HYDROLOGY

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Summary

To interpret the language of the Meteorologist and make it applicable to the specific use of the engineers, a new science has grown up, known as Hydrology. This science is the product of the present century called up by the demands of engineers dealing with multi-purpose river projects. When a river project deals with only one object such as irrigation, power or flood control, the problem is simple and can be dealt with easily, but with the combination of two or three of these objects the complexity of the problem increases and it becomes necessary to know not only the intensity and variation of rainfall throughout the seasons but also their correlation with run-off and river discharge.

The incidence and distribution of rainfall over a catchment have been a subject of intensive study with the meteorologist for the last century, while the observations of discharge of river have been of a very recent growth. The technique of these observations is not yet fully developed and has to be crude in many cases due to the difficulties of the terrain. Hydrology has been mostly concerned in recent years in developing in two directions, increasing and improving the technique of its own observation and secondly, correlating its own data with those collected by the meteorologist. This has not always been easy.

The correlation between the rainfall and the run-off, that is river discharge, is clear enough even to a layman. But for engineers charged with the duty of designing structures across such rivers something more definite than the layman's statement is required. Hence we have such empirical formulae as those of Dickens, Ryves and Inglis based on Indian records, of Fanning, Murphy, Cooly, Kuichlug, Brunner and Hermann based on the gauging of American rivers. Considering the very nature of the problem such attempts at generalization are likely to be misleading.

In recent years attempts have been made from the theoretical side to correlate rainfall with run-off. Of these the method of 'Unit Hydrograph', first introduced by Sherman in 1932 and developed by others, has been one of the most successful. Zoch has also tried to work out a syrthesis of Flood Hydrograph mathematically.

Besides these attempts at correlation between rainfall and run-off, the other line along which the activities of Hydrology have been mostly directed has been in tackling the problem of 'Silt Movement' in rivers. The factors that tend to increase the supply of silt and sand in rivers have been studied carefully and attempts are being made to control these. Methods of land management and erosion have also been improved.

The technique of measuring stream flow and silt charge had been crude in the beginning of the present century and demanded considerable improvement. The collection of basic data for the planning, design and operation of multi-purpose dams, is of great importance and requires to be presevered with great efforts and precision.

Contents

Introduction

The previous speaker has discussed the various aspects of rainfall, its incidence, its distribution in area and time and its forecast. He has in fact told us how far the

Science of Meteorology can help the Engineers in designing, constructing and operating a multi-purpose river project. But to interpret the language of the meteorologist and make it applicable to the specific use of the Engineers a new science has grown up known as Hydrology. This Science is the product of the present century called up by the demands of Engineers dealing with multi-purpose river projects. When a river project deals with only one object such as irrigation, power or flood control the problem is simple; but with the combination of 2 or 3 of these objects, the complexity of the problem increased. It became necessary to know not only the run-off discharges, their intensity and variations throughout the seasons but also their correlation with rainfall. The incidence and distribution of rainfall over a catchment has been a subject of intensive study with the Meteorologist for the last half a century while the observations of discharge of rivers have been of very recent growth. The technique of these observations is not yet fully developed and has to be crude in many cases due to the difficulties of the terrain. Hydrology, therefore, has been mostly concerned in recent years in developing in two directions, increasing and improving the technique of its own observation and secondly correlating its own data with those collected by the Meteorologist and gaining thereby from their longer experience and intensive studies. Meteorologists deal with a series of natural phenomenon that are more amenable to scientific treatment while Hydrology is concerned with occurrences that are controlled by natural circumstances whose effects are so varying from place to place and time to time as to be almost unpredictable.

Rainfall add Run-off—Run-off Ratios

To illustrate my point I will cite a few cases of rainfall over the different areas of the Damodar Valley and their effects on the river flow and silt charge during different parts of the year. The complete information has been given in Appendix I. It will be seen from this that the run-off percentage is very small for pre-monsoon precipitation and very considerable for the mid-monsoon precipitation, while for the post-monsoon the run-off percentage is of the medium order. Not only are there seasonal variations from pre-monsoon to mid-monsoon and after monsoon, there are variations from storm to storm. We know if a rain storm is preceded by a few days of light drizzles, the run-off ratio can go up very high, while a dry spell even in mid-monsoon may affect very considerably the run-off ratio for rain storm of the same intensity.

Further the effect of the terrain on the run-off ratios is very pronounced. Even in such a small catchment as that of the Damodar (7,000 square miles) the run-off ratios from the different sub-catchments as those of Usri at Giridih (350 square miles) Konar at Konar Bund (500 square miles), Damodar at Ramgarh (1,250 square miles), Barakar at Barhee (325 square miles) vary very considerably. The difference between the run-off ratios of the river Damodar at Ramgarh where the catchment is yet unoccupied by man and fully wooded, and that of the same river between Ramgarh and Sudamdih an area fully occupied by active coalfields and badly deforested is remarkable. Further the amount of silt charge carried by the river at these two places is also an index of the amount of erosion that is going on in these two catchments. Incidentally these figures of run-off ratios and silt charges should serve as a pointer to us that unless proper precautions are taken the upper valley will very soon degenerate to the same stage as that of the lower valley with the development that is likely to follow the activities of the Damodar Valley Corporation.

In view of the uncertainty and variations met with while determining the values of run-off ratios for different areas and different storms attempts are being made by the Hydrologists of the U.S. Bureau of Reclamation to assess the rates of infiltration and retention in a river valley with the help of a detailed knowledge of the nature of the sub-soil in the area and also with a few infiltration and retention tests in different parts of the valley. These tests coupled with a careful study of the nature of the soil provide them with sufficient information about the base flow and run-off ratios that could be expected in the area.

Run-off and River Discharge

The correlation between the rainfall and the run-off that is river discharge is clear enough even to a layman. It does not require a scientist to say that if there is rainfall in an area, the river gauges will go up. But for engineers charged with the duty of designing structures across such rivers something more definite than the layman's statement is required. Hence we have such empirical formulae as those of Dickens, Ryves and Inglis based on old Indian records, Fanning, Murphy, Cooley, Kuichling, Brummer and Harman based on the gauging of American streams. All these formulae involve only the area of the catchment raised to different powers and the constant is generally given a range within which it is supposed to vary. These formulae are of the type

$$Q = CA^n + B$$

In some other formulae attempts have been made to incorporate other factors such as Rainfall Intensity and river slope and to vary the constant with the extent and nature of the catchment. Less ambitious but more practical engineers have been content with figures of run-off per square mile of catchments confined to certain specific localities, such as Addams Williams or T. A. Curry's figure for Bengal. Similar figures applicable to very localized areas are also often met with in different parts of the world. They serve the local needs. Attempts are very often made to generalize these local formulae and evolve a universal one. Considering the very nature of the problems such attempts are likely to be misleading and are to be deprecated.

In recent years attempts have also been made from the theoretical side to correlate rainfall with run-off. Of these the method of 'Unit Hydrograph' first introduced by Sherman (1932) and developed by others have been most successful. The basic idea of this method is that every river with its catchment area form a unique system for which if a discharge-hydrograph can be worked out for a certain unit precipitation during a certain unit time then it should be possible to calculate the discharge hydrograph for rainstorms of any magnitude within any units of time. This indeed is a powerful weapon and has already proved its worth in many cases. (See Appendix II.)

Zoch (1934, 1936, 1937) has also tried to work out a synthesis of flood hydrograph mathematically. The determination of a mathematical equation to represent observed stream flow hydrograph has been attempted in two ways. One approach is by fitting a mathematical curve to the observed data and the other by explaining the underlying ideas and observational facts from which the complete solution of the stream flow problem can be obtained in the sense of mathematical physics. Complete solution of the general case has not as yet been obtained. (Appendix III.)

Silt—Soil Erosion

A river in spate not only brings down enormous volumes of water, it also transports, in very considerable measures, silt and sand from the upper reaches of the valley. These are the immediate outcome of the deforestation and denudation of the upper area accompanied by heavy soil erosion and gulley formation. In their turn these silt and sand charges deposit in the river bed as the river enters the flat planes and thereby raise its level. A delta is formed, the capacity of the river is reduced, the flood levels are raised and flooding occurs at a much lower stage.

To control this chain of action, it is certainly preferable and more effective to strike at the root of the cause, deforestation and denudation of the upper reaches than to try to stop flooding by erecting embankments and levees along the lower reach where actually the evil effects manifest themselves. A combination of the two methods is very often necessary depending on the nature and extent of the trouble. This aspect of the problem will be dealt with by other speakers. For the 'Hydrologist' it is necessary to stress on the importance of measuring silt and sand charges carried by the river and also to determine how they are affected by weather, terrain and methods of measurement. For the preservation of the useful life of a reservoir, it is very necessary to deal with this charge of silt and sand brought down by a river. There are various devices to do this. Sluice gates are generally provided at different levels on the body of the dam to deal with different grades of silt and sand charges. A more recent method has been that of the use of the 'Density Current'.

Measurement of River Discharge and Silt Charge

The technique of measuring 'Run-off and river discharge' is of very recent origin and is at present far from very accurate. As against river flow measurement river levels had been observed from very olden days. Man in his own safety noted carefully the highest flood levels. Though these gauge readings served very useful purpose in their own way, yet they were not sufficient when rivers had to be controlled or hydraulic structures were to be put up across them. In Italy where rivers had been put to the services of man from very early days, river gauging though in an elementary way had been practised quite extensively. Of late the necessity of accurate river gauging had been felt very acutely in the U.S.A. a land of very fast developing industries. The loss to human life and property that follow in the wake of devastating floods, becoming more and more frequent and intense with the rapid industrialization of the banks of the rivers, has drawn the attention of the Engineers to the necessity and utility of setting up very accurate and elaborate gauging stations all along the river valley. These stations not only read water stages and discharges but also measure silt charge, and temperature. With the possibility of the establishment of various factories and manufacturing concerns on its banks, these stations are now required to assess some chemical characteristics of the river water also. These river gauging stations are now as useful and permanent adjuncts to any river project as the meteorological ones. They should be set up and maintained with the same order of thoroughness and efficiency because the planning, designing and operation of the whole project, nay, its very success depend on the accuracy and sufficiency of the hydrological information supplied by these stations. It is indeed a very short-sighted policy to deal with this fundamental aspect of 'Hydrology' in a stepmotherly way. A well organized Hydrological section should be set up as soon as a River Valley Project is taken up for investigation. Though this section will not bear direct revenue, yet its indirect benefit will exceed many times the direct benefits of any of the operational sections of the Project.

I will now close with the remark that 'Every River is a Law unto itself' and 'Hydrology' which is the Science of River Behaviour will have to study every river individually and intensively before any detailed project on the development of the river and its valley can be drawn up.

References

Sherman, L. K. (1932). Streamflow from rainfall by the Unit Graph Method. *Eng. News Record*, **108**, 501–505.

Zoch, R. T. (1934, 1936, 1937). On relation between rainfall and streamflow. *Monthly Weather Review*, **62**, 315-322; **64**, 105-121; **65**, 135–147.

APPENDIX I

Note on the variability study of the Surface Run-off Ratio for different catchments of Damodar

1. An examination of the variability of the surface run-off ratio with the different stages of the monsoon over the Damodar catchment reveal a generally increasing trend in the 'ratio' from the pre-monsoon to the immediate post-monsoon period, to a certain maximum for the ratio. And perhaps, as we recede further from the immedite post-monsoon stage the ratio falls off gradually to reach a minimum in the period just preceding the next monsoon.

2. Probably this maximum state for the run-off ratio is attained when:—

(i) The steady stage for infiltration is reached. At this stage the rate of infiltration is exactly equal to the rate of the internal drainage, that is, the soil is completely saturated with water; and

(ii) there remains no extra capacity for the catchment area to retain water in storage as surface pondage.

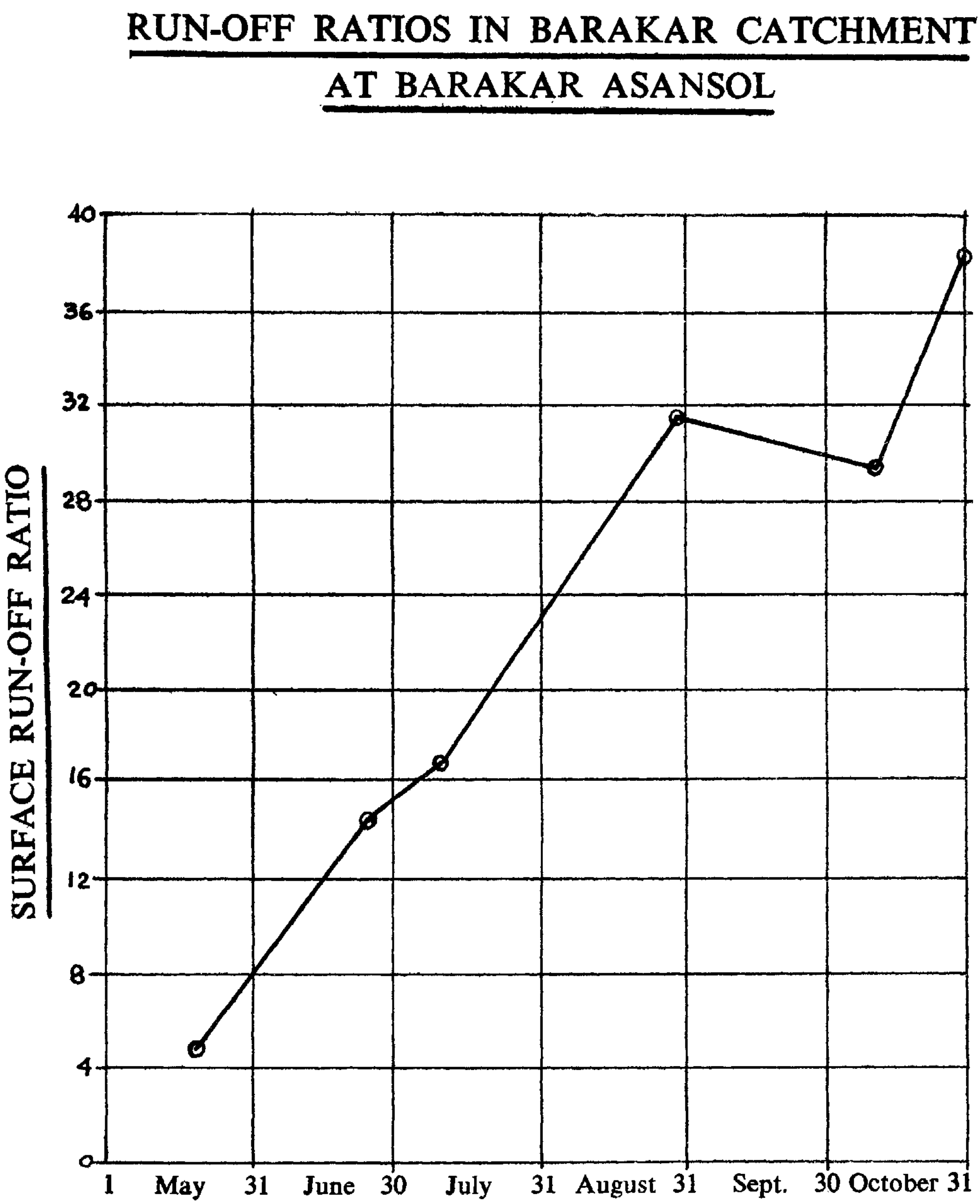
3. The trend is apparent from the graph shown for Barakar (Asansol) in Fig. 1.

4. Besides being subjected to fluctuations of this seasonal type which is mostly due to soil moisture and surface pondage, the ratio is greatly affected by intensity, rate of rainfall and its distribution over the catchment.

It has not been possible to eliminate completely the effect of these latter factors or to isolate the observations of rainfalls on which the run-off ratios are based to the same degree from the effects of preceding rainfall. These have introduced irregularities besides the chance errors to which any observational data is subject.

5. The silt intensities for pre-monsoon period were not obtainable. Those obtained do not show any definite trend in the stage of the monsoon. But for a single rainfall the silt content seems to be higher during early period of the discharge and gradually diminishes.

Observation stations.	Period.	Rainfall date.	Rainfall in inches.	Total volume of run-off in acre-ft.	Total volume of rainfall in acre-ft.	Run-off ratio per cent.	Average silt intensity (parts per thousand of discharge vol.).
Barhi ..	Pre-monsoon	13-3-47	0·78″	..	..	6	
Barakar (Asansol) ..		10-5-46	0·71″	..	..	4·7	..
Ramgarh ..		30-5-47	1·02″	..	..	1·3	0·005
Sudamdih ..		..	..	..	..	..	..
Barhi ..	Mid-monsoon	17-8-47	0·92″	..	..	25·4	0·219
Barakar (Asansol) ..		25-6-47	0·52″	..	..	14·4	..
Do. ..		10-7-47	0·77″	..	..	16·8	1·75
Do. ..		30-7-45	0·46″	..	..	31·6	..
Ramgarh ..		11-9-46	0·94″	..	..	33·3	0·89
Sudamdih ..		11-9-46	0·78″	.	..	51·0	0·53
Do. ..		19-7-46	0·37″	..	..	29·4	..
Barhi ..	Post-monsoon	..	..	..	..	..	..
Barakar (Asansol)		10-10-46	0·8″	..	..	29·2	0·62
Do. ..		15-10-45	0·43″	..	..	38·1	..
Ramgarh ..		1-10-46	0·64″	..	..	44·0	1·28
Do. ..		8-10-46	0·75″	..	..	49·0	0·70
Sudamdih .		19-10-46	1·05″	..	..	47·0	0·97


RUN-OFF RATIOS IN BARAKAR CATCHMENT
AT BARAKAR ASANSOL
SURFACE RUN-OFF RATIO
40
36
32
28
24
20
16
12
8
4
0
1 May 31 June 30 July 31 August 31 Sept. 30 October 31

Appendix II

The Unit Hydrograph as a Tool for Analysis of Surface Run-off

The concept of the unit hydrograph was first introduced by Sherman (1932) and later developed by different authors into a useful and efficient tool for the analysis of surface run-off. The unit hydrograph may be defined as 'the hydrograph resulting from the total run-off of a uniform one inch rainfall over the entire catchment occurring in a single unit of time and isolated either ways with respect to time (that is, neither preceded nor followed by any other rainfall whose run-off might overlap the run-off from this rainfall). Merrill Bernard (1935) modified this as the distribution graph giving the distribution of the total run-off in different units of time given in percentages.

The principle of the unit hydrograph is based on the following assumptions:— (i) that the duration of the run-off from any rainfall over one unit of time would be the same irrespective of the magnitude of the rainfall; (ii) that the time distribution of the run-off would be in the same proportion for every rainfall, that is, the proportion of the contributions of the run-off on the successive units of time would remain the same; and (iii) that these contributions to the run-off from rainfall in different units of time would be summable, that is, should be added together to get the resultant run-off.

A direct advantage of the principle of unit graph is that by a judicious application of it, the run-off hydrograph may be predicted from the rainfall records. The only uncertain factor contributing to the inaccuracy in the application of this principle is the run-off ratio or, which is practically complementary to it, the infiltration index whose determination is difficult and inexact.

For the derivation of the unit hydrograph it is necessary to search the rainfall records for an ideal rainfall, viz. isolated rainfall in a single unit of time, sufficiently high and fairly uniform over the catchment. The derivation is shown in the following table.

(1) Unit of time.	(2) Observed discharge in cusecs. (Q)	(3) Base flow in cusecs. (Q')	(4) Net flow in cusecs. ($Q''=Q-Q'$)	(5) Distribution graph percentage of total run-off. (p)	(6) Ordinates of unit hydrograph in cusecs. (q)
1	Q_1	Q'_1	Q''_1	P_1	q_1
2	Q_2	Q'_2	Q''_2	P_2	q_3
.	.	.	.	.	.
.	.	.	.	.	.
.	.	.	.	.	.
n	Q_n	Q'_n	Q''_n	P_n	q_n
			Q''	100	q

$$P_1 = Q''_1 \frac{100}{Q''}\,; \quad q_1 = \frac{100}{P_1}\, q$$

The base flow in column (3) is the flow as it would have been in the absence of this rainfall, increased by the contribution due to ground water flow. Column (5) gives the percentage distribution of the net run-off of column (4). The total q of column (6) is obtained by working out the rate of discharge if one inch of rain over the entire catchment runs off totally in one unit of time (which would be sum of the ordinates of the unit hydrograph), and then distributing this over different units of time according to the percentage distribution of column (5).

For a rainfall giving a total run-off of x inches the run-off hydrograph is obtained by multiplying the unit hydrograph by x, that is, $(xq_1, xq_2, \ldots\ldots xq_n)$. For rainfall on different days these run-off hydrographs obtained from them would have to be superimposed to give the total run-off hydrograph.

References

Sherman, L. K. (1932). Stream Flow from Rainfall by the Unit Graph Method. *Eng. News Record*, **108**, 501–505.

Bernard, M. M. (1935). An approach to determinate Stream Flow. *Trans. A.S.C.E.*, **100**, 347.

Appendix III

The Mathematical Synthesis of Flood Hydrograph

Determination of mathematical equations to represent observed stream flow hydrograph can be attempted in two ways. One approach is by fitting a mathematical curve to the observed data and the other by explaining the underlying ideas and observational facts from which the complete solution of the stream flow problem can be obtained in the sense of mathematical physics. Complete solution of the general cases have not yet been obtained but the characteristics of some of the simpler cases are explained here.

Of the various factors like rainfall, run-off, discharge, infiltration and the internal drainage which govern the stream flow, dependable and considerable amount of data are available only for rainfall and discharge. Hence the principles have been deduced entirely from the observations of the discharge.

When discharges following rain are plotted against time on a semi-logarithmic paper the shape of the rising position of the hydrograph is not very apparent but in two cases the falling portion of the hydrograph follows a straight line:—

(i) Shortly after the peak discharge following a rain which was sufficiently heavy to cause a relatively large run-off or a light rain coming near the end of a long wet spell;

(ii) After a long dry spell.

In the first case the hydrograph when plotted on an arithmetic paper is asymptotic to a straight line which represents the discharge at the beginning of the rain, in the second case it is asymptotic to the straight line which represents the zero discharge. From this it is found that when the discharge is primarily due to run-off or primarily due to internal drainage, it is a simple exponential function of time for the falling portion of the hydrograph, and so are the corresponding rates of run-off and the internal drainage.

Further analysis of the exponential function of the *rate of run-off* shows that it is proportional to the depth of water remaining with the soil, and this is the basic assumption for solving stream flow problem.

For the simplest stream flow, the drainage area, the rate of rainfall, the duration of rain, the velocity of water and the capacity of the soil are assumed constants for a particular catchment and rain. The distinction between the discharge due to run-off and discharge due to internal drainage is ignored. In such cases the hydrograph for a very small drainage area consist of two parts—a falling part after the rain stops, which is a simple exponential, and a rising part which is complementary to the falling part. For appreciably larger area in this simplest case when the rain lasts longer than the concentration time, the hydrograph generally consists of four sections. For each one of these four sections a distinct mathematical equation is necessary to express the discharge as function of time. The four sections being:—

(i) *A concentration curve*:—The concentration curve extends from the beginning of the rain to the concentration time, that is the time when water from the source first reaches the gauge.

(ii) *A saturation curve*:—This extends from the concentration time till the rain stops. This curve tends to become a straight line as the rate of run-off gradually approaches the rate of rainfall.

(iii) *A transition curve*:—This extends from the end of the rain until a time equalling the sum of the concentration time *plus* the duration of the rain. During this interval the peak of the hydrograph occurs.

(iv) *A depletion curve*:—This extends from the end of the transition interval, until an infinite time later (theoretically). This depletion curve is a simple exponential function.

When the duration of the rain is less than the concentration time, the hydrograph again consists of 4 sections with certain modifications. The concentration time extends only up to the end of the rain, instead of saturation curve we get a curve of slow rise extending from the end of the rain to the concentration time, and range of the transition curve changes. If the duration of the rain is exactly equal to the concentration time then the hydrograph consists of but 3 sections, that is, the saturation curve is altogether absent. In two special cases, the hydrographs even for large catchment area have only two sections: (i) when the duration of the rain is practically very short (theoretically zero), (ii) when a storm moves down the stream with a speed exactly equal to the velocity of water in the stream.

The solutions have been obtained for drainage areas with regular shapes, these can easily be extended to the catchments of irregular shape and the varying rates of rainfall may also be considered to a certain extent. Although, this solution for the stream flow problem for the simplest case is only an approximation to the condition found in nature it is broader than any empirical method and indicates the approach to the general solution.