinds and their size may vary from infinitesimally small cavities to large flats covering many acres. In addition to the above, on sodded areas water is held in wedge-like capillary spaces between grass blades. Mr. R. E. Horton estimates* that this alone may amount to at least quarter-inch depth. He also estimates that the combined initial detention due to the above and to the effect of plant cover described in paragraph 1 supra ranges from $\frac{1}{8}$th to $\frac{3}{4}$th of an inch for flat areas and $\frac{1}{2}$ inch to $1\frac{1}{2}$ inch for cultivated fields and for natural grass land or forest.

(*d*) *Effect of Cultivation.*—In a cultivated area the field dowels provide immense storage capacity depending on the height and strength of the dowels. It is not perhaps widely known that runoff from cultivated areas is little except in an extraordinary heavy downpour. This view is confirmed by observations made during experiments† on the determination of runoff performed in the Irrigation Research Institute. In an area of 70 acres on the Upper Chenab Canal near Khambranwala no runoff was received from cultivated areas although the rainfall on any one day was as high as 3.6 inches and intensity of rainfall as much as 0.72 inches per hour. In another area near Sialkot the field dowels in the catchment area were not very strong and were not well-maintained. A part of the area was irrigated by well water but a very large part was cultivated *barani*. It was noticed that during rains water broke through the bunds and ran into depressions. In another tract near Sagar on the Lower Chenab Canal out of a total catchment of 160 acres, 100 acres were cultivated and the rest was waste land. Observations showed that there was no runoff from cultivated areas although the rainfall on any one day during the period of observation was 1.38 inches and the intensity as high as 0.9 inch per hour.

*R. E. Horton—" Surface Runnoff Phenomena," page 114.

†Punjab Irrigation Research Institute—Report for the year ending April, 1939, page 118.

CHAPTER IV

THE PROBLEM SIMPLIFIED

1. Necessity of a Simplified Case

To determine the runoff for any storm over a catchment, the factors involved are so varied and interdependent that it is almost impossible to evaluate them. As in other complicated problems, it is proposed to first attempt to solve a simplified case under ideal conditions. A few factors are ignored altogether; the effect of others is considered as applied more uniformly than what occurs in nature; and the effect of the most important of all is considered in as detailed a manner as possible.

Having solved the simplified case, it will be comparatively easy to make due corrections for other factors which were not considered at all, or were considered as acting in a more uniform manner than in actual practice.

2. Assumptions Made

In the solution of the simplified case the following assumptions are made:

(*i*) Area considered is small, such that it can be wholly covered by a storm and the intensity of the storm over it does not vary appreciably;

(*ii*) Absorption losses are considered uniform over the area and constant during the duration of runoff;

(*iii*) Velocity of storm water flowing over the catchment is considered uniform over the whole width throughout the period of runoff. In other words, there is no relative movement in the different parts of the sheet of water over the catchment;

(*iv*) There is no vegetable cover over the catchment;

(*v*) There is no natural or artificial pondage over the area; and

(*vi*) The quantity of water flowing over the catchment during the period of the storm is ignored.

It is also taken for granted that a rainfall graph of the storm is available and that the inlet time of the catchment is known. Rainfall graphs can be obtained by means of an Integrating Rain Gauge installed in the area. The determination of inlet time is described later in this Chapter.

3. Determination of Runoff for a Rainfall of Known Intensity

Let A B (Fig. 3) be the watershed, and D C the drain. Let A B C D be a sub-area of the catchment which has a small length. Let T hours be the time taken by water to travel from watershed A B to the drain C D (inlet time). Now if this sub-area of A square miles be divided, as shown, into n number of equal narrow strips of area a

square miles, and storm water flows with a uniform velocity V, water will take $\frac{T}{n} = t$ hours in travelling from one strip to another.

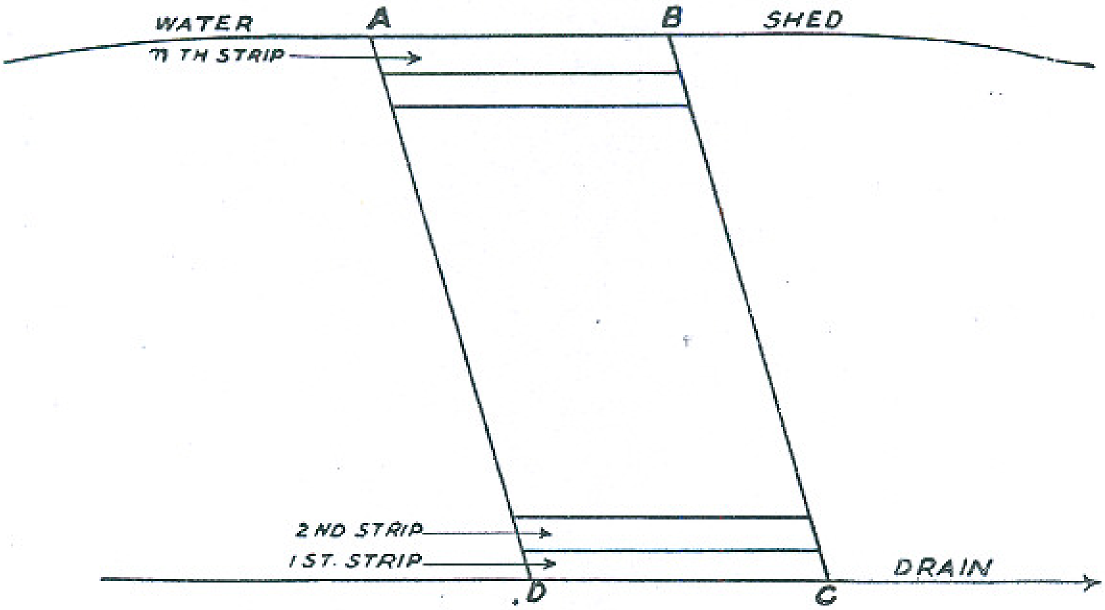


FIG. 3

Let the graph of the storm be as shown in Fig. 4. The abscissæ of the graph represent the time from the beginning of the storm, and the ordinates show the total precipitation of rainfall up to that time.

Draw ordinates R_1, R_2, R_3..................R_s giving the total rainfall up to end of time intervals t, 2t, 3t...........st

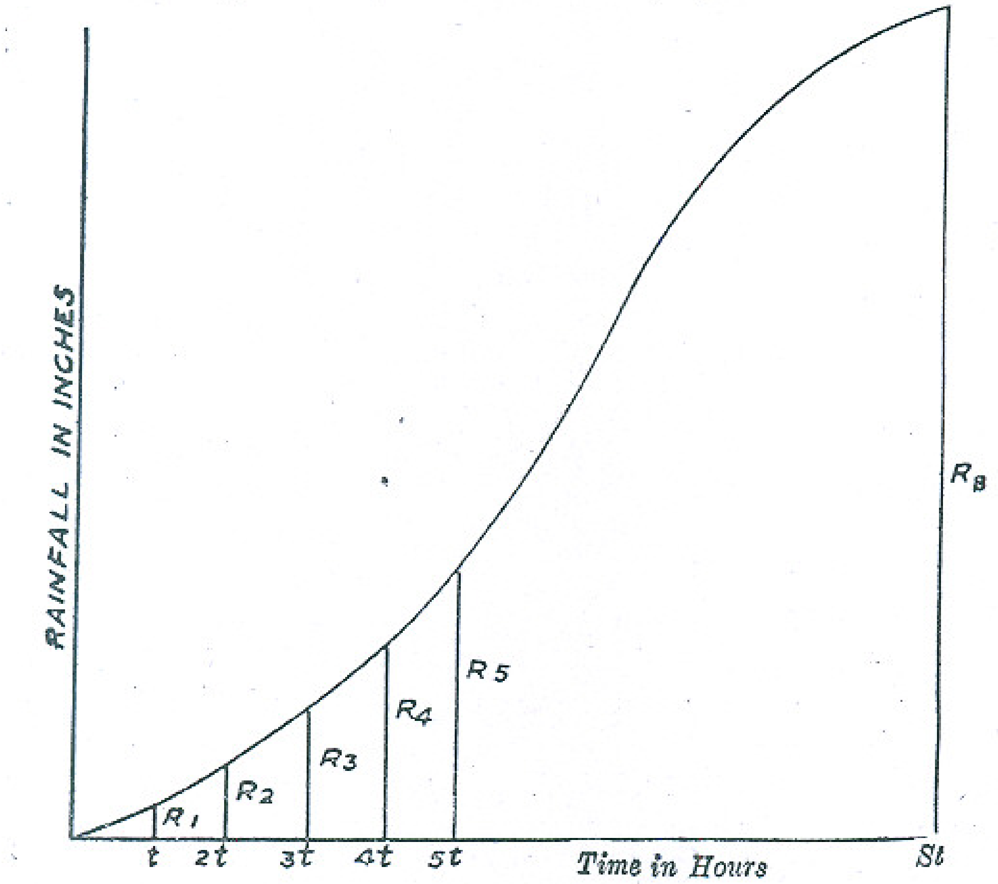


FIG. 4

If r_1, r_2.........be the rainfall in inches during successive time intervals t, then

$$R_1 = r_1$$
$$R_2 = r_1 + r_2$$
$$R_3 = r_1 + r_2 + r_3$$

and so on.

If the absorption into the soil, and evaporation including transpiration losses are considered uniform over the area and constant during the period of runoff, and are equal to D inches per hour, then the loss during time interval t is equal to t D inches of depth.

Assume that :

$$r_1 > t\,D$$
$$r_1 + r_2 > 2\,t\,D$$
$$r_1 + r_2 + r_3 > 3\,t\,D$$

and so on.

This implies that every strip will contribute its runoff from the very beginning of the storm.

Now let the duration of the storm be equal to s time intervals, or st hours, when st may be greater than, equal to or less than the inlet time $n\,t$.

(*a*) *Duration of Storm less than inlet time* ($s<n$).—The discharge q_1 reaching the drain during the first time interval t is only from strip No. 1, water from the second strip does not yet arrive, and

$$q_1 = \frac{a\,(r_1 - tD)}{t} \times 645 \text{ cusecs.*}$$

In this expression the quantity of water held on the surface to give the depth required for flow has been ignored.

In the second time interval both the first and the second strips will be contributing. The runoff from the first and second strips will be due to rainfalls of r_2 and r_1 respectively. Discharge from the second strip reaching the first strip is equal to 645 $\frac{a}{t}(r_1 - t\,D)$.

To this will be added the rainfall at that time on the first strip, and from the total must be deducted the absorption in the first strip. Thus discharge reaching the drain in the second time interval,

$$q_2 = \left(\frac{a\,(r_1 - t\,D)}{t} + \frac{a\,(r_2 - t\,D)}{t} \right) 645$$
$$= \frac{a}{t}\,(r_1 + r_2 - 2\,t\,D)\ 645$$
$$= \frac{a}{-}\,(R_2 - 2\,t\,D)\ 645 \text{ Cusecs.}$$

Similarly, during the third time interval discharge reaching the drain will be :

$$q_3 = \frac{a}{t}\,(R_3 - 3\,t\,D)\ 645 \text{ cusecs.}$$

* One inch of rain in one hour over one square mile is equivalent to 645 cusecs.

And during the *s*th time interval—

$$q_s = \frac{a}{t} \quad (Rs - st\,D) \quad 645 \text{ cusecs.}$$

$$= \frac{n\,a}{n\,t} (Rs - st\,D) \quad 645 \text{ cusecs.}$$

$$= 645 \; \frac{A}{T} \; (Rs - st\,D) \ldots\ldots\ldots\ldots (1).$$

Just after the *s*th time interval, that is, when rainfall has just ceased, the 1st strip adjacent to the drain will cease to contribute. In its place the runoff from the $(s + 1)$th strip will commence to reach the drain. The number of strips contributing will thus still remain the same, viz., *s*. The absorption would, however, occur in $s + 1$ strips, and

$$q_{s+1} = 645 \; \frac{A}{T} \left\{ R_s - (s + 1)\, t\, D \right\} \quad . \; . \; . \; (2)$$

It follows that for finding the maximum discharge, it is not necessary to consider any time interval after the *s*th.

Now refer to Fig. 5 on which the graph in Fig. 4 is reproduced. Draw on it a line O U through the origin such that this line cuts the first ordinate R_1 at a height t D above the X axis, cuts the second ordinate R_2 at a height 2 t D above the X axis, and so on.

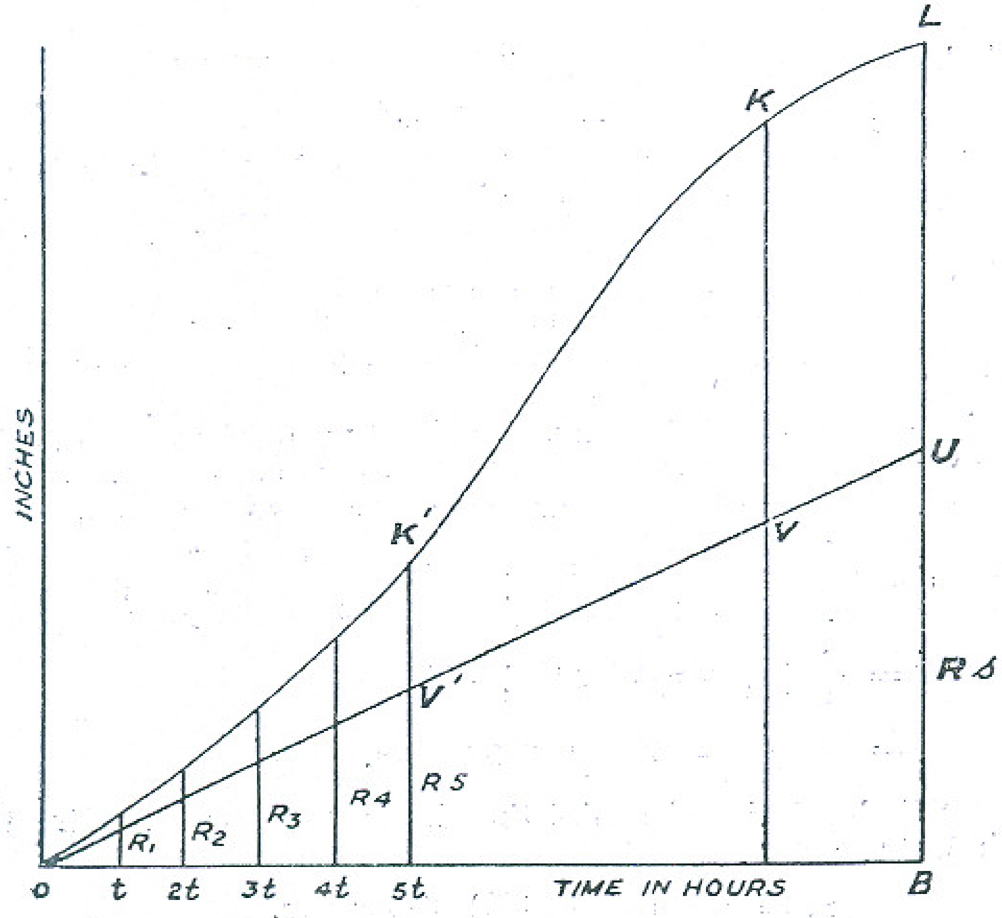


FIG. 5

It will be noticed that the lengths of the ordinates between the graph of the storm and the line OU are equal to $(R_1—t\ D)$, $(R_2—2\ tD)$, ...$(Rs—stD)$..................and thus represent graphically the values of q_1, q_2..........q_s, etc.
Thus

$$q_5 = 645 \frac{A}{T} \overline{K'\ V'} \text{ cusecs}............(3)$$

The longest of these intercepts $\overline{K\ V}$ will give the maximum discharge that reaches the drain at any time due to the storm, and this can be easily scaled off the graph.

To draw the hydrograph of runoff, a little modification and extension of the above graph is necessary. It has been shown above that the intercepts between the line O U and the graph of the storm represent to a definite scale the rates of discharge at each moment. Flow into the drain will, however, not cease with the storm, but will continue for some time after the storm is over. Fig. 6 explains how the rate of flow after the storm has ceased could be determined.

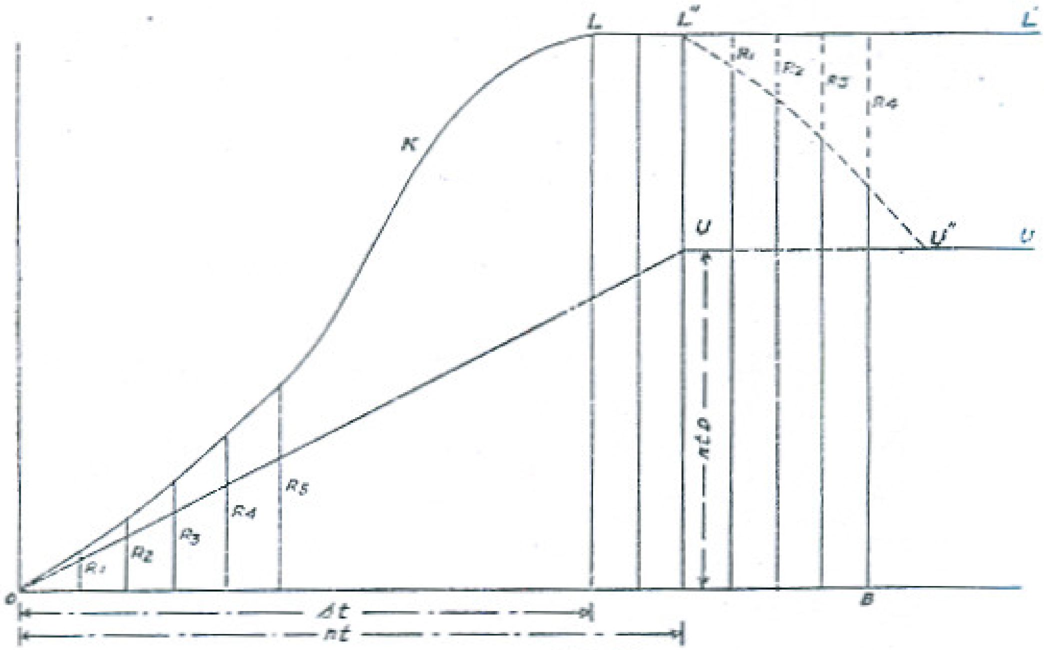


FIG. 6

The intercepts between the lines OKLL"U" and OUU" when plotted on a horizontal base as shown in Fig. 7 give a hydrograph of runoff.

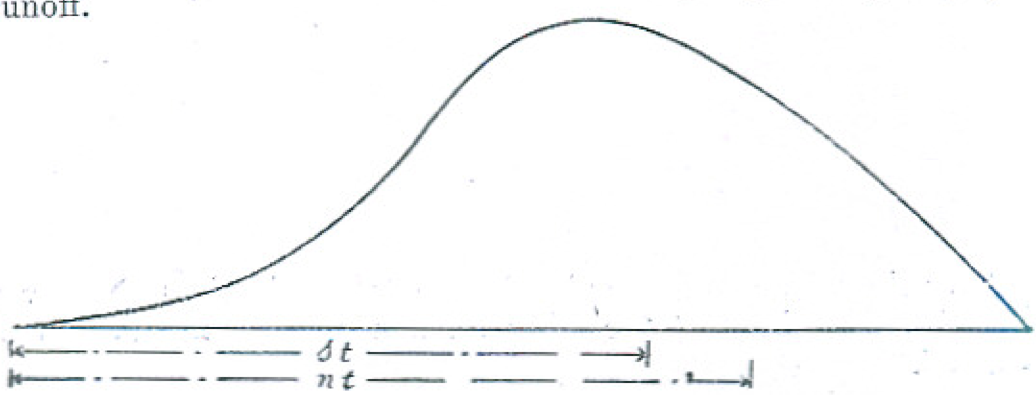


FIG 7

It is clear from equation (1) that to get the discharge in cusecs the ordinates of the hydrograph require to be multiplied with $645 \frac{A}{T}$.

(*b*) *Duration of Storm equal to inlet time* ($s = n$).—If s is equal to n, the hydrograph can be drawn in the same way as when s is less than n.

(*c*) *Duration of storm greater than inlet time* ($s > n$).

If s is greater than n, the diagram will take the form shown in Fig. 8.

The differences are :

(1) That the absorption after time T becomes constant.

(2) In the $(n + 1)$th interval, the discharge reaching the drain will be :

$$q_{n+1} = 645 \frac{A}{T} \left(r_2 + r_3 + \ldots\ldots\ldots r_{n+1}\right) - n\,t\,D$$

$$= 645 \frac{A}{T} \left(R_{n+1} - r_1\right) - n\,t\,D$$

$$= 645 \frac{A}{T} \left(R_{n+1} - R_1\right) - n\,t\,D \text{ cusecs}$$

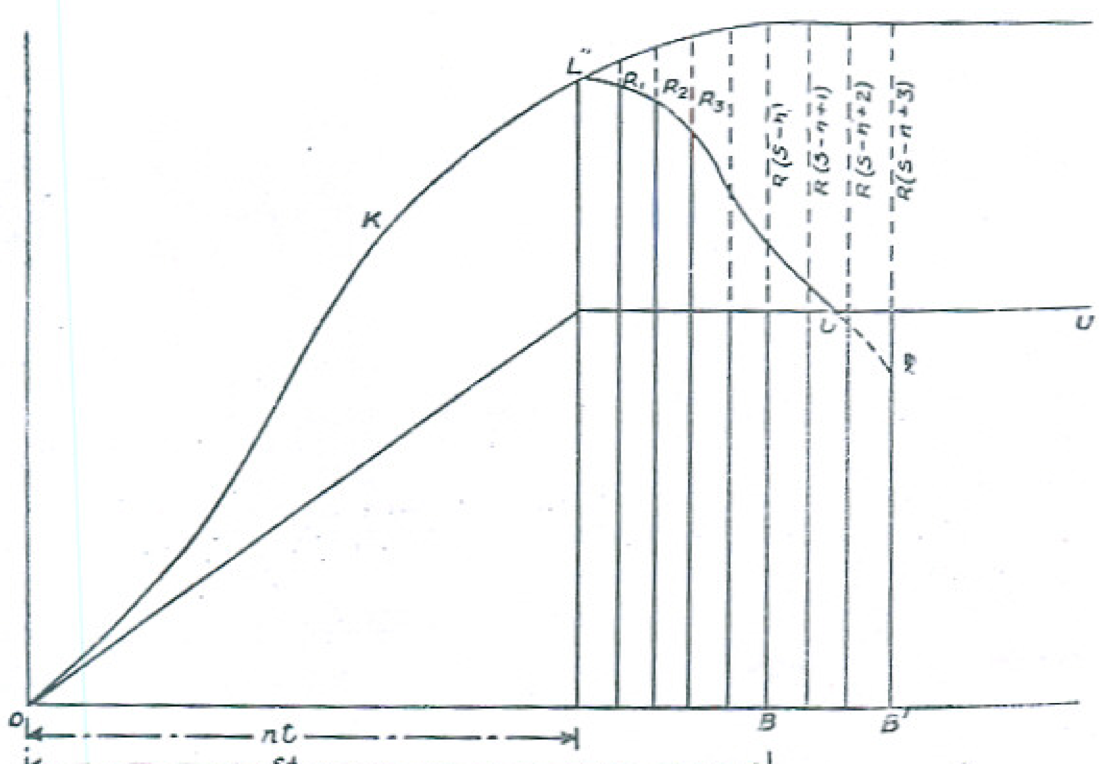


FIG. 8

After time st, the diagram has been extended in the same way as in Fig. 6 and the intercepts should be taken from the modified curve OK L" U".

4. Correction to be made when rainfall over part of the area is totally absorbed

If the condition assumed on page 21 does not hold good, that is, if:

$$r_1 \text{ is not } > tD$$
$$r_1+r_2 \text{ is not } > 2tD$$
$$\text{But } r_1+r_2+r_3 \text{ is } > 3tD$$

the diagram will take the form shown in Fig. 9.

In the first and second time intervals no discharge will reach the drain. During the third time interval the discharge reaching the drain will be due to rainfall r_3 in the first strip. The second and third strips will not be contributing and

$$q_3 = (r_3 - tD)\frac{a}{t}\,645 \text{ cusecs.}$$

$$\text{Now } r_3 - tD = (r_1+r_2+r_3-3tD)-(r_1+r_2-2tD)$$
$$= (R_3-3tD)-(R_2-2tD)$$

$$\therefore \quad q_3 = 645\frac{a}{t}\left\{(R_3-3tD)-(R_2-2tD)\right\} \text{ cusecs.}$$

$$\text{Similarly } q_4 = 645\frac{a}{t}\left\{(R_4-4tD)-(R_2-2tD)\right\} \text{ cusecs.}$$

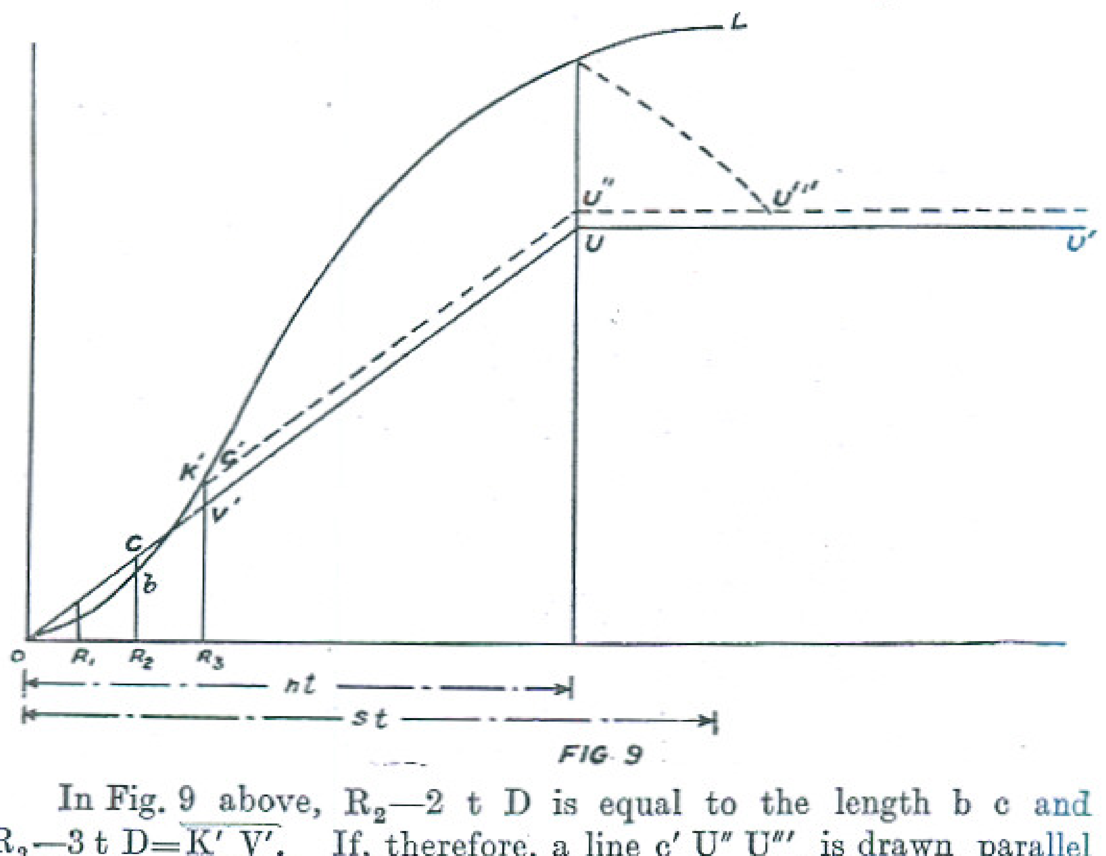


FIG. 9

In Fig. 9 above, R_2-2tD is equal to the length b c and $R_3-3tD=\overline{K'V'}$. If, therefore, a line c′ U″ U‴ is drawn parallel to the line O U U′ at a distance of b c above it, the intercepts between the line c′ U″ U‴ and the graph will represent graphically the rate of discharge to the same scale as before.

The same method would be applicable if water started to flow into the drain at any interval after or before the third.

5. Combination of Hydrographs of Various Sub-areas

Consider now an area shown in Fig. 10 and assume that the length of drain is so small that there is no appreciable decrease in intensity of flood discharge as it travels down.

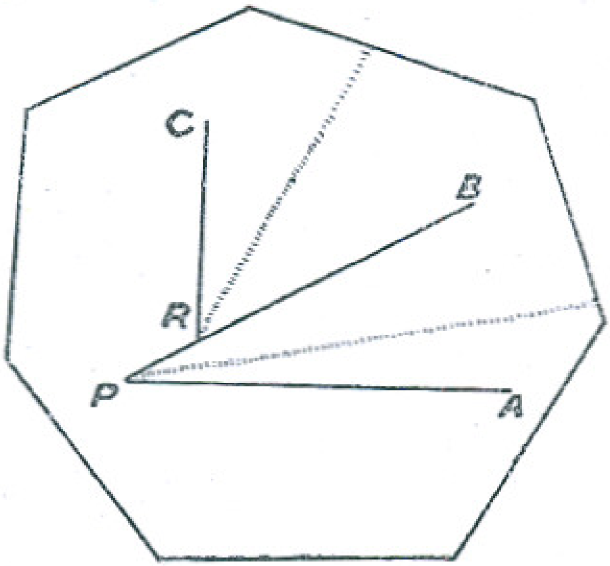


FIG. 10

Divide the entire area into sub-areas. Assuming that rainfall graphs for each of the sub-areas are available, it is possible to draw hydrographs for each of the sub-areas by the method explained on the preceding pages. The resultant hydrograph at the point P will be a combination of the three hydrographs and can be prepared as shown in Fig. 11. The resultant hydrograph is shown as A A_1 C D E.

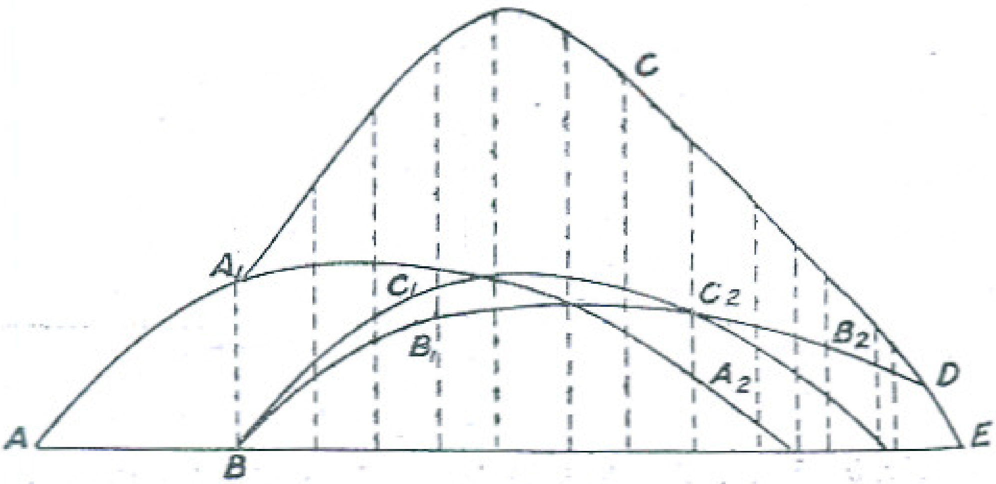


FIG. 11

A A_1 A_2 is the hydrograph for sub-area A, B B_1 B_2 that of sub-area B, and B C_1 C_2 of sub-area C. The distance A B represents the time taken by flood to travel from point R to P.

6. Determination of Inlet time

The inlet time for any drain depends on:

(*a*) The distance of the watershed from the drain;
(*b*) The slope of the catchment towards the drain;
(*c*) The intensity of rainfall and the permeability of the soil;
(*d*) The vegetable cover on the soil and the nature of cultivation; and
(*e*) The natural and artificial pondage on the area.

It will be realized that it is almost impossible to evaluate all these varied factors accurately.

If the entire catchment area is covered by a stcım ar.d if V is the average velocity of runoff, then

$$T \times 60 \times 60 = \frac{L}{V} \quad \ldots\ldots\ldots\ldots(4)$$

Assume now that water is flowing in a thin sheet all along from the watershed to the drain. This flow may be laminar, turbulent or mixed. Mr. R. E. Horton* has given a very interesting discussion of the mathematics of overland flow. It is not proposed to enter into an analysis of his theory which (to the authors)appears only of academic interest. He refers, however, to some experimental determination of the law of sheet flow over soil surfaces made by Messrs. Lewis and E. H. Neal at the Agricultural Experiment Station at Moscow. These experiments were performed in a trough 20 feet long, 1.9 foot wide, and 1.5 foot deep, so arranged that the slope S could be varied. Depths were measured by means of hook gauges and discharges by means of orifice. The experiments comprise of 62 satisfactory observations with slopes varying from 1/2,000 to 1/300 and depths from 0.07 inch to 0.54 inch. These are the only known results on the subject and, until better information is available, may be used. The results obtained can be expressed by the formula—

$$V = 1100\ \delta^{0.9}\ S^{0.7} \quad \ldots\ldots\ldots(5)$$

where δ is the average depth of sheet flow in feet and V the velocity in feet per second.

A little consideration will show that the average value of $\overline{K'V'}$ of equation No. 3 is equal to δ, which can thus be found fom the hydrograph.

We have two equations:

$$T = \frac{L}{3600\ V} \quad \ldots\ldots\ldots\ldots\ldots(i)$$

and

$$V = 1100\ \delta^{0.9} \times S^{0.7} \ldots\ldots(ii)$$

*R. E. Horton—" Surface Runoff Phenomena," page 26.

From these two equations we can determine the value of T. It should be noted that the average velocity used in the above determination of inlet time is the same as assumed in assumption No. (*iii*) of Paragraph 2 supra.

The above is a fairly simple method of determining the value of T, but it assumes sheet flow in the entire width of catchment from watershed to the drain. Those who have ever watched surface flow can appreciate that rain water over a catchment never flows to the main drain like a sheet in its entire length. What happens is that a number of small streams are formed and the sheet flow is restricted to the area between the various small streams. It would therefore be necessary, on this account, to reduce the inlet time as calculated above by an amount depending on the configuration of the country. On the other hand, there may be a large number of obstructions to the flow and the inlet time on this account shall have to be suitably increased. The net result in many cases would probably be that the value of inlet time as calculated on the basis of sheet flow is very nearly the same as the inlet time obtained in actual practice.

It will be seen that the proper determination of inlet time must be guided by the judgment of the engineer. The method described and a study of the various factors enumerated above will help in an accurate judgment.

CHAPTER V

PRACTICAL APPLICATION OF THE SIMPLIFIED CASE

1. Rainfall Intensities to be Catered for

In the last chapter, a method has been described of obtaining under certain simplified conditions a hydrograph of runoff for a storm of which the intensity is known for each moment during its duration. Thus, if the shape of the graph of a typical storm, which occurs in a catchment frequently enough, is available, it would be possible to obtain a hydrograph of runoff for such a storm. It is well known that occasionally the rains are exceptionally heavy. To design drains to deal with such exceptional downpours would be financially impracticable and also undesirable from other points of view. For what discharge and frequency a drain should be designed would depend on the extent of the development of the area to be served by a drainage scheme. The cost of a more expensive scheme has to be justified by the occasional damage likely to occur in case a less costly scheme is carried out.

For drainage projects in the irrigated areas of the Punjab, it is recommended that the capacities of drains should generally be based on intensities of discharges likely to be attained once in three years. The damage likely to occur on account of overflow from or breaches in the banks of drains in cultivated areas cannot be heavy, particularly when peaks are of a short duration. Some of the drains could, with advantage, be designed for discharges having a lower frequency than once in three years.

So far in this country, no graphs of rainfall exist from which it could be possible to work out the intensities and frequencies of rainfall of various degrees and as such some indirect method has to be adopted for the present for determining the probable runoff.

2. Hydrograph for the Severest Storm

The shape of a graph for the heaviest storm that can occur with the maximum possible intensity and duration has already been determined in Paragraph 6 of Chapter II. A hydrograph based on this curve of maximum intensity would give a runoff that would occur in a drain only during exceptional downpours which come rarely, say, once in 50 years. Such a hydrograph, prepared according to the method explained in Chapter IV, is shown on Plate V. OKL is the curve of the severest storm, and OUU′ is the absorption line for an inlet time of T hours. The modified rainfall curve OKL″U″

has been plotted as explained in Paragraph 3 of Chapter IV. T[he] lengths of the ordinates between the lines OKL″U″ and OU[…] have been scaled off, and also plotted on Plate V. This gives th[e] hydrograph of runoff for the severest storm. The runoff in cusec[s] at any time can be obtained by multiplying the length of the ordinat[e] measured in inches by $645\frac{A}{T}$.

3. Intensity of a Normal Flood

To obtain the intensity of runoff which would have a frequency of once in three years the maximum discharge obtained for the most intense storm should be reduced suitably. In rivers, a discharge which has a frequency of once in three years is about ¼th to ⅓rd of the maximum flood discharge ever recorded. The data of flood discharges at Khanki, Marala and Mangla, tabulated in Appendix I, and the flood frequency graphs on Plate VI, fully corroborate this view.

It will be seen that the ratio of the intensity of a flood that occurs on an average of once in three years to that of the highest recorded flood is as follows:

River Jhelum at Mangla	..	22 per cent.
River Chenab at Marala	..	28 per cent.
River Chenab at Khanki	..	37 per cent.

Khanki is comparatively away from the main catchment—the hills—and the results obtained from Marala and Mangla should be adopted for drains. On this analogy, to obtain the intensity of what may be called the normal flood, the maximum discharge determined for the severest storm should be reduced to, say, ¼th.

For design of drains in an open country, it would not cause any appreciable damage if the very maximum discharge obtained for a short period of an hour or so was ignored. It would do to design a drain for the average discharge for the period of flood. Thus, if the average height of the hydrograph during time T is denoted by Z, the discharge for which a drain may be designed is obtained from the equation

$$Q = \tfrac{1}{4} \times 645\frac{A}{T} \times Z = 161\frac{A}{T} \times Z.$$

It would be clear from assumption (*i*) made in Paragraph 2 of Chapter IV that the area A in the above equation is that part of the catchment which contributes to flow in the drain and is so small that every point in it simultaneously receives rainfall of the intensity shown by the graph. For the sake of distinction, let such an area be called A_o, then

$$Q_o = 161\frac{A_o}{T} \times Z \ldots\ldots\ldots (6)$$

4. Corrections for the Assumptions made in the Solution of the Simplified Case

The runoff as determined above is based on the solution of a simplified case described in Chapter IV and it is now necessary to consider what corrections are required on account of the assumptions made not holding in practice. These may now be considered one by one :

(*i*) *Variation in Absorption Losses.*—As already explained in Paragraph 2, Chapter II, absorption losses are not uniform during the entire period of runoff. Further, they vary from place to place in a catchment area. The correction of the hydrograph for the variations in the absorption losses during the period of runoff is a simple affair. In the beginning of a storm, soil is dry and parched and losses due to evaporation and absorption into the soil are comparatively high. As the soil gets saturated, absorption decreases. This decrease in losses due to absorption can be accounted for by a slight modification of the absorption line as shown by the dotted line in Fig. 12.

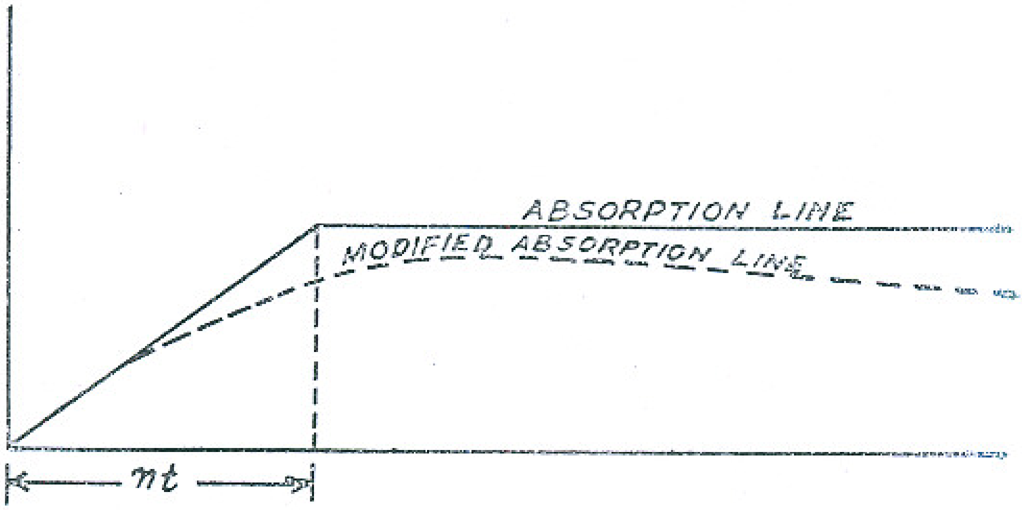


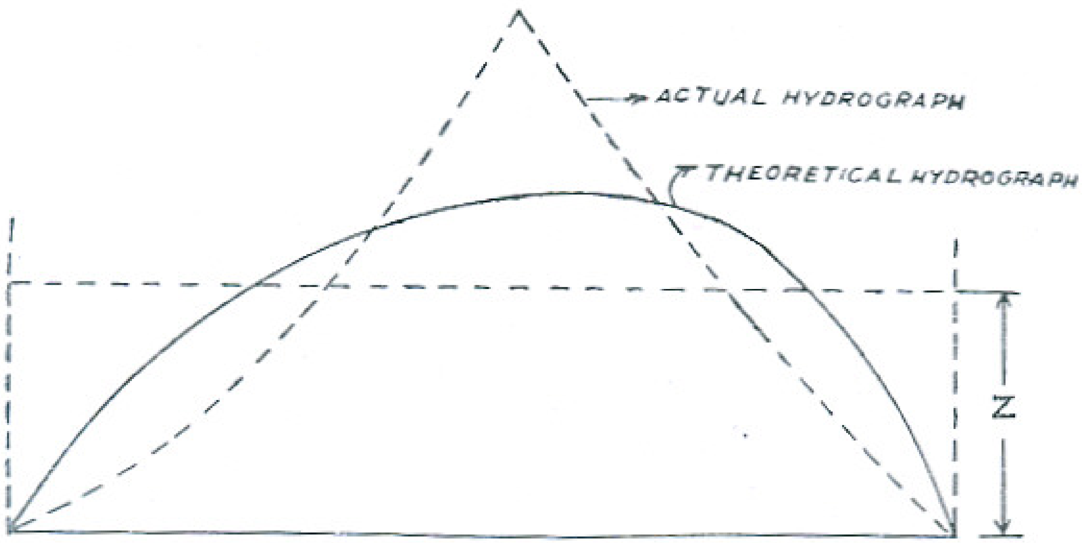
FIG. 12

To account for the difference in the infiltration capacity of different parts of the catchment is not so easy. A good approximation can, however, be obtained by taking the weighted average of the absorption capacity of different parts of the catchment. As an illustration, let 20 per cent. of an area be good soil and 80 per cent. *kalrathi*. Also, let the area of each class under crop be 30 per cent. These figures can accurately be obtained from a survey plan of the catchment. From the results given in Table V, Chapter III, the absorption loss is :

For good soil under crop 6% × 0.5 ..	.03
For good soil under banjar 14% × 0.57 ..	.080
For *kalrathi* soil under crop 24% × .18	.043
For *kalrathi* soil under *banjar* 56% × .22	.123
Total =	.249

Say .25 inch per hour.

(*ii*) *Variation in Velocity.*—The velocity of runoff across a catchment varies for two reasons—space (distance from watershed to drain) and time (duration of runoff). Throughout the period of flow a continuous increase in runoff from the watershed to the drain results in a corresponding increase in velocity towards the drain. Also there is a variation in velocity from nothing to a maximum due to an increase in runoff from zero to the peak and back to nothing when the runoff ceases. On the chart below, an indication is given of the way in which the velocities would vary both across the catchment and during the time of flow. For simplicity, assumed velocities of flow have been shown.



WATERSHED

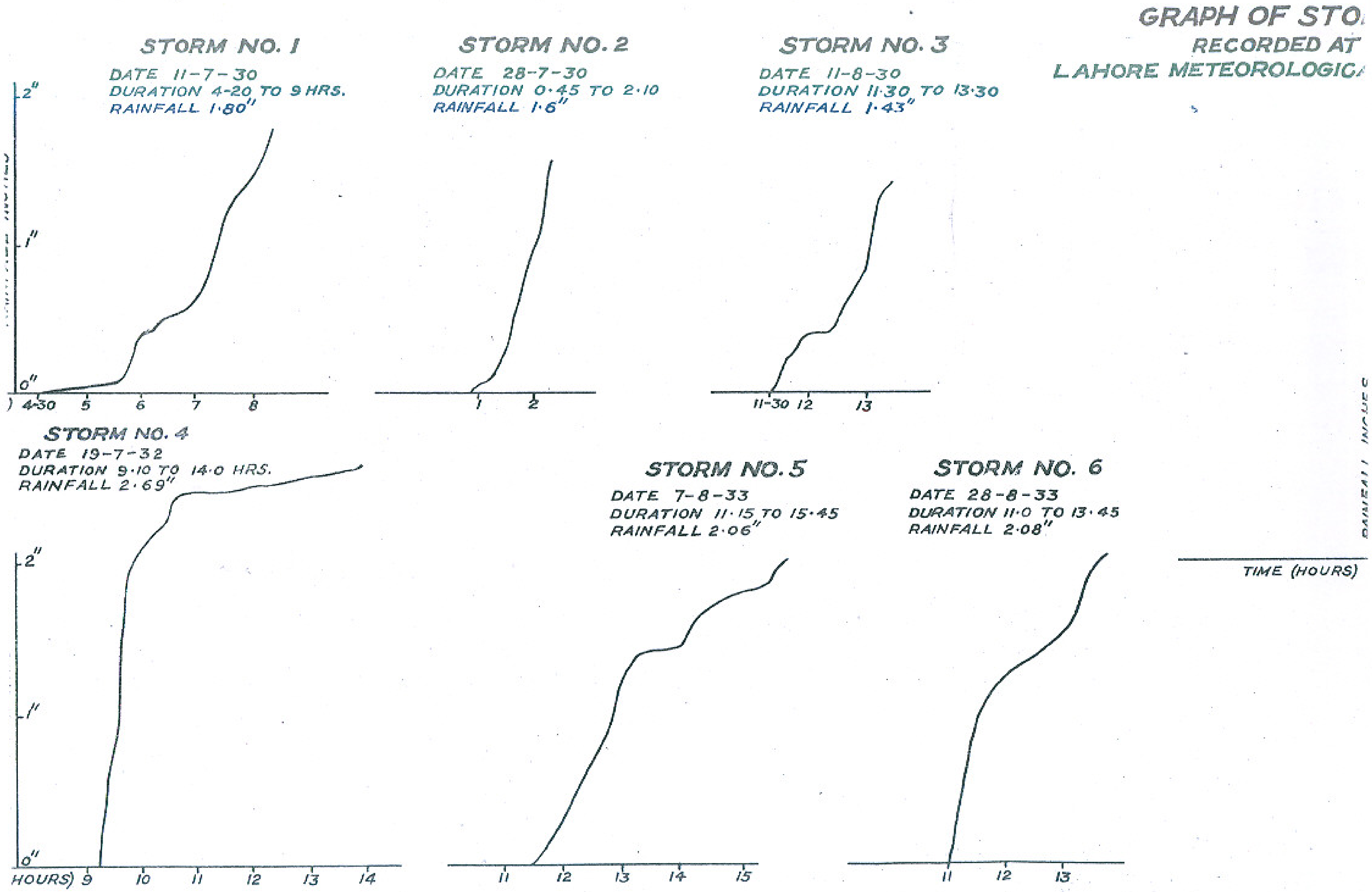
			o	o	o	o	o				
			.4	.5	.6	.5	.4				
		0	.8	1.0	1.0	1.0	.8	0			
		.2	.9	1.2	1.4	1.2	.9	.4			
		.5	1.2	1.5	1.8	1.5	1.2	.6	0		
	0	.8	1.5	1.7	2.2	1.7	1.5	.9	.5	0	
	.2	1.0	2.0	2.5	3.0	2.5	2.0	1.5	1.0	.2	
	.5	1.2	2.5	3.0	3.7	3.0	2.5	1.8	1.2	.4	
	.8	1.5	3.0	3.6	4.5	3.6	3.0	2.2	1.5	.8	
0	1	2	4	5	6	5	4	3	2	1	0

← WIDTH OF CATCHMENT →

DRAIN

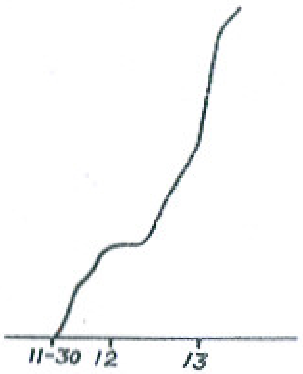
← PERIOD OF FLOW →

Fig. 13

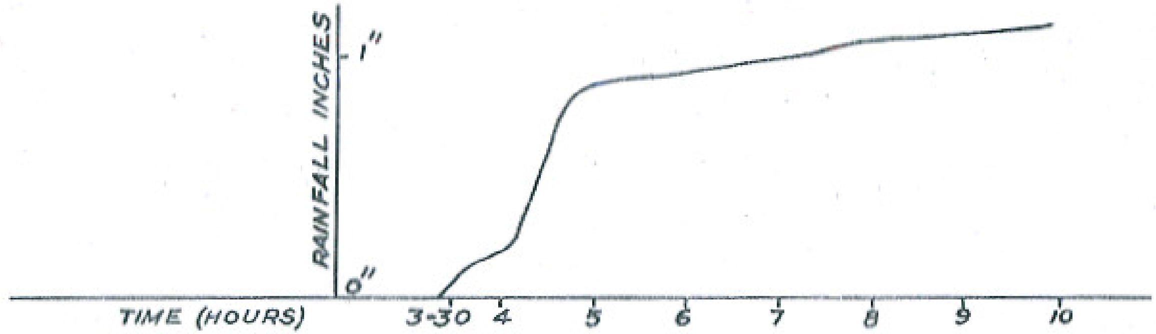

GRAPH OF STO
RECORDED AT
LAHORE METEOROLOGICA
STORM NO. 1
DATE 11-7-30
DURATION 4-20 TO 9 HRS.
RAINFALL 1·80"
STORM NO. 2
DATE 28-7-30
DURATION 0·45 TO 2·10
RAINFALL 1·6"
STORM NO. 3
DATE 11-8-30
DURATION 11·30 TO 13·30
RAINFALL 1·43"
2"
1"
0"
4-30 5 6 7 8
1 2
11-30 12 13
STORM NO. 4
DATE 19-7-32
DURATION 9·10 TO 14·0 HRS.
RAINFALL 2·69"
STORM NO. 5
DATE 7-8-33
DURATION 11·15 TO 15·45
RAINFALL 2·06"
STORM NO. 6
DATE 28-8-33
DURATION 11·0 TO 13·45
RAINFALL 2·08"
TIME (HOURS)
2"
1"
0"
HOURS) 9 10 11 12 13 14
11 12 13 14 15
11 12 13

GRAPH OF STORMS
RECORDED AT
LAHORE METEOROLOGICAL STATION

STORM NO. 3
DATE 11-8-30
DURATION 11·30 TO 13·30
RAINFALL 1·43"

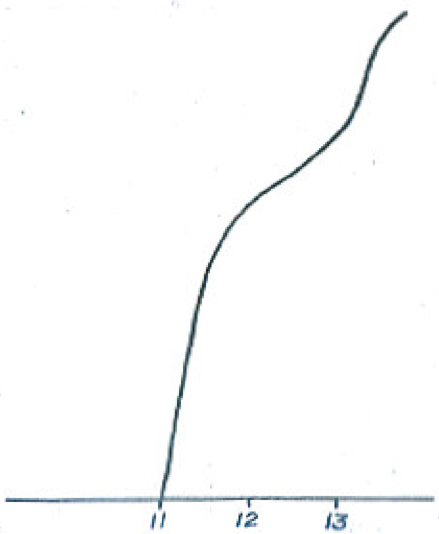


STORM NO. 7
DATE 27-7-33
DURATION 3·25 TO 10·0
RAINFALL 1·12"

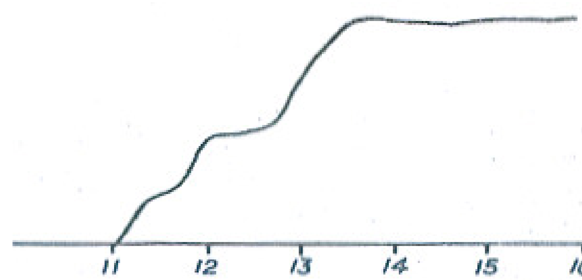


NO. 5
3
15 TO 15·45
6"

STORM NO. 6
DATE 28-8-33
DURATION 11·0 TO 13·45
RAINFALL 2·08"



STORM NO. 8
DATE 22-8-33
DURATION 11·0 TO 16·0 HRS.
RAINFALL 0·95"



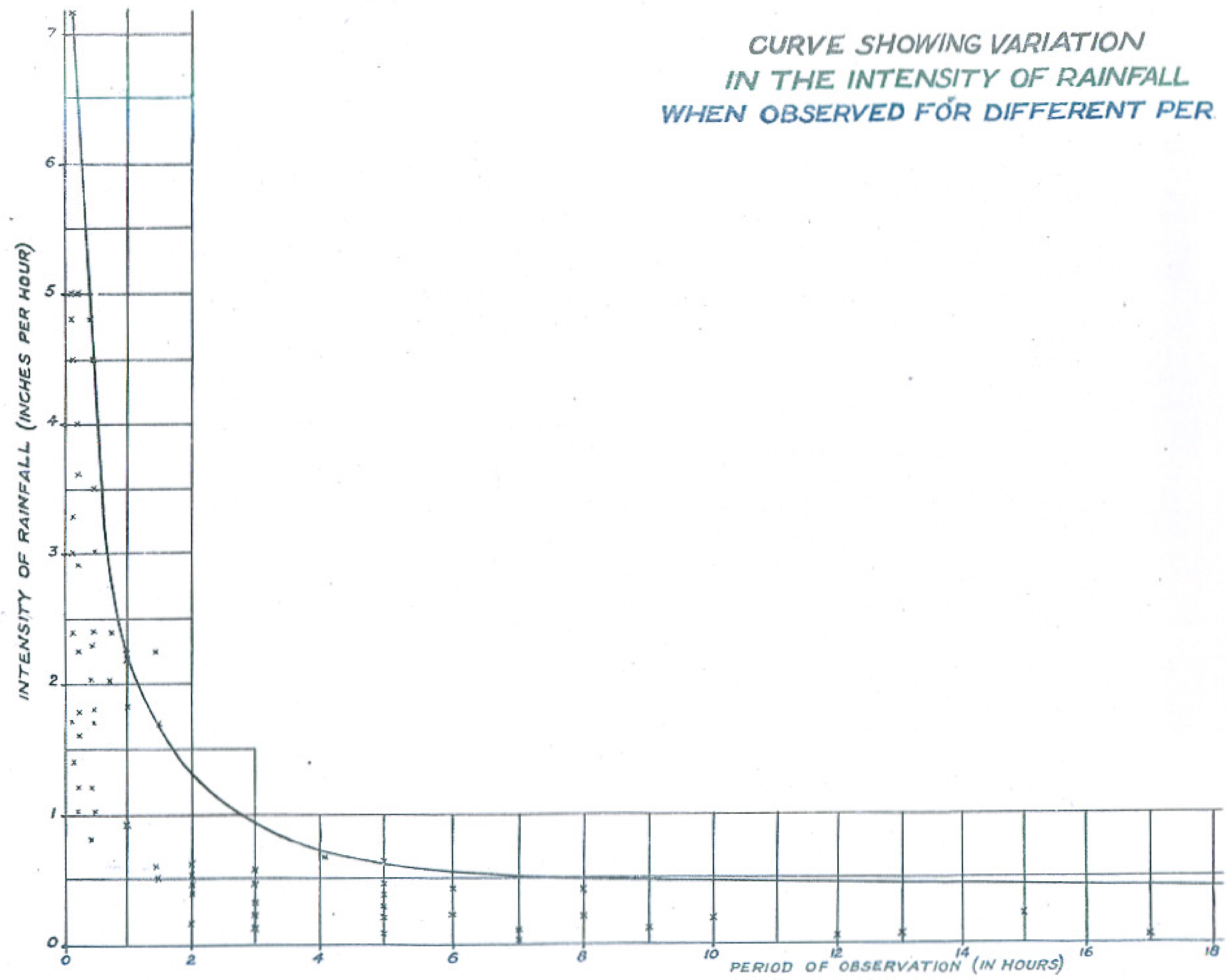
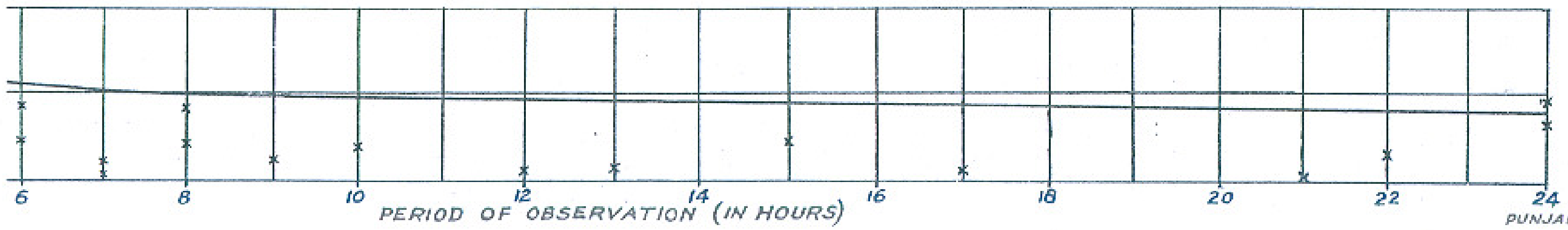
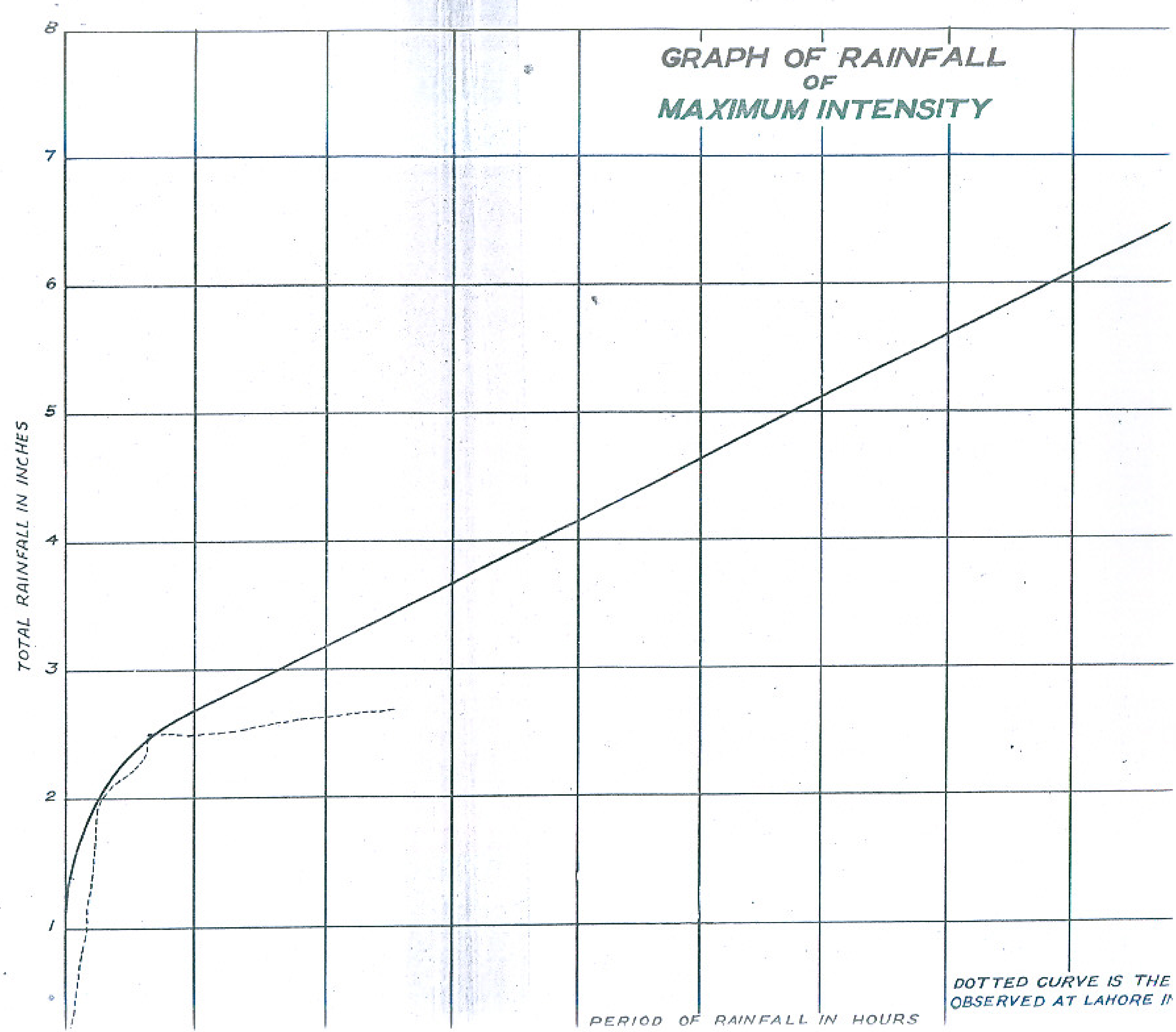

CURVE SHOWING VARIATION
IN THE INTENSITY OF RAINFALL
WHEN OBSERVED FOR DIFFERENT PER
INTENSITY OF RAINFALL (INCHES PER HOUR)
0
1
2
3
4
5
6
7
PERIOD OF OBSERVATION (IN HOURS)
0
2
4
6
8
10
12
14
16
18

PLATE II
PAPER NO. 245

CURVE SHOWING VARIATION IN THE INTENSITY OF RAINFALL WHEN OBSERVED FOR DIFFERENT PERIODS




GRAPH OF RAINFALL
OF
MAXIMUM INTENSITY
TOTAL RAINFALL IN INCHES
1
2
3
4
5
6
7
8
PERIOD OF RAINFALL IN HOURS
DOTTED CURVE IS THE
OBSERVED AT LAHORE I