Mr. Lillie.

Papers, and explained much that it was useful to know in regard to the distribution of rainfall. Dr. Simpson confirmed the contention in both Colonel Hearn's Paper and Mr. Lillie's, that there was no relation between the annual rainfall and the maximum intensity of rainfall in any locality. His suggestions as to the relation between the frequency and the intensity of storms were most interesting, and Mr. Lillie hoped to follow them up some time. He gathered that the suggested equation was $f = K\epsilon^{-\alpha d}$, where f denoted the frequency, d the peak rate of discharge, ϵ the base of Napierian logarithms, and K and α were numerical constants.

Correspondence.

Major Anderson.

Major E. P. **Anderson**, R.E., remarked that four heavy storms had occurred in the Khyber since he took over charge of the construction of the Khyber Railway from Colonel Hearn, namely, on the 20th and 21st May, and the 12th and 19th August, 1923. Details regarding the first two were reported to Colonel Hearn while his Paper was under preparation, but, with three exceptions noted below, they were unimportant compared with the later two, though all showed that actual discharges from catchments of 0·004 to 0·8 square mile in no case exceeded 78 per cent. of the quantities calculated by Colonel Hearn. The maximum intensity of rainfall at Shahgai Camp, the only rain-gauge station anywhere near the area affected, was estimated at 1·25 to 1·75 inch per hour in the first two storms, but on the 12th August it was 2 inches per hour, and on the 19th August a fall at the rate of 2·3 inches per hour was actually measured during a period of 15 minutes. The area of all four storms appeared to have been very small, probably only 1·2 square mile, and it was doubtful whether the rain-gauge had recorded the true maximum intensity in any of them, owing to its being outside the paths of their centres. Reliable measurements of discharge were made at the bridges and culverts indicated in the following Table (p. 364), the data for the calculation of which, by Colonel Hearn's method, were also shown. None of these catchments except that of the Medanak Nulla extended right back to the main range. They were all situated within an area about 3 miles long by 2 miles wide, and their extreme lengths ranged from about 2 miles (Medanak Nulla) to a few chains; the elevation ranged from about 2,000 to 5,000 feet above sea-level. They included bare

Major Anderson.

KHYBER RAILWAY—DISCHARGES THROUGH VARIOUS BRIDGES AND CULVERTS.

Bridge or Culvert.	Area of Catchment.	As Calculated.					Storm of 21st May.		Storm of 12th August.		Storm of 19th August.	
		Shape Factor.	Soil Slope Factor	Combined Factor.	Rainfall.	Discharge.	Actual Discharge.	Proportion of Calculated. Discharge.	Actual Discharge.	Proportion of Calculated Discharge.	Actual Discharge	Proportion of Calculated Discharge.
	Sq. Miles.				Cusecs.	Cusecs.	Cusecs.	Per Cent.	Cusecs.	Per Cent.	Cusecs.	Per Cent.
Rai Killa Nulla .	1·0	1·5	0·5	0·75	2,350	1,897	..	57[1]	..	..	..	51[1]
Bagiari Nulla .	4·9	2·0	0·5	1·0	7,600	7,600	6,912	91	4,150	55	2,216	29
Medanak[2] Nulla (at bridge-site)	2·13	2·0	0·5	1·0	4,430	4,430	3,075	70	1,345	31	640	14
Kafirtangi Nulla	0·802	2·0	0·5	1·0	2,180	2,180	1,150	53	1,010	47	..	..
6-foot culvert at Ch. 38,000 .	0·06	1·5	0·8	1·2	230	276	..	..	..	..	71·4	26

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[1] Velocity of discharge not measured. Cross section as calculated 150 sq. ft. Actual 90 and 80 sq. ft. respectively.

[2] Observations made about ¼ mile downstream from bridge-site.

Major Anderson.

shale and limestone slopes as steep as 1 to 1 near the summit, easing off to about 1 in 12 in the nulla-beds, and were almost devoid of soil or vegetation, except on the lower slopes and shingle beds of the larger nullas, in the latter of which alone absorption of flood-water took place to a considerable extent. The longest time recorded from the commencement of the rain to the arrival of a flood at a bridge was $\frac{3}{4}$ hour, the shortest $\frac{1}{4}$ hour. While time alone would show whether rethese sults really indicated the maximum possible rainfall intensity and discharges for the area concerned, it would appear that under the local conditions described the application of this method of calculation to the design of railway-bridges and culverts for small catchments would give results which could be relied on as likely to be safe under the worst possible conditions.

Mr. Bellasis.

Mr. E. S. BELLASIS remarked that the information afforded by the Papers was valuable, and the new formula proposed by Mr. Lillie would be useful. As regards river discharges, a protest must be entered against the use of old and discarded formulas and the belittling of Kutter's formula. An excellent, and exhaustive discussion of such formulas had recently been given by Mr. I. E. Houk,[1] who concluded that Kutter's formula was the best. The discussion had been summarized by Mr. Bellasis.[2] The "complication" of Kutter's formula meant only that rather extensive Tables had to be used. The resistance met with by the water in any river was not chiefly due to simple friction against the channel: it was greatest with a rough channel, but it was chiefly due to eddying and irregular movements. The Mississippi observations had been duly taken into account by Kutter. The Mississippi formula was not now used. It was still given in one book. Engineers clung in a remarkable manner to obsolete formulas of various kinds, and much waste of money resulted.

Mr. Buyers.

Mr. W. A. BUYERS observed that the records of downpours given by Colonel Hearn were most interesting and informative. Care, however, must be exercised in using such information, as the effective discharge was intimately connected with the physical characteristics of the country. Similarly, if recorded periodic intensities were to be used as a guide to arrive at maximum discharges, it was necessary to know the class of country from which such data had been obtained,

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[1] The Miami Conservancy District. Technical Reports, Part IV. "Calculation of Flow in Open Channels." Dayton, Ohio, 1918.

[2] E. S. Bellasis, "Hydraulics with Working Tables," 3rd ed., p. 192. London, 1920.

Mr. Buyers. and the time-period in which the maximum discharge was effected. It had been proved without doubt that a constant coefficient, such as 825 in Colonel Dickens's formula, was misleading, and that any alternative figure to suit other localities was unreliable. Mr. Buyers had worked out the relative coefficient for seven rivers on the Ondal-Sainthia Chord line of the East Indian Railway, all flowing through somewhat the same class of country relatively; and the variation of the coefficient was nearly 200 per cent. Colonel Hearn's remarks on the relation of rainfall-intensity to area had an important bearing on the subject of discharges. The difficulty was that, although maximum intensities were confined to relatively small areas, data had not been collected in a general way, so far as India was concerned, to give accurate figures for the size of drainage-area for which the railway-engineer had frequently to estimate. He had a recorded discharge, in 1913, of a drainage-area of 14 square miles in the Province of Bengal, which worked out to an estimated discharge of 1·36 inch per hour over the whole area, which was equivalent to 123,555 tons of water in the hour. On checking that drainage-area with Colonel Hearn's proposed formula for maximum discharge, namely, $Q = 640\,A\,(4 - \log_e A)$, the result was within 1 per cent. That drainage-area was what he considered would be described as "balloon-shaped" in Colonel Hearn's Paper. The formula $Q = 640\,A\,(4 - \log_e A)$ was based on the curve plotted in *Fig. 3*, p. 273, the latter being obtained from the figures given in Appendix V. There would, however, appear to be some discrepancy in co-ordinating the figures given, say, for No. 32, Dhok and No. 30, Puran. It would also appear that the results for areas exceeding 15 square miles began to get too low. Although the factors of soil, slope, and protection had a distinct bearing on discharges, he considered the "time" of concentration had just as important a bearing on the problem—particularly for such catchment-areas as discharged within 24 hours. The question of applying such a factor in the equation could only be empirical, and still required much more research and trial to make it of use in a correct form.

Mr. Lillie, in his interesting and instructive Paper, took into account the factor of length in application to his formula, which also had an indirect bearing on the time factor. As Mr. Lillie quite rightly emphasized, what the railway-engineer had to consider in designing bridges was the maximum rate of discharge due to the maximum rate of precipitation of rain and the duration of phenomenal downpours. Here, again, another factor came in which affected the rate of discharge, namely, the balancing effect of low-

Mr. Buyers. lying areas, which were all too common in river-basins after the rivers emerged from the high ground. It was generally conceded that floods arising from phenomenal downpours spilt over their virtual banks, and in a large number of cases poured their spill-water into low-lying parts of the country contiguous to the main stream. In fact, it was known that in many cases a large quantity of water found its way down into entirely separate catchment-areas and never returned to the parent stream. Cases of the latter type had taken place from the Adjai to the Hingulu, above the Ondal-Sainthia Chord Railway in Bengal, and from the Durgauti to the Karamnasa, and vice versa, on the Grand Chord Railway in Bihar; and as recently as August, 1923, the Sone river in Bihar spilt across country for a width of about 10 miles, the spill-water taking a course of its own across country, and emptying into the Ganges. A most interesting example of the former case was the Adjai river, which was crossed at the uppermost site by the Chord line of the East Indian Railway, on a bridge of twenty spans of 42-foot girders, and had a catchment-area of 178 square miles. About 80 miles farther down it was crossed by the Ondal-Sainthia Chord of the East Indian Railway, on a bridge of sixteen spans of 100-foot girders, and had there a catchment-area of 1,350 square miles. Thirty miles farther down it was crossed by the Loop line of the same railway, on thirty-two spans of 50-foot arches, and had a catchment of 1,542 square miles. The fourth crossing of this river, on the Bandel-Azimganj line, was effected 33 miles farther down, close to its junction with the Bhagirathi river, an offshoot of the Ganges. The catchment-area was 1,980 square miles, the railway-bridge having ten spans of 60-foot girders. The four crossings, commencing with the uppermost, thus gave 840, 1,600, 1,600 and 600 linear feet respectively. It would be seen, therefore, that the lowest crossing, with a catchment-area eleven times larger than the uppermost, and 143 miles lower downstream, had actually 240 linear feet less waterway. This was entirely due to the fact that the river, after emerging from the high ground, spilt its flood-water into many low-lying tracts contiguous to the stream, which to all intents and purposes acted as balancing-reservoirs. It was difficult to contemplate any formula in this case which could embrace so many factors of maximum discharge. It would be interesting to know whether the foregoing effect had not something to do with the falling-off in the maximum rate of discharge and sectional area in the Chambal, as depicted in *Figs. 2* of Mr. Lillie's Paper (p. 304). This point raised another question, namely, what was to be the standard value of V for a stream in maximum flood? If a standard area of

Mr Buyers. maximum flood section and a standard mean velocity of the stream in flood were available, what assistance would an actually measured area and an actual value of V' (which, he took it, could be actually measured or estimated) be in solving the equation? It was difficult to believe that, as Mr. Lillie stated, there would not be ordinarily a great variation in V, the standard flood velocity throughout the whole course of a river. If it were desired to discover the maximum discharge due to the maximum rainfall possible on a given area, abnormal conditions would have to be examined; and one of those conditions would certainly be a maximum flood section which would not be contained within the virtual banks of the river. This complicated the working-out of a mean velocity for the whole section, as he had experienced in computing the mean velocities for the rivers discharging across the Ondal-Sainthia Chord line during the record flood in 1913. In all cases the water topped the virtual banks and ran over rough broken ground, rice-fields, through scrub jungle and trees growing down to the banks of the rivers. It was impossible to say how much would be represented by dead water or water moving with greatly reduced velocity. As, however, this was a case when discharges could be determined fairly accurately at the bridge-sites, owing to direct observations of afflux, and from high-flood marks on the banks, the only other factor required was the velocity of approach. When the flood slopes showed no appreciable backing-up of the water in front of the bridges, the head due to the velocity of approach had to be computed. That velocity was calculated by taking the mean of the velocities computed for the full flood section $\frac{1}{2}$ mile upstream, and for the maximum discharge of the river flowing full to the brim. If this velocity was denoted by V, then

$$V_a = V \frac{A}{A_a},$$

where V_a denoted the velocity of approach, V the mean velocity of the main channel $\frac{1}{2}$ mile above the bridge, A the area of highest flood section $\frac{1}{2}$ mile above the bridge, and A_a the area of highest flood section immediately above the bridge. But here again the velocity of approach was not the true mean velocity of the flood sections, as the restriction of the flood-water was very great at the bridge-sites. It was evident, therefore, that in arriving at discharge it was a simpler matter to compute a velocity of a channel section, with water flowing, say, at the level of the top of its banks, than when the stream topped its banks and spread over the country. The following Table showed, for five rivers

Mr. Buyers.

mentioned by Mr. Lillie in the Table on p. 322, the mean rainfall discharge per hour from the catchment with the rivers flowing brimful:—

River.	Area of Catchment.	Nature of Catchment.	Discharge with River Brimful.	Percentage of Maximum Rainfall Discharge.	Additional Discharge Per Square Mile above Virtual Section.
	Sq. Miles.		Inches Per Hour.		Cusecs.
Singaran .	35	Clay, overlying sandstone and coal measures, low banks and spill basin.	0·22	33	277
Tuni Khal .	14	High ground laterite, lower clay and laterite, nodules, little vegetation.	0·90	66	260
Salko . .	37	,,	0·86	60	373
Baklesar .	44	Rugged, impervious and bare except in low-lying ground.	0·97	80	157
Chandur .	22	,,	0·87	80	140

The nature of the catchment had a good deal to do with the quantity of water passed down between the river-banks. Also there was a marked similarity in the quantity of rainfall discharged between the virtual banks of four of the rivers, thus going to show that Nature had worked out a section which was adapted to the normal discharge. As Mr. Lillie rightly remarked, the potential maximum, with the exception of the Salko, the Baklesar, and the Adjai, was somewhat in excess of the figures given in Mr. Buyers's report for the actual maxima experienced. It appeared that a possible way of obtaining a suitable formula for maximum discharge could be arrived at by tabulating data worked out in the following way. The field-work preliminary to arriving at discharges should include a topographical and physical survey of the catchment-area, to the extent necessary to deduce a value for the characteristics tending to increase or retard discharge. In the case of large catchment-areas the use of maps would probably have to supplement the information obtained, owing to the limited time available for making such surveys. A longitudinal section of the stream should be

Mr. Buyers. taken as far as possible, but at least for 1 mile above and below the proposed point. Cross sections at $\frac{1}{2}$-mile intervals should be made above and below the discharge-site at right angles to the general direction of the river, care being taken to locate the section in the position giving the best results to deal with the local conditions. At each cross section should be noted the level of the highest known flood, of the ordinary flood, and of ordinary low water. The velocity of the river running full to the top of its banks, or to the level of the highest known flood, should be worked out by Kutter's or the Mississippi formula, extending the slope of the banks up to that level for the purpose, if the highest flood topped the banks. This would enable the discharge in the channel up to that level to be determined fairly accurately. The mean rainfall run off from the catchment for that discharge could then be found. Next came the question of determining the maximum potential rainfall over the catchment, the percentage discharged, and whether this was equal to or greater than the discharge already determined. Records of such a kind should be available from many sources, and it should not be insuperably difficult to arrive at the maximum potential rainfall over varying areas. The balance of the maximum potential which was effective at the desired point, after deducting that portion which was taken by the virtual section, must have a ratio which was dependent on the general characteristics of each catchment-area. He happened to be in charge of the railway district of Gya during the great storm of the 29th July to the 2nd August, 1917, mentioned by Mr. Glass on p. 340. That district lay on the reverse drainage-shed to the Damodar, and between the latter and the Sone river. As would be seen by Figs. 7–10, Plate 4, the maximum intensities of rainfall were centered just to the west and east of the Sone river in 1913 and 1917 respectively. That was corroborated by the discharges which passed under the railway-bridges, which in the 1913 flood damaged the railway-line between the Sone river and Sasaram and occasioned the provision of 220 linear feet of additional waterway, and in the case of the 1917 flood caused damage along 80 miles of the railway, completely stopping all through running for more than a month. The estimated maximum discharges which were passed by the Phalgu and the Morhar (the latter forming two streams just above the railway) during the 1917 flood were 260,000 cusecs and 189,000 cusecs respectively. The maximum mean rainfall discharged from the Phalgu basin above the railway-line with a catchment-area of 1,286 square miles was 10 inches, against a mean total fall of 17·5 inches; and the Morhar, with a catchment of 800 square miles, discharged 9 inches of mean rainfall, against a mean total fall of 18·8 inches. These two rivers were clearly shown in Figs. 8 and 10, Plate 4, with the centres of maximum rainfall-intensity directly over the two catchment-areas. It was not surprising, therefore, that such extraordinarily high discharges were recorded. These figures of greatest rainfall fitted in fairly well with Mr. Glass's figures in Table IV (p. 344), although Mr. Buyers was inclined to think that the figures in the Table for the 1917 storm were somewhat high. He had recently been engaged on two surveys for railway projects in the basin of the Damodar river. The location necessitated crossing the Damodar twice, once in the upper reaches with a drainage-area of 70 square miles, and 50 miles lower down with a drainage-area of 1,294 square miles. The estimated mean velocities in flood worked out at 13·4 feet per second, and 12·7 feet per second respectively, and the discharges were 64,500 cusecs and 210,200 cusecs. It would be interesting to know what the mean velocity of the river was at the Raniganj gauge for the different discharges. Assuming an average velocity of 10 feet per second from the source to Raniganj, and a length of 200 miles, a downpour over the whole area should reach its maximum peak at Raniganj in about 28½ hours. Mr. Glass might be able to give the maximum recorded 2-day fall on the entire Raniganj catchment, which would be of interest to railway-engineers. Mr. Buyers.

Mr. F. V. Elsden, who had been engaged for 8 years on the construction of various portions of the Upper Jhelum canal, including many of the works for passing across the canal the torrents which formed the basis of Colonel Hearn's investigation, remarked that Colonel Hearn had frankly stated that considerable scepticism existed as to the correctness of the discharges which he had tabulated in Appendixes IV and V; and it would not be out of place to indicate the ground for that scepticism, which related, at any rate so far as Mr. Elsden was concerned, to the actual volumes of flow which were accepted, rather than to their order of magnitude. The latter he considered, on the strength of his experience of these torrents, including a few personal observations of which unfortunately he had not the details at hand, to be, broadly speaking, correct. Before the construction of the cross-drainage works on these torrents, their flood-discharges were for the most part estimated by calculation from such flood-marks as it was possible to observe, though a few isolated observations of a much more reliable character were made by means of surface floats while the water was still flowing. Maximum values for the discharges during this period thus rested for the most part on observations of the crudest description, so that very little reliance could be Mr. Elsden.

Mr Elsden. placed on them. Since the cross-drainage works were constructed, observations had for the most part been made at the culverts or siphons through which the flood-waters passed beneath the canal, the discharges being computed from the recorded readings of gauges located on the upstream and downstream wing walls of the works. At first glance it might seem that results of a very fair degree of accuracy might be obtained in this way; but his experience led him to doubt if they were in reality much superior to the older observations. In the first place, it was a matter of no small difficulty to place the gauges in positions which would give useful results; while the selection of suitable coefficients, and even of satisfactory formulas, from which to calculate the discharges, was difficult. Moreover, only very rarely could it occur that a trained observer chanced to be on the spot at the time of a really large flood, so that, as a general rule, reliance had to be placed on the readings of automatic gauges of a simple type, or on the reports of patrols having little training. Another, and perhaps even more serious, cause of error arose from the fact that all the torrents brought down with them large volumes of silt which, on the falling flood, was deposited in the barrels of many of the culverts or siphons, in some cases to such an extent that a few inches only of the upper part of the waterway remained open. A rising flood would thus often find the barrels seriously reduced in cross section by this deposit of silt, and it was not possible to know how much of the silt had been scoured out, and what was the effective waterway, at the time of the occurrence of the apparent maximum discharge; nor, in such circumstances, was it certain that the apparent maximum as indicated by the gauges occurred at the time of the real maximum discharge; while, even if the apparent maximum was fairly correct, the temporary heading-up which was caused by the silt in the barrels would give a false and exaggerated value to that maximum. During the past 5 years, it was true, some of those siphons which were most liable to silt up had been fitted with sluicing-valves, by means of which much of the silt was scoured out after each flood, so that less error was now likely from that cause; but they were not all so provided, and the accepted maximum discharge even of those which had valves often dated from the period before the valves were put in. It was evident, then, that little reliance could be placed on the accuracy of the recorded maximum discharges, and he considered even their relative values to be untrustworthy, owing to the very diverse hydraulic conditions which prevailed at different siphons or culverts. At the same time, the discharges recorded for these torrents were probably at least as reliable as any others which were on record, Mr. Elsden.

for the difficulty of obtaining anything approaching to accuracy in observations of this character, except by the most elaborate and costly preparations and organization, was stupendous. Colonel Hearn had evidently appreciated the difficulty, for he claimed no exactitude for his figures, nor universality of application for the formula which he propounded; and he was to be congratulated on having made the best use of the rough data obtainable, in bringing together such figures and showing from them the variety of causes which might influence the discharge. Mr. Elsden would hesitate to accept Colonel Hearn's formula or any other as likely to give results of any accuracy, but his formula seemed at any rate to mark an advance in the right direction and to be likely to prove more satisfactory than the forms of guesswork which had been made use of heretofore. With his general conclusions as to the factors which affected the relation between area and discharge there was little ground for disagreement, though he had omitted to consider the factor of direction of travel of the storm. That might be of some importance, for the discharge must evidently vary considerably with the direction of travel of the storm, and it seemed necessary that the orientation of the catchment with reference to the prevailing direction of travel of storms in the district should also be taken into account. Some confirmation of the value of the formula would perhaps be provided by applying it to other flood-observations, and it would be interesting to know whether Colonel Hearn had been able to test it by application to any of the other observations cited in his Paper. Mr. Elsden found the characterization of certain catchments in Appendixes IV and V as "High Concentration" somewhat obscure. For instance, so far as could be judged from Fig. 1, Plate 3,[1] catchment No. 25, Kohar, N, which was placed in this class, would be more appropriately classed as "sausage-shaped," whereby its "shape factor" would become 1·5 instead of 2·5, and its "combined factor" 0·82 instead of 1·37, while the "established rainfall" would become 3·11 inches per hour, a figure which agreed more nearly with the Author's curve than did the tabulated value 2·45.

Mr. Glass.

Mr. E. L. Glass considered it remarkable that, as shown by the examples given by Mr. Lillie, the use of his formula gave such consistent results for rivers differing so much in their natures as the

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[1] In Plate 3, the name Suketar No. 2 is wrongly given to a small torrent, the Channi torrent, situated between the Suketar No. 1 and Suketar No. 2 torrents. What is shown in the Figure as the Bandar Kas is really the Suketar No. 2 torrent, Bandar Kas being its local name.—F. V. E.

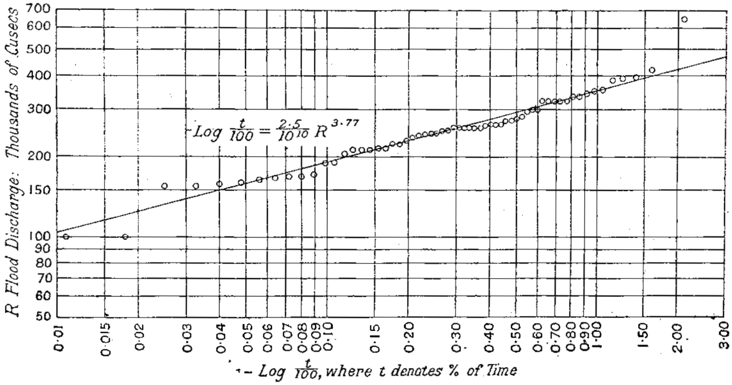
Mr. Glass. Chambal, the Irrawaddy, and the Ganges; and it was these results more than anything else that inspired confidence in the reliability of the formula. It was difficult however to agree with Mr. Lillie's primary assumption that the contribution to the peak rate of discharge from an element of area (*dw*) was inversely proportional to its distance from the discharge-point. Perhaps this was more generally true than not, and hence the very consistent results obtained; but conditions could easily be conceived when the areas nearest the discharge-point contributed least to the peak of the flood, their run-off having passed the discharge-point before the flood crest arrived, while the bulk of the flow at this crest period might be due to a fortuitous concurrence of flood peaks from tributaries situated at the upper end of the catchment. This point of chance coincidence of flood-peaks of distributaries had scarcely been noticed by either Mr. Lillie or Colonel Hearn, and perhaps it was not of much importance in the case of the small catchments to which the latter restricted his considerations; but in the case of a large, flashy torrential river the nature of the reticulation of its distributaries was undoubtedly contributory to the occurrence of its extreme floods. It was conceivable to have two catchments of identical size and shape visited by identical rain-storms, but which owing to differing geological formations and consequent valley and ridge systems, discharged the resultant flood volume past their lowest points with very different peak rates. It was chiefly these peak rates of flow that interested the designer of bridges, but in the design of reservoir spillways it was important to estimate also flood volumes, and especially the periods of high rate of discharge. Hence the value of hydrographs of observed floods such as those given on Fig. 6, Plate 5, and the desirability of observing flood flows in detail where suitable sites were obtainable. Actual velocity-observations were difficult in the case of a large and swiftly-flowing flood, unless a line of floats could be dropped from a bridge or wire ropeway above the discharge-site. An excellent site for such observations was found on the upper Damodar at the gorge just below the B.-N. Railway bridge, and it was to be hoped that the float observations which he had started in 1920 would be continued for an extended period. He could but agree with Colonel Hearn that it was from the comparatively small catchments that phenomenal flood-peaks were to be expected; and as in catchments of such size absorption played a very small part in dealing with really heavy rainfall, it was really the relation between the maximum rate of fall and the maximum rate of discharge that it was necessary to ascertain. Would it not be possible, therefore, to do something towards finding this relation, Mr. Glass.

and perhaps a useful empirical formula, by the use of scale models of catchments having various shapes, sizes, and valley systems? It should be possible to imitate typical rain-storms over the models and, by a sufficiently extended series of experiments, to learn something of the law governing the relation of discharge to rainfall for typical catchments.

Mr. Goodrich.

Mr. R. D. Goodrich remarked that the Paper by Mr. Glass was of considerable interest because of the data presented and the methods used in their analysis. While conditions in the northern States (U.S.A.) and in North China were very different from those of India, the problems requiring solution were often similar in some respects; and proved methods of attack were most helpful. Study of flood conditions in China was greatly handicapped by lack of detailed and reliable data. One problem which had engaged his attention had therefore been to develop the best possible methods of utilizing and extending information collected by the Chihli River Commission. As the 62-year record of floods on the Damodar river at Raniganj afforded an excellent check on Mr. Goodrich's recently developed method of analysis of the frequency of the occurrence of floods, a diagram, with a brief explanation of the conclusions derived from it, was here presented (*Fig. 2*). This diagram was prepared from the data of Fig. 4, Plate 5, in the hope that it might prove of interest, and perhaps be of assistance in some case where such a long record was not available. The data were first arranged in the order of the magnitude of the discharge, beginning with the largest. One hundred per cent. of the time was then divided into sixty-two equal parts, and the percentage of the time

Fig. 2.



Mr. Goodrich. from the beginning to the mid-point of each part was assigned to the corresponding discharge, thus: 650,000 cusecs, 0·81 per cent.; 422,000 cusecs, 2·42 per cent.; 393,000 cusecs, 4·03 per cent., etc. The flood-discharge in thousands of cusecs was then plotted against the colog ($-\log t/100$) of the percentage of time, expressed as a decimal, as shown. A straight line was then drawn so as to average these points as well as possible, and its equation was found to be:

$$-\log(t/100) = \frac{2 \cdot 5}{10^{10}} R^{3 \cdot 77}$$

This equation was in the simplest and limiting form between two more general equations (one with three and the other with four constants) developed to express the laws of variation of hydraulic data (rainfall and discharge) which followed any of the skew frequency laws of the seven equations developed by Professor Karl Pearson, of University College, London, except his two types IV and VII, in which the lower limit of the possible frequency-distribution was minus infinity. A detailed discussion of the derivation and properties of Mr. Goodrich's equations would be out of place in this brief discussion, as a Paper on the subject was in preparation for presentation to the American Society of Civil Engineers. It might be stated, however, that his equations were for "integral" or "duration" curves, from which the "differential" or "frequency" curve equations could be written. These equations of the frequency curves differed from those of Professor Pearson in that the equation of the integral curve could always be written, whether the exponents were integral or fractional, and it was of simpler form than that of the frequency curve. This was not true of the forms developed by Professor Pearson, which could only be integrated when the exponents were integers, and then took more complicated and cumbersome forms. A comparison of the deduction as to general flood conditions made by Mr. Glass from his study of the floods of the Damodar, with those to be drawn from the diagram, might be of considerable interest. Mr. Glass's first conclusion was: "The average of the peak discharges of all maximum floods experienced during each year for the period of 62 years, 1857–1918, was 250,000 cusecs." The probable average flood-discharge of a much longer series of observations, as obtained from the equation of the curve, was 253,000 cusecs; while the discharge to be most frequently expected (the "mode" of the frequency or differential curve) was 260,000 cusecs. It was interesting to note that discharges of 257,000 to

Mr. Goodrich. 264,000 cusecs occurred ten times during the 62 years of record. (ii) "Normal floods range between 200,000 and 300,000 cusecs, with a year-maximum frequency of about 55 per cent." The range of "normal floods" was also evidently the same on the diagram. But the percentage of frequency from the curve was only about 48 per cent. of the time for floods between those limits. (iii) "Floods exceeding 400,000 cusecs are extremely abnormal, as only one was experienced during the 62 years of record (the 1877 record is very doubtful). It is on record, however, that similar extraordinary floods occurred in 1823 and 1840, and it is probable, therefore, that the frequency of such floods is about 2 per cent." This was also evident from the curve, with a frequency of about 2·5 per cent. or from two to three times in 100 years, and, in fact, three such floods had been recorded during the past 100 years. (iv) "Abnormal floods range between 300,000 and 400,000 cusecs, having a frequency of 21 per cent." The frequency of these floods as obtained from the diagram was nearly 26 per cent. (v) "The frequency of years of sub-normal floods below 200,000 cusecs is about 22 per cent." For this the curve gave 24 per cent. The remarkable similarity of the results which could be obtained by two different investigators, at widely separated places, working with the same data and probably using entirely different methods, was very gratifying, as it served to increase materially the confidence with which this graphical method might be used with less complete data. The maximum flood-record shown by the small circle near the upper right-hand corner of the diagram called attention to one very important point. All such aids to the judgment should be used by the engineer with great caution and in conjunction with all possible information which could be gathered as to local conditions. While the diagram showed correctly that floods exceeding 400,000 cusecs were not to be expected more than, say, three times in 100 years, in the light of the actual records it did not follow that the maximum flood to be expected once, say, in 1,000 years, would be only 470,000 cusecs. Yet that conclusion might be drawn from the diagram in the absence of actual records to the contrary. This and similar curves, therefore, could safely be used as a guide to certain general conclusions regarding the size and frequency of floods, while all available sources of information must be exhausted before determining upon the probable maximum discharge to be adopted for the purposes of design. That Mr. Glass had followed this conservative practice was clearly shown in his comments on the flood of August, 1913. Mr. Glass was also to be commended for his careful analysis of the location and effect of the storms producing floods in the catchment-basin of the river under

Mr. Goodrich. investigation. Similar methods might well be adopted in many future studies of such problems.

Mr. Granville. Mr. H. C. **Granville** remarked that engineers were indebted to Mr. Lillie for new ideas and methods of treatment of a difficult subject, and though Mr. Granville's readings of this subject had been extensive, he had seen nothing so unique and so well-reasoned. Mr. Lillie seemed to have omitted no causes and phenomena which usually affected the maximum rate of discharge. Both size and shape of a catchment affected the rate of discharge. Mr. Lillie proved clearly that the maximum rate of discharge from a catchment was $D = K\int\frac{dw}{y}$ when the catchment varied in shape only. This factor $\int_0^L\frac{dw}{y} = \int_0^L\frac{s\,dy}{y}\left(\textit{Fig 3}, \text{p. } 308.\right) = \int_0^L\frac{\theta y\,dy}{y} = \Sigma(\theta\cdot L)$, where θ was in radians and was constant. Accordingly, the discharge (and therefore S when V was a constant) varied, in catchments of similar shape, as L. If B denoted the breadth of the catchment, then area $= LB$, and $B = \mu L$, as the shape was fixed, $\mu L^2 =$ area, and $L \propto \sqrt{\text{area}}$. Mr. Craig's formula corresponded with Mr. Lillie's for the maximum discharge from the whole zone FK (shown in Mr. Craig's *Fig. 1*)[1], $D = (440\,Cvi)\dfrac{B\,dy}{\sqrt{y^2+\dfrac{B^2}{16}}}$; but $B = 2y\tan\frac{\theta}{2}$, where θ° was the apex angle of the triangle and was constant for a fixed shape. For the whole triangle $D = 880\ Cvi\dfrac{\tan\frac{\theta}{2}}{\sqrt{1+\frac{1}{4}\tan^2\frac{\theta}{2}}}\displaystyle\int_0^L dy = KL$, that was to say, $D \propto L$. Therefore Craig's formula when properly evaluated gave the same result as Mr. Lillie's, when the catchment had a fixed shape and varied in size. Mr. Lillie considered that the curve of variation of the maximum rate of discharge due to variations in size might possibly be logarithmic. Mr. Granville would not be surprised to find this true, for logarithmic functions frequently represented physical laws. Mr. Lillie had found by experience that the rate of variation of Craig's formula accorded with Nature, and he had kindly shown Mr. Granville how he obtained

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[1] Minutes of Proceedings Inst. C.E. vol. lxxx, p. 202.

Mr. Granville. the factor $L\,(1{\cdot}1 + \log L)$, for variations in size of catchment, the shape being constant, from Craig's variant $B \log \frac{8L^2}{B}$. Since $B = \mu L$, then $D \propto \mu L \log \frac{8L}{\mu} = \mu L\,(\log \frac{8}{\mu} + \log L)$. But μ was a constant, therefore $D \propto L(\text{constant} + \log L)$. The constant $\log \frac{8}{\mu}$ in a catchment which was as broad as it was long, was equal to $\log 8 = 0{\cdot}9$. In narrow catchments Mr. Lillie found in practice that $\mu = \frac{1}{3}$ to $\frac{1}{4}$. Thus $\log \frac{8}{\mu}$ ranged between 0·9 and 1·47. He had taken a mean value of 1·1 for this constant, and found that this mean value would not involve errors of more than about 3 per cent. unless the catchment was of very unusual shape. The reasoning that, since $D = VS$, a change in the general slope of the river would cause variation in D and V and leave S unchanged, was new. The particular form of the slope of the river at any point would of course affect the rate of discharge, but it was necessary in the first instance, in studying the effect on the maximum discharge due to the general slope of the river, not to take into consideration the particular slope. Mr. Lillie's argument that it was best to propose a formula for S instead of D was very reasonable. Sections (*c*) and (*d*) of Mr. Lillie's Paper needed close study. The essence of Mr. Lillie's formula, which included the factor R, was that a rainfall of 3 or 4 inches per hour, lasting for 2 or 3 hours in succession, might occur anywhere in India, and that such storms were independent of the annual rainfall. But such phenomenal downpours did not cover the whole of the catchment-area if it exceeded about 10 square miles. Mr. Lillie denoted the effects on the rate of discharge arising from this set of phenomena by a constant A, the effect of phenomena depending on the annual rainfall being denoted by a variable Q, such that $Q = kI$. Mr. Lillie had also also kindly given him the following explanation as to how he obtained $R = (2 + \frac{I}{15})$ as a practical value of $R = A + kI$. In a district of the same annual rainfall throughout, and in tracts of the same natural characteristics in such a district, no variation in the rate of discharge could be traced to causes (*c*) and (*d*) (p. 296). Hence, applying the factors already determined $S \propto \lambda\Sigma(\theta L)$, which did not take into consideration the variation in S due to the annual rainfall. With such limitation $S = K\lambda\Sigma(\theta L)$. Mr. Lillie used the formula in this form in 1903–4 in Eastern Rajputana, where $I = 25$ inches. He compared the results obtained by its application to all rivers and streams for which

Mr. Granville. he had actual measurements of phenomenal floods, and found that $\lambda\Sigma(\theta L)$ with θ in degrees and L in miles gave results showing, with remarkable reliability, one-quarter of the record peak discharges in cusecs. In consequence of this he adopted $S = 4\lambda\Sigma(\theta L)$ as his formula, and worked with it for years before he realized that it had not the same reliability where I was different from 25 inches. This discovery induced him to think over the effect the annual rainfall of a district had on the maximum rate of discharge from medium-size and large catchments, for Q had no bearing in the cases of small areas up to 10 square miles. The result was that he determined to use a fixed factor 4·0 for $I = 30$ inches, but to vary it according to the annual rainfall. This gave a point on the R–I curve (*Fig. 5*, p. 309), at $I = 30$ inches, for $R = 4{\cdot}0$, and to find where the curve cut the R axis he assumed $A = Q$ for $I = 30$; therefore $A = 2$ for $A + Q = 4$, i.e., $2A = 4$, and since $Q = kI$ and $Q = 2$ when $I = 30$, therefore $k = 1/15$, and the general formula for R became $2 + I/15$. The assumptions were that for all medium-size and large catchments the effect on the maximum rate of discharge of phenomenal downpours of 3 or 4 inches per hour for 3 hours or more (which could only occur on very small areas) was equal to the effect produced on the maximum rate of discharge by the mean annual rainfall of the district when $I = 30$ inches; that the rate of variation of Q was directly proportional to I; and the curve of the rainfall-factor R was a straight line. According to *Fig. 5* (p. 309), $Q = 3\frac{1}{3}$ for $I = 50$ inches, and $A = 2$; hence the effect produced on S by a mean annual rainfall of $I = 50$ inches was $\frac{10}{16}$, and that produced by phenomenal downpours over small areas during 3 to 4 hours was $\frac{6}{16}\,\lambda\Sigma(\theta L)$. Reference to the Table of mean rainfall on area given by Mr. Glass, adjoining Fig. 7, Plate 4, where the mean annual rainfall was 50 inches, which storm produced a record peak discharge of 650,000 cusecs, showed that on 300 square miles there was 25 inches depth, on 1,623 square miles 22·8 inches, on 6,269 square miles 18·9 inches, and on 14,110 square miles 15·9 inches during 5 days; and that if the centre of that storm had been over the centre of area of the catchment, namely, about 100 miles to the south-east, a very much higher rate of discharge would have been recorded at Raniganj. Could Mr. Lillie state what the values of A and Q separately were for that peak flood? The value of R in the formula $S = R\lambda\Sigma(\theta L)$ had a very important effect on the value of S, and without reliable statistics (which might be obtainable from Chief Engineers of Provinces in India and Burma), Mr. Granville.

of cross sections, discharges, and mean velocities of phenomenal floods, topographical contoured survey plans of catchment-areas, mean annual rainfall of districts, etc., from which values of R to suit Mr. Lillie's formula could be calculated for all districts in India, etc., engineers were dependent on one value of R obtained by Mr. Lillie from calculations of maximum flood-discharges in rivers and streams in Eastern Rajputana where $I = 25$ inches. Mr. Granville had no records or statistics at hand whereby to refute the assumptions on which the curve for R had been drawn, nor could he suggest a more reliable curve for R. He noticed that in calculating the value of the factor $\Sigma(\theta L)$ Mr. Lillie included all values of L, but in calculating the value of λ he used only the maximum value of L, namely, the length of the longest sector. Had he any special reason for doing so? Looking through the applications of the proposed formula and the comparison with measured results on various rivers, he found the following details:—

Name of River.	Mr. Lillie's value of S.	Measured value of S'.	Drainage-Area.
	Square Feet.	Square Feet.	Sq. Miles.
Irrawaddy at Prome .	219,000	205,617	128,000
Kala Nadi in the United Provinces, India	23,100	23,325	2,660
Jumna Allahabad .	$VS = 1\frac{1}{2}$ million cusecs	$V'S' = 1\frac{1}{3}$ million cusecs	135,000
Ganges at Sara . .	$VS = 2{,}644{,}000$,,	$V'S' = 2{,}380{,}000$,,	..

These were very noteworthy results for catchment-areas of immense size, and the formula might certainly be accepted as reliable for very large catchments in India. The Paper was certainly a remarkable communication, and likely to cause Civil Engineers all over the world to compile records to prove the accuracy or otherwise of Mr. Lillie's deductions.

Mr. Gurtu.

Mr. S. K. Gurtu observed that the factors which affected discharge could be considered under the following five heads:—(*a*) Rainfall, (*b*) temperature, (*c*) configuration of catchment, (*d*) soil conditions, and (*e*) miscellaneous unforeseen factors.

With regard to rainfall, when the maximum intensity of precipitation for periods of 1 hour, 3 hours, 24 hours and 1 week had been recorded over a long series of years for any country, it would be possible for discharges to be worked out with greater accuracy. Rapidly-succeeding heavy precipitations during a short

Mr. Gurtu. interval, say a fortnight, sometimes stultified all calculations. This phenomenon was so erratic that it could not be allowed for definitely in flood calculations; nor could it be wholly ignored. Mr. Lillie contemplated a maximum precipitation of 12 inches in 4 hours, which was high enough, but Nature sometimes refused to be tied down to man-made maxima! The following Table of heavy precipitations recorded at different stations widely distributed was of considerable interest:—

Name of Rain-Gauge Stations.	Fall.	Period.		Year.
	Inches.	Hrs.	Min.	
Calcutta	4·0	1	15	..
„	12·0	3	0	May, 1835
Bombay	4·22	1	0	June, 1847
Madras	17·0	12	0	October, 1846
Nagpur	3·55	0	45	„ 1872
Gwalior	22·0	24	0	1919
Cherrapunji . . .	40·8	24	0	June, 1876
Purnea	35·0	24	0	September, 1879
Dehra Dun	19·5	24	0	„ 1880
Rewah	30·4	24	0	June, 1882
Delhi	19·5	24	0	September, 1875

Mr. Gurtu had no doubt that thick forests helped in the condensation of vapour. Even if their influence in attracting moist currents from a distance were doubted, their local effect was a matter of common observation. While in Gandamanayakanur, in South India, he had often noticed slight drizzling on the tops of hills 4,000 to 5,000 feet high, while the atmosphere in the valley was dry and warm. Another function of forests was to act as rain-absorbers and flood-moderators. Part of the water absorbed passed out slowly as springs, which, if the forest was at all extensive and thick, became perennial. Forests occupying a considerable portion of any catchment basin would have a sensible effect on the coefficient of discharge. He would refer engineers interested in this aspect of the subject to Mr. S. E. Wilmot's Paper.[1]

Temperature had more influence on discharge than was generally

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[1] "On the Influence of Forests on the Regulation and Storage of the Water-Supply." See also Report of the New Jersey Geological Survey for 1894, vol. iii.

Mr. Gurtu.

known, though it was admitted that all meteorological phenomena were dependent on variations of temperature. The hygroscopic condition of the atmosphere at the time of precipitation had a marked effect on the amount of discharge. Evaporation was more active in the monsoon than in other months, as would be borne out from the following figures, extracted from the New Jersey Report referred to on previous page :—

December . . . . $e = 0{\cdot}42 + 0{\cdot}10r$
January. . . . . $e = 0{\cdot}27 + 0{\cdot}10r$
February . . . . $e = 0{\cdot}30 + 0{\cdot}10r$
March . . . . $e = 0{\cdot}48 + 0{\cdot}10r$
April . . . . $e = 0{\cdot}87 + 0{\cdot}10r$
May. . . . . $e = 1{\cdot}87 + 0{\cdot}20r$
June . . . . $e = 2{\cdot}50 + 0{\cdot}25r$
July . . . . $e = 3{\cdot}00 + 0{\cdot}30r$
August . . . . $e = 2{\cdot}62 + 0{\cdot}25r$
September . . . . $e = 1{\cdot}63 + 0{\cdot}20r$
October . . . . $e = 0{\cdot}88 + 0{\cdot}12r$
November . . . . $e = 0{\cdot}66 + 0{\cdot}10r$

Total for the year . $E = 15{\cdot}50 + 0{\cdot}16R$

where R denoted the yearly rainfall, r the monthly rainfall, E the yearly evaporation, and e the monthly evaporation. The foregoing figures established a direct relation between monthly rainfall and evaporation. The State geologist was the authority for the statement that the capacity of atmospheric air was doubled for each 20° of increase in temperature. The ordinary discharge-formulas, however, did not allow for variations in temperature. Conditions in India were akin to those of New Jersey. In India too the greatest precipitation took place in July, August, and September. Evaporation proper was most active in July and June; with the onset of steady showers it decreased or remained stationary, but absorption and transpiration rapidly increased and were at their climax in August. With the advent of October they sensibly diminished. In spite of active evaporation in July, August, and September, the discharge was the greatest because the precipitation was the greatest—the paradox was only apparent. Winds exercised a great influence in changing the direction of the moisture-laden currents, and the cultivators of India could, with tolerable accuracy, prognosticate weather from the direction and velocity of winds in different months. Winds also greatly intensified the action of floods approaching bridges or waste weirs, by causing waves which carried the water much higher than the still-water level. He had measured waves higher than 3 feet impinging against high dams

Mr. Gurtu. with a long "fetch." It was, therefore, conceivable that a bank 2 to 3 feet higher than high flood-level might be overtopped. This factor could hardly find room in discharge-formulas, but could not safely be ignored. In designing dams and fixing the principal levels, he had had to make special calculations for such wave-action, and he had issued for the guidance of his staff a special memorandum entitled "Wave Wash in Tanks."

The extent of catchment had a direct bearing on the quantity of discharge, and though, owing to the longer distance over which the water had to travel, the rate per mile was less than in smaller catchments, the aggregate quantity was considerable in bigger catchments. All discharge-formulas allowed for extent of the catchment, but its shape had only recently been recognized as being an important element of such a formula. A circular or wide catchment, *ceteris paribus*, could give a larger discharge than a long one, as in the latter case the time element came into operation, and large quantities were lost by evaporation and absorption. Mr. W. L. Strange, M. Inst. C.E., had rightly suggested that, in comparing a catchment on which few actual flood-observations had been made, with one for which a long record was available, it would be best to analyse them into constituent areas under similar conditions, and, from actual experience or observation, to allot coefficients of discharge to each of these minor areas, so as to arrive at their total relative discharging-capacity. If to this were applied the distance-time factor, the result would be correct: otherwise the calculated discharge would exceed the true value. In big catchments —say more than 2,000 square miles in extent—rain seldom fell all over the catchment with equal intensity, or with other conditions the same. If the maximum conditions affecting the discharge were allowed for, the resulting figure would be quite out of proportion to actualities. It was for this reason that different engineers modified the discharge from 3 inches to 0·1 inch, according to the size of the basin. These empirical fractions seldom accorded with the actual discharges. The situation of the discharge-point in some cases seriously disturbed the escaping power of rivers and destroyed their regime. The element of situation did not find recognition in discharge-formulas and yet in deltaic rivers it was a potent factor of evil. The configuration of catchments, in regard to presence of hills or otherwise, also bore on the question of discharge; high, bare mountains gave a much higher discharge than plain country. In the case of the Western Ghats in India, which stopped rain-bearing currents of air, there was plenty of rain in the littoral to the west, while 10 miles to the east the land habitually suffered from drought.

Mr. Gurtu.

The texture of the soil and sub-soil greatly influenced the discharge, and the character and extent of cultivation required to be kept in mind when working out discharges. Artificial retardation of floods above the outfall had to be considered. The presence of large artificial or natural lakes, like the Chalan Beel in North Bengal, and huge railway-embankments across the drainages of a country, greatly impeded the progress of floods and must be taken into account.

Even if it were possible to take cognizance of all the foregoing factors there was an element of uncertainty in the operation of all the laws of Nature, and it was not always possible to make provision for maximum conditions. The average rainfall in Sind in Upper India (in the same latitude as Cherrapunji) was 12 inches per annum, and yet precipitations of 12 inches in a day had been recorded there. Who would, when dealing with local drainages in Sind, venture to allow for a precipitation of 12 inches in 24 hours? The Punjab engineers were constructing a dam over 150 feet high at Bakhra, with an impounding-capacity in cubic feet running into ten or eleven figures: could the discharges of drainages below the dam be fixed in view of the contingency of this dam breaching? In each case the engineer had to depend on his own experience and judgment. No formula could be devised which could be applied universally.

Mr. Lillie's treatment of variable factors was interesting; he attempted to allow for yet more variants than Mr. Craig, but failed to take cognizance of all the factors Mr. Gurtu had mentioned, which, indeed, was well-nigh impossible. It was to be feared that Mr. Lillie's statement that the standard velocity of a river generally would vary very little from source to mouth, and that where there was a change, it would be very gradual and might be easily calculated by taking slopes over long stretches of the river, assumed too much. The discharge-velocity of a big catchment, with its parts differing widely in physical characteristics, varied considerably; and it was not possible ordinarily to calculate it easily by taking the slope ver long stretches of the river. Such opportunities were seldom joyed by engineers, except for schemes of sufficient magnitude permit of a proper hydrographic investigation being carried ut. Again, the assumption that the maximum intensity of precipitation would not exceed 4 inches per hour, and never last for 2 or 3 hours in succession, was unwarranted. What of precipitations of 30 to 40 inches in 24 hours? How were such 24-hour intensities to be converted into hourly intensities?

He considered that Mr. Glass's investigations were useful in

Mr. Gurtu. dealing with the Damodar river and its affluents, but could hardly be of use when dealing with basins differently constituted. Colonel Hearn wisely suggested the keeping of extended records for different catchments.

During his experience in Gwalior, from 1902 to the present day, he had had to calculate discharges of no less than 1,500 catchments, differing widely in their physical characteristics, from 1 square mile in area to 2,000 square miles. In the beginning Dickens's formula was in vogue, but the actual measured discharges of drainage-areas, mostly small, far exceeded the figures worked out in accordance with that formula. The value of the coefficient was therefore raised to 1,000. In 1907, under the direction of Mr. Sidney Preston, M. Inst. C.E., who was then Chief Engineer, Irrigation, Gwalior, the value of the constant was raised to 1,900, and numerous projects, formulated during the succeeding few years, were based on this figure; but the cycle of 1907–14, being dry, gave a false sense of security, and the coefficent swung back again to 1,000, though in certain hilly catchments other values between 1,000 and 1,400 were assigned. The Gwalior practice was akin to Mr. Beale's. Both Gwalior and the Bombay Presidency were situated within the Deccan trap area, with similar physical characteristics; and this perhaps accounted for assimilation of practice, unconsciously on both sides, as a result of similar experiences.

His next step was to divide the catchments into four classes and make the values of C for different classes elastic to cover all the diverse cases. He achieved, by making the coefficient elastic, what Colonel Hearn desired to compass by assigning varying values to the variable factors of soil, slope, and protection. Colonel Hearn, however, expressed a doubt whether each factor had really the assigned value. That was, indeed, the crux of the matter. Whatever form might be given to a formula, it was not possible to dispense with the personal equation. Mr. Gurtu pursued a simpler process: he noted the discharges on anicuts and weirs under maximum conditions, and divided the catchments into four classes, and even in these classes he allowed great divergence of practice, by making the coefficients variable within certain limits. His classification was:—

		Coefficient.
Class 1.	Bare catchments, covered with precipitous hills .	1,400–2,000
Class 2.	Catchments, with hills on the skirts, with undulating country below up to the outfall . .	1,000–1,200
Class 3.	Undulating country, with hard indurated clay soil	800–1,000
Class 4.	Flat, sandy, absorbent or cultivated plains . .	200–600

Mr. Gurtu. In practice he found that, if the coefficients were selected with discrimination, the maximum discharges, even in years of abnormal rainfall, did not exceed the calculated figures, but followed them closely. Engineers should study the hydrography of all the important basins of the country, and gaugings of rivers should be taken, extending over long periods, say 100 years, during which time all sorts of weather cycles might be expected to supervene. No record of less than 35 years could be made the basis of calculations with safety. Dependence on discharge formulas was a fruitful cause of many disasters every year in India. The Geological Report on Water Supply in New Jersey exemplified the lines on which hydrographic studies should be carried out in India and elsewhere.

With regard to permissible maximum discharges, it was not reasonable to assume that all the factors to which he had referred would come into operation in their full force simultaneously. If they were to do so, such immense discharges would have to be provided for as would make all projects financially unfeasible. In Mr. Gurtu's view, the maximum working flood should be the average of all the maxima of a long series of years—35 years as a minimum; and a provision of 25 per cent. in excess of this average would be ample.

Colonel Hearn. Colonel G. R. **Hearn** drew attention, in Fig. 6, Plate 5, to the extraordinarily rapid rise from 50,000 to 212,000 cusecs in about 7½ hours on 30th October, 1917. The details of the rainstorm producing that rise were not given in Table II of Mr. Glass's Paper (p. 340), but it was stated that its centre was near the centre of the Damodar catchment.

Mr. Horton. Mr. **Robert E. Horton** observed that there was no single rule or method which could be followed in estimating the maximum rate of flood-discharge from a catchment. The procedure in a given case must depend upon the extent, character, and reliability of the data available. Probably the safest guide was to follow the rule that the best possible use should be made of all the available information. To get the best results might require engineering knowledge and experience of a high order, in relation both to hydraulics and hydrology, to an extent probably not generally recognized. It was unfortunate that a problem of such prime importance as determining the requisite spillway-capacity for a reservoir sometimes received scant attention, as compared with other problems of design in which the solution could be more directly reached, such as, for example, determining the allowance to be made for upward pressure beneath a dam. In attempting to determine the maximum flood-discharge from a catchment-basin, three general classes of

Mr. Horton. cases arose: (1) where there was a more or less extended and reliable record of maximum discharges from the same drainage-basin, either at the required or any other place; (2) where scattered records of high flood-stages only were available, such as might generally be obtained from old residents and mill-operators where there were dams and mills on the stream; and (3) where no reliable data were available as to maximum flood stages or discharges for the given stream, and where reliance must be placed on methods of estimation from rainfall, existing flood-discharge formulas, or estimation by comparison with known flood-records of other streams. Fortunately, in the United States, where an extensive system of stream-gauging was maintained by the Federal government, a more or less complete record of flood-discharges over a series of years was generally available for any large stream. It was perhaps unfortunate that so many of these records had been obtained by the use of open-section current-meter rating curves. Discharge-measurements with the current-meter were seldom obtained at flood-peak stages, partly because of the short duration of flood-peaks and partly because a current-meter which was well adapted to determine the discharge of a stream like the Mohawk river at ordinary stages, or with flows between 1,000 and 20,000 cusecs, might be very poorly adapted to measurement of the discharges of the same stream when upwards of 100,000 cusecs was flowing past the gauging-station. It was true that reliable results could be obtained with the current-meter in the measurement of flow of very large and deep rivers, as had been done, for example, in the St. Lawrence river, and in connecting channels of the Great Lakes; but to obtain results of the first order of accuracy under flood conditions in a stream like the Mohawk river by means of a current-meter required more extensive equipment and a larger personnel than for measurement at ordinary stages; further, it was likely to take more time than was available during the passage of a flood-peak on a torrential stream. Again, on many rivers in the United States great floods usually occurred in the spring, when there was likely to be ice, driftwood, and often logs running in the river; and the successful use of the current-meter under such conditions was nearly impracticable. And even if there was available a reliable record of flood-discharges covering a series of years on a given stream, it did not follow that the true maximum discharge could be simply determined from such a record. He believed that there was a natural limit to the volume of flood-discharges in any locality or on any stream, which limit would never be exceeded as long as

Mr. Horton.

general climatic conditions remained as they were now. This proposition might be illustrated in a homely way by stating that the ordinary domestic hen could not lay an egg a yard in diameter: the reason was that the hen was not large enough. Similarly, a stream like the Mohawk river, in the state of New York, which had produced flood-discharges exceeding 100,000 cusecs from a drainage-area of about 2,800 square miles, could never produce a flood-discharge of 1 million cusecs, because Nature's capabilities in supplying water to the drainage-basin were inadequate. In some instances, e.g., in relation to maximum rain-intensities for short intervals, the limit of Nature's capabilities could be determined, approximately at least, from meteorological considerations alone. In the case of flood-discharges from large catchment-basins the natural maximum limit could not be determined directly from meteorological considerations. He believed that in an instance where there was a fairly extended record of actual flood-discharges, the maximum possible flood-discharge could be determined—at least, to a good degree of approximation—by a method of statistical analysis of the existing data. Details of this method of analysis need not be presented here. It sufficed to say that the results, based on long records for a number of streams in the United States, indicated that there was no reason to expect flood-discharges more than 15 to 25 per cent. greater than those which had usually been experienced within the past century, in the case of most streams studied by this method. Further, flood-discharges approaching the maximum value apparently occurred at not infrequent intervals, ranging from 15 to 25 years as a rule. The great flood of 1913 which was so destructive in the Miami Valley in Ohio was apparently very close to the maximum limit. Methods of determining maximum flood-discharges from actual measurements, from high-water marks above dams, or from high-water marks in conjunction with slope and channel-section data might properly be referred to as hydraulic methods. Where the flood-discharge must be estimated solely from rainfall, physiographic, and other factors, the procedure might be described as the hydrologic method. Many factors affected the flood-discharge from a catchment-basin. These included:

(1) Size or area of catchment.

(2) Its shape.

(3) The drainage density or length of stream-channels per unit of area.

(4) The type of drainage-net. This comprised the character and distribution of natural drainage-channels and the extent of

Mr. Horton. dendrition or frequency of small tributaries reaching to every part of the area; in other words, the thoroughness with which the area was naturally drained.

(5) The distance which water must travel over the ground surface before it reached a definite stream-channel.

(6) Average slope of the ground-surface.

(7) Average slope of stream-channels.

(8) Storage-capacity in stream-channels between the initial and peak stage of the flood.

(9) Extent of temporary storage in lakes, marshes, swamps, and on flat- and stream-margins.

(10) Texture and structure of the soil, with special reference to porosity and fineness of soil-grains, or in other words, the permeability of the soil.

(11) Initial condition of the soil, not only with regard to its moisture-content but also with reference to other factors. For example, a clay soil initially dry and thoroughly sun-cracked would temporarily absorb rainfall at a relatively rapid rate, but as the soil became moistened it swelled, closed the cracks, and the rate of infiltration was greatly reduced. Again, a soil which was under cultivation and normally highly permeable, might have formed a crust, by drying after previous rains, through which infiltration proceeded but slowly until the soil became thoroughly moistened.

(12) Soil-temperature. The investigations of Mr. C. S. Slichter[1] indicated that the rate of ground-water flow was a function of temperature. This result apparently applied also to infiltration, or in other words, the "absorption" of rainfall by the soil. On the basis of Mr. Slichter's formula the relative rates of absorption by a given soil at different temperatures would be

Temperature: F. . . .	32°	40°	50°	60°	70°	80°
Relative absorption . . .	0·74	0·85	1·0	1·16	1·34	1·51

For example, for a midsummer flood, with a soil-temperature of 80° F., the rate of absorption would be double that for a winter flood with the soil not frozen but at a temperature just above 32° F. The importance of this factor in relation to flood causation did not appear to have received proper recognition. Floods approaching the maximum for very small areas were usually the result of local storms

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[1] "The Motions of Underground Waters." Water Supply Paper, No. 67, U.S. Geological Survey, 1902.

of the convective or thunderstorm type, the occurrence of which was mostly confined to the summer season. Great floods on large streams occasionally occurred in midsummer, but more generally in the autumn, winter, and spring. They were usually the result of general storms of the cyclonic type, since only such storms would produce heavy rains over the entire area of a large basin. Such storms were generally believed to be more prevalent in winter than in summer, and they were the prevailing type of storms for the winter season in extra-tropical latitudes. Nevertheless, as revealed by statistics collected by the Miami Conservancy District, great general storms occurred in summer as well as in the other seasons. The following data showed the distribution, by months, of 150 of the greatest storms of 1 day or more duration which occurred in the Eastern United States during the 25-year period 1892 to 1916.[1] Storms classed as northern were those which occurred in the region east of the 103rd meridian and north of latitude about 36° 30′; storms classed as southern occurred south of this latitude and east of the 103rd meridian. Mr. Horton.

	Jan.	Feb.	Mar.	Apl.	May.	June.	July.	Aug.	Sept.	Oct.	Nov.	Dec.	
Northern storms .	4	0	2	0	3	3	9	6	14	4	1	1	= 47
Southern storms .	4	4	9	12	12	8	12	14	19	8	2	9	=113

In view of the preceding data the question might properly be asked : why did not great floods of medium-size streams more often occur in midsummer ? The answer probably lay mainly in the relative permeability or absorptive capacity of the soil. Consider for example a rainfall of 4 inches per 24 hours on a medium-size area. If this storm occurred in midsummer with the soil-temperature at 80° F., and if for that temperature the infiltration capacity of the soil was 4 inches per 24 hours, then practically the entire fall could be absorbed; there would be no flood and only a moderate rise in the stream, resulting from rainfall on water surfaces, local impervious areas, and the like. Such a condition was not of infrequent occurrence on relatively flat, sandy drainage-basins. If, on the other hand, the same rate of rainfall occurred in the spring or late autumn when the soil-temperature was just above 32° F., but the soil was not frozen, the absorptive capacity would be only half as great, or 2 inches in 24 hours, and 2 inches of rain would be left to run off the surface—enough to produce a flood of some magnitude.

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[1] "Storm Rainfall of Eastern United States"; by the Engineering Staff of the Miami Conservancy District. "Technical Reports," Part V, Dayton, O., 1917.

Mr. Horton. (13) Vegetation. The extent of vegetal cover on a drainage-basin was an important factor in flood-discharge. Experiments by himself,[1] and others, indicated that, with a good forest cover, about 10 to 20 per cent. of the rainfall did not reach the ground, but was intercepted by, and directly evaporated from, the extended surface of the leaves and tree crowns. On an area covered by a growing crop a smaller but still an appreciable percentage of the rainfall was intercepted. On a bare area none was intercepted.

(14) The preceding factors were mainly of a topographical or cultural character, and indicated sources of differences in flood-discharge for different areas subjected to the same rainfall. To these must be added another, namely, orientation. If a stream flowed in a direction parallel with that in which the storm travelled, and at an average rate less than the rate of storm travel, then the time required for concentration of a discharge from the most remote portion of the drainage-basin to the outlet would equal t_0, the time consumed in overland flow, plus t_c, the longest time required for water to traverse the stream-channels from the source of any tributary to the mouth of the stream. If, on the other hand, the basin was so oriented that the storm travelled directly upstream, then there must be added to the preceding the length of time required for the storm to travel from the outlet to the head of the drainage-basin.

(15) In the foregoing remarks it was assumed that the ground was not frozen, and that there was no snow. If the ground was frozen, then infiltration would still take place, but at a less rate, depending on the extent to which the pore-space in the soil was occupied by ice. If there was snow on the ground, then its water-equivalent and the temperature of the air during the occurrence of the flood rains became important factors.

(16) Flood-discharges from the same catchment-basin varied with such of these factors as were subject to seasonal or other variations. In addition, flood-discharges on a given drainage-basin varied with the quantity, duration, and areal distribution of rainfall.

Many flood-discharge formulas took one or more of these factors into consideration, and some involved several of them. There was no formula in existence in which all the factors, or even all of those which were of prime importance, were included. Mr. Lillie's Paper was directed to the evaluation of the effect of one of these factors, namely, the effect of the shape of the drainage-basin. The derivation of Mr. Lillie's formula appeared to be empirical and in

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[1] "Rainfall Interception," *Monthly Weather Review*, Sept., 1919, pp. 603-623.

Mr. Horton.

fact arbitrary to some extent, especially as it was based on the assumption, not specifically proved in the Paper, that the maximum rate of discharge from an element of area (*dw*) was inversely proportional to its distance from the discharge-point. Mr. Lillie's statement, which implied that the actual discharge-rate from unit area varied inversely as distance from the outlet, seemed contrary to the fact. If the rainfall on a drainage-area was of sufficient duration to concentrate the discharge from every element of area at the outlet simultaneously, then there was apparently no reason why the actual quantity of discharge from unit area located at the extreme limit of the basin should not be substantially as great as the rate of discharge from unit area located adjacent to the outlet. Mr Lillie suggested that the reduction in the rate of discharge with increased distance was due to greater absorption, because the water must travel farther to reach the outlet. This statement did not seem to be well founded. Absorption took place mostly on the ground-surface and not from the water which had reached definite stream-channels. If it were raining at a uniform rate over the entire area, the rate of absorption would be substantially the same on every unit of area of the land-surface, provided the soil was uniform. There would be, of course, a slight difference in the case where water accumulated to an appreciable depth on the soil-surface, as it would do if it flowed for any considerable distance overland. Infiltration was undoubtedly greater if water stood on the soil-surface to a depth of 1 inch than if it was raining at such a rate that the soil could just absorb the rain as it fell and there was no depth of standing water on the ground-surface. In other words, it seemed that the loss by absorption or infiltration was proportional to the length of overland flow rather than to the distance of the unit area from the stream-outlet. The length of overland flow from unit area located near the mouth of the stream might be, and commonly was, as great as for a unit of area located at a point most remote from the outlet. It was mainly through variation in rainfall depth, rather than through rate of absorption, that the size and shape of catchment affected the rate of flood-discharge per unit area.

The maximum average precipitation over any area for any time-interval and frequency in a given storm decreased as the size of the area increased. This relation was expressed through what were called rainfall-depth-area relation curves. It would be convenient to use the term " rain-splash," suggested by Dr. H. R. Mill of the British Rainfall Organization, to represent the area on a map on which rain fell in a given shower or storm. The point in the rain-splash

Mr. Horton. where the heaviest rain fell might be called the focus of the rain-splash or shower. If, for example, the rainfall at the focus of a rain-splash was 4 inches, the average rainfall over an area of 10 square miles would be less, and so on. In the Paper by Colonel Hearn an example of a rainfall-area relation curve was given (p. 273), together with the formula therefore

$$R_{\text{av}} = 4 - \log_e A \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

where R_{av} was the average rainfall over the area A in square miles. This formula gave $R_{\text{av}} = \infty$ for $A = 0$, whereas the curve showed $R_{\text{av}} = 8{\cdot}5$ for $A = 0$. From a study of rainfall-depth area relation data for great storms, collected by the Miami Conservancy District, and similar data for local storms recently compiled by Mr. Frank A. Marston,[1] Mr. Horton had found that the rainfall-depth area relation curve in almost any well-developed typical storm covering either a large or a small area could be very accurately represented by an equation of the type

$$R_{\text{av}} = (R_0 + c)\,\epsilon^{-kA^n} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

in which R_0 was the highest measured rainfall at or near the focus of a storm. In case it was evident that the highest record did not represent quite the maximum or focal rainfall, a small correction c was added. The values of the constants k and n were easily determined from the observed data. This formula, like that of Colonel Hearn, was, of course, empirical, but it was also rational to the extent that it gave finite rainfall for zero area. Further, there was always a limit to the rain-splash in any shower or storm. It could readily be shown that the average radius of the rain-splash or average distance from the focus at which the precipitation became zero in accordance with the preceding formula was

$$r_0 = \frac{1}{\pi}\sqrt[m]{\frac{1}{kn}} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)$$

Considering the rain-splash of an intense local convective storm nearly circular in area, as was typical of such a storm, where r_0 was 2 miles, so that the area of the rain-splash was 12·56 square miles, if the focus was at the centre of a circular catchment-area of 12·56 square miles, this catchment received the entire precipitation of the storm; but, if the catchment was 2·28 miles wide and 6 miles long and the focus was central, a considerable part of the catchment would lie outside the area covered by the rain-splash, and the

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[1] Proceedings, Am. Soc. C.E., 1924.

Mr. Horton.

average precipitation on the catchment would be less than before. It might be noted in passing that the values of the constants k and n in the preceding formula (2) differed for every storm. Applying formula (2) to depth-area data given by Colonel Hearn

$$R_{av} = 8\cdot5^{0\cdot755\sqrt[3]{A}} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (4)$$

The graph of this equation was nearly identical with the rainfall-intensity curve of *Fig. 3* in Colonel Hearn's Paper (p. 273).

Since the average rainfall in depth over a rain-splash for maximum storms decreased as the area of the rain-splash increased, and since it took a storm of larger radius to cover all portions of a long narrow catchment than to cover all portions of a circular or square catchment of the same area, it followed that the average flood rain per unit area would in general be less for long narrow catchments than for those which were nearly circular in form. The reduction in rainfall did not apply merely to the most remote portions of the area, but to the entire area. It was evident from the preceding that the type and size of storm or rain-splash which would produce the maximum total rainfall or maximum average rainfall-depth over a catchment of a given area was dependent to a considerable degree on the shape of the catchment. It might be true that the effect of shape was taken into account fairly well, even though empirically, by the formula and method of calculation given in Colonel Hearn's Paper. However, the shape of catchment could also be taken into account equally well, and probably with a greater degree of certainty, by the use of a rainfall-depth area relation curve for the assumed maximum storm.

Mr. Lacey.

Mr. J. M. LACEY remarked that Mr. Glass's Paper described a method of analysing the floods in a river, when the construction of flood-moderating reservoirs in the basin was contemplated. In India, heavy wide-spread falls of rain occurred only in cyclones and cyclonic storms, and their frequency at any given place was likely to vary with the liability of that place to come within the track of such storms. The cyclonic storms of the south-west or summer monsoon, which most frequently crossed India in a west north-west direction from the Orissa coast, usually traversed this region, and in their passage westwards were accompanied by heavy rain. Falls of great intensity had occurred in the belt of maximum storm-frequency which extended in a broad band from Bengal nearly across the Peninsula. The extent of country simultaneously affected by these heavy rainfalls was sometimes very great, and usually some thousands of square miles in extent. In September the south-west monsoon began to decline, on the Carnatic coast the monsoon began

Mr. Lacey. to recur in October, and a copious rainfall was discharged over the hitherto scantily-watered plains of the Carnatic. Thus July and August were generally the months of severe cyclones or cyclonic storms on the Bengal and Orissa coasts, while October and November were the months in which such storms frequented the Carnatic coast. The gaugings of the floods in the Damodar river, as stated in the Paper, were calculated from observed surface slopes and cross sections of the river, but details as to how the surface slopes were observed, and the cross sections of the river taken, were not given. As the discharges were calculated from surface slopes of the river, it was not surprising that the maximum calculated discharge of 645,000 cusecs agreed with Colonel Dickens's formula $Q = 825\,M^{0\cdot75}$, as Colonel Dickens based his formula upon an observed flood in the Damodar river[1] and very probably estimated the flood-discharge by a method similar to that adopted by Mr. Glass. It seemed desirable that the estimated flood-discharge should be verified by current-meter or float observation. The maximum 3-day recorded rainfall was stated to be 10 inches. The extreme length of the basin as measured on Fig. 1, Plate 4, was 160 miles, and it fell from an elevation of more than 2,000 feet above sea-level to the deltaic plains; so that the time taken for the flood-water to reach Raniganj from the extreme limits of the basin would be about 24 hours. To compare, therefore, the maximum rate of discharge (645,000 cusecs) with the maximum rate at which the rain fell, the maximum rainfall in 24 hours during the 3-day period was required. It was shown in Column No. 11 of Table III (p. 343) that the ratio rate of discharge/rate of rainfall ranged from 45 to 67 per cent. It had been stated that the Damodar river formerly flowed into the Hooghly north of Calcutta, and, following a natural tendency of these rivers to work to the west, it was highly probable that the Rupnarayan river would eventually have to carry the waters of the Damodar river.[2] Were there indications of that trend of the river towards the west or to its right? The removal of the 10 miles length of the right flood-embankment of the Damodar in 1854 was considered detrimental to the navigation of the Hooghly.[3] Mr. Glass stated that since the removal of this embankment the land had gradually silted up, and the proportion of flood-volumes spilled had been reduced. Were there records to show that the reduction of those spills had had any beneficial effect

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[1] "Professional Papers on Indian Engineering," vol. ii (1865), p. 133.

[2] Minutes of Proceedings Inst. C.E., vol. cli, pp. 281, 282, and vol. clx, p. 201.

[3] *Ibid.*, vol. clx, p. 128.

Mr. Lacey.

on the navigation of the Hooghly? Had the navigation of the Hooghly been considered in the proposals for flood-moderating reservoirs in the basin of the Damodar?

With reference to Colonel Hearn's remarks regarding Colonel Dickens's formula in the "Professional Papers on Indian Engineering," cited on previous page, the formula was stated by Colonel Dickens to be considered only as a rough approximation. With regard to Colonel Hearn's remarks on railway-bridges and culverts, the Nellore section of the East Coast Railway presented considerable difficulties in dealing with floods, for, as the rivers draining that district approached the coastal plains, they spilt to a considerable extent—so much so, that during the cyclonic storms which visited the coast, the country above the railway-embankment, which ran parallel to the coast and intercepted all cross drainage, presented a sheet of moving water, and breaches in this section occurred at most unexpected places. Colonel Hearn assumed that the intensity of rainfall on a river-basin bore some relation to its area. Mr. H. F. Blanford had stated[1] that in cyclonic storms rainfalls of great intensity covered very large areas. The variation of rainfall-intensities with the period of fall, coupled with the time of concentration of the flood-waters at the outlet, would necessarily result, at the outlet, in a flood-discharge which would bear some relation to the shape, length, and area, and to the physical and other features of a hydrographical basin. He had prepared a diagram, *Fig. 3* (p. 398), which gave the rate of discharge, in inches per hour, of recorded floods. This might be compared with Colonel Hearn's *Fig. 3* (p. 273).

Mr. Lillie's reasoning was difficult to follow: according to his formula $S = R\lambda\Sigma(\theta l)$, a greater flood-intensity might be expected from localities with a large annual rainfall than from localities with a low rainfall. It might be admitted that the frequency of high floods might be greater in the former locality than the latter; but a single flood of extraordinary intensity might occur in comparatively dry areas, and might be of greater intensity than an extraordinary flood in a country of copious rainfall. One example was that of the river Musi, Hyderabad and Deccan (*Fig 3*, p. 398); on the 28th September, 1908, the Musi came down in a great flood, causing considerable damage to the town of Hyderabad. The maximum rate of discharge was estimated at 0·75 inch per hour from a catchment-basin of 862 square miles. Mr. Lillie's standard velocity, V, had also to be estimated; which involved a knowledge

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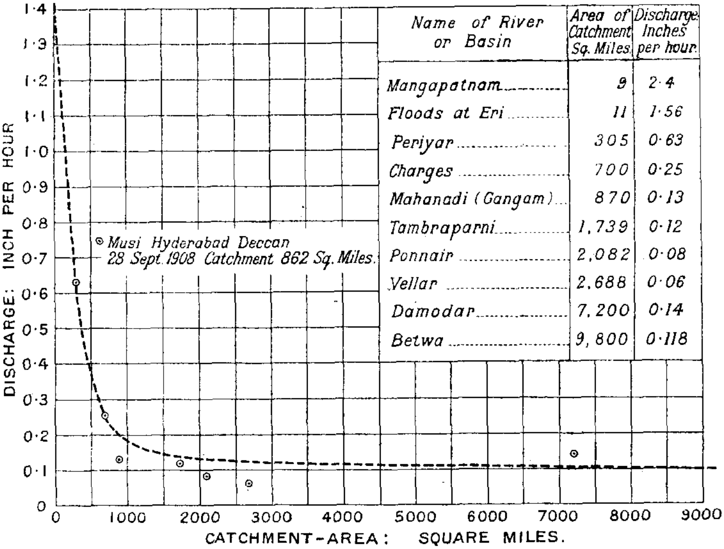
[1] "A Practical Guide to the Climates and Weather of India." London, 1889.

Mr. Lacey. of the character of the bed and banks of the river draining the basin under consideration, and of the slope of its bed. If these data were collected, and if highest flood-marks were observed, or ascertained from local residents, it would be possible to calculate the maximum flood-discharge from known formulas as accurately as it could be done with Mr. Lillie's formula. With reference to his remarks regarding the maximum flood-discharge of the Kistna at the Bezwada anicut, the obvious course, in order to obtain correct figures, would have been to address the Irrigation Branch of the Public Works Department at Madras.

Fig. 3.



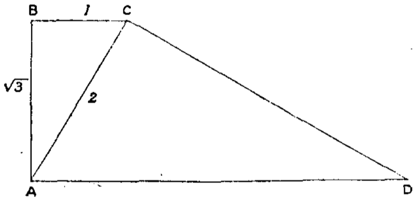
Name of River or Basin	Area of Catchment Sq. Miles	Discharge Inches per hour
Mangapatnam	9	2·4
Floods at Eri	11	1·56
Periyar	305	0·63
Charges	700	0·25
Mahanadi (Gangam)	870	0·13
Tambraparni	1,739	0·12
Ponnair	2,082	0·08
Vellar	2,688	0·06
Damodar	7,200	0·14
Betwa	9,800	0·118

Mr. Lindley. Mr. E. S. **Lindley** observed that Mr. Lillie put forward a formula containing only factors whose values would generally be ascertainable when an investigation was opened; and these values yielded a definite estimate of maximum flood, without need or room for personal judgment. Colonel Hearn, on the other hand, did not attempt a rigid solution, but reduced estimation to method, went as far as he could in suggesting values to be used for some factors, and left the method to be tried and completed. Mr. Lillie worked by theory with an eye to fact: Colonel Hearn from data, with an eye to possible theory. Where time and other resources did not allow of a proper investigation, Mr. Lillie's formula seemed to be an advance on previous rigid formulas: in giving a definite means of evaluating the shape of a catchment it was also generally useful; but where safety without an extravagant factor of safety and greater certainty were wanted, fuller investigation could not be dispensed with.

Mr. Lindley

Before discussing the Papers in more detail, Mr. Lindley would offer what he was able to contribute to the subject. He had arrived at a diagram on which to plot flood data of different catchments for comparison, the basis of which was shown in *Fig. 4*, namely, a pair of triangles having angles of 90, 60, and 30 degrees. AB was the direction of the axis of co-ordinates for plotting areas, and the unit length for the logarithmic scale for plotting them; similarly AC was the direction and unit for discharges. It could be shown that CD was the direction and unit for discharge, and AD the direction and unit for the coefficient in the Ryves formula which made discharge proportional to the $\frac{3}{4}$ power of the area. On *Fig. 5* was also given a triangular scale by which to measure the exponent of any straight line drawn on the diagram; the scale for the Ryves coefficient was drawn through unit area, and so with any other exponent, the coefficient was given by the intersection of the corresponding line with this scale. The diagram might also be considered an ordinary logarithmic Cartesian diagram, with areas at right-angles to coefficients and plotted to half the scale for coefficients; superimposed on this was a second network, at 30 degrees to the first, with scales in the same ratio to each other and appropriate ratio to the first pair, representing discharge and run-off; to avoid a confusion of interlacing lines, the lines of this network were drawn only at unit intervals, the rest being represented by scales formed by their projections on the axes. The data plotted on the diagram were mostly Indian (black dots), but a few outstanding data were also given from other countries. Data which did not approach the maxima for their size of catchment were not shown. Research that was not possible in India and in a limited time would add to the data worth showing on the diagram. The Indian data plotted included those given in Colonel Hearn's Paper;

Fig. 4.



Mr. Lindley. also the three maxima given for the Damodar, of which the greatest was roughly put down as 850,000; most of the rest were among the data collected in the chapter "Maximum flow off a catchment" of

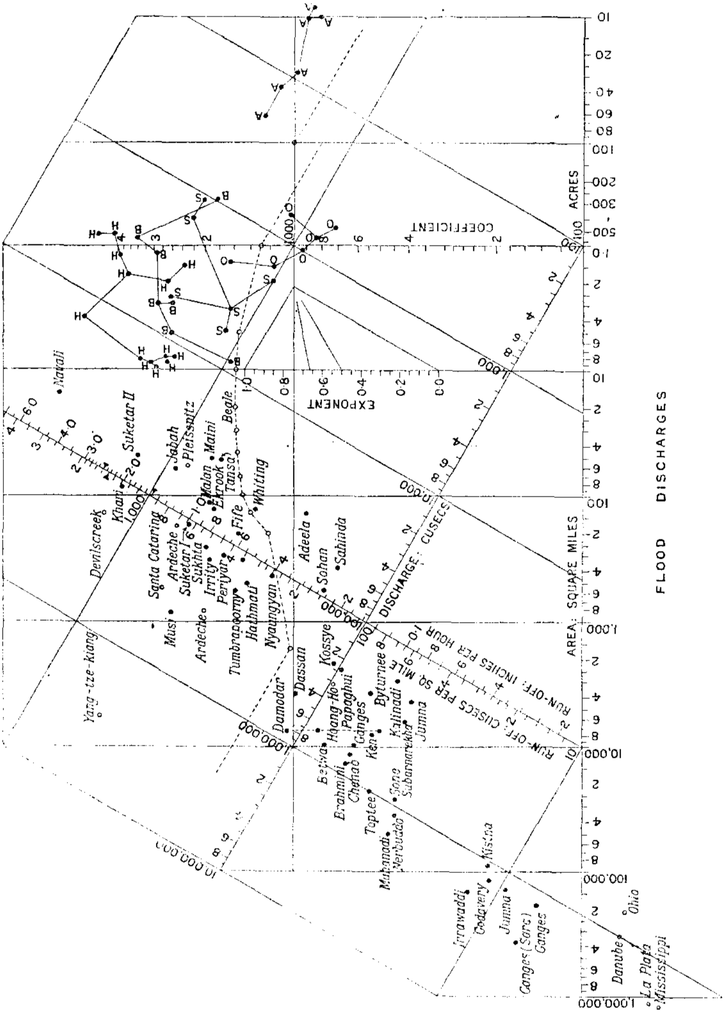


Fig. 5.

Mr. R. B. Buckley's Irrigation Pocket-book, except the Musi and Irrity, and the Ganges at Sara, taken from Sir Robert Gales's Paper on the bridge there.[1] Of the non-Indian data most (as well as the

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[1] Minutes of Proceedings Inst. C.E., vol. clxxiv, p. 1.

Mr. Lindley.

Musi and Irrity) were taken from p. 66 of Part IV of the Miami Reports; the Danube and Ohio were given by Mr. Buckley; the Hoang-ho was as estimated by Mr. John R. Freeman,[1] and the Yangtze-kiang was given by him.[2] The La Plata was said[3] to have a catchment of 1,200,000 square miles and discharge 2,150,000 cusecs; the Mississippi at New Orleans was said to have a catchment of 1,200,000 square miles and a discharge of 1,000,000 cusecs, while Mr. C. W. Chapin gave 2,000,000 cusecs[4] above the Red river, reduced below the junction by spills. Data of Beale's curve, referred to by Colonel Hearn, were also plotted.

Rarely would any estimate of the maximum possible flood-discharge at a site be so reliable that any method could be ignored which promised to give results—these could at least be compared with the results given by other methods. A method by which Mr. Lindley was now estimating floods at sites on the Punjab rivers contained a few points that were believed to be novel and worth describing; it entailed extrapolating from observed data. In a method commonly employed, the section of the valley up to flood-level was made to yield a gauge-area curve; from observations, velocities were plotted against gauges, and a fair curve was drawn and extended to maximum gauge; the products of areas and velocities yielded discharges from which a rating curve was constructed. This method was not applicable at most of the sites here referred to, because the river-bed was shifting sand; but there were possibilities in plotting discharges directly against gauges. When a discharge-curve was drawn with ordinary scales, in which equal increments on paper represented equal increments of the quantities, the curve was of a parabolic form. It was difficult to judge the best curve of such kind to draw through a plot of scattered points, and again difficult to judge a suitable decreasing curvature for the extrapolation. A correct principle in fitting curves to plotted points was to choose scales for the observed quantities such that the "curve" would become a straight line; this involved choosing a formula that would sufficiently fit the data, containing only two unknown variables. Such a course was not possible in the present problem, but it would be seen that a great improvement was possible. A common method of reducing curves to straight lines was to plot to logarithmic scales, that was, in effect, to assert that $D = kg^n$, where D

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[1] Transactions Am. Soc. C.E., vol. lxxxv, p. 1,423.

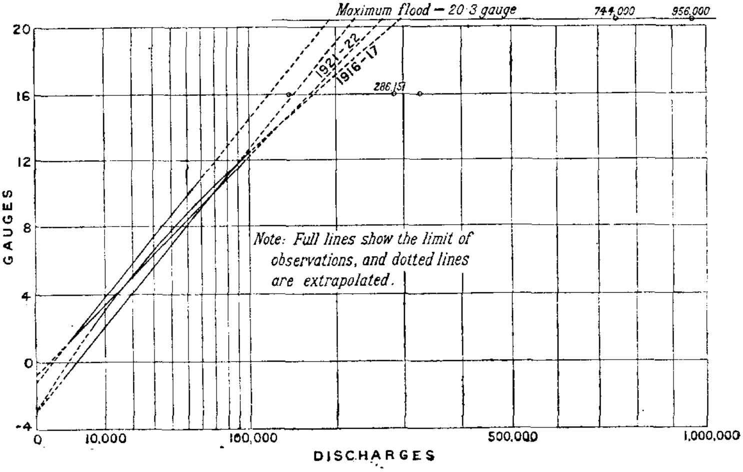
[2] *Ibid.*, p. 1,410.

[3] *Encyclopædia Britannica*, (11th ed.), xxi, 788.

[4] Proceedings Am. Soc. C.E., 1923, p. 1,634.

Mr. Lindley. was the discharge corresponding to any gauge-reading g, and k and n were unknowns to be ascertained for the site. Comparing this with an alternative formula, $D = k\ (g - s)^n$, in which s was the gauge-reading at virtual bed-level or at zero discharge, s was actually far more uncertain than n, and had been considered more likely to vary from time to time at a site. In a rectangular trough the discharge would vary as the 1·5 power of the depth, and in a triangular trough as the 2·5 power of the depth; it had therefore been thought that if the square-roots of discharges were plotted against gauges, the resulting discharge-curve should have at most a slight curvature in one sense or the other, which could be practically represented by a chain of straight lines of reasonable lengths. Trial showed that, more often than not, a single straight line served throughout the range of observed data. At some sites data of more than average reliability distinctly indicated a straight line, while where the data were sufficient but scattered, there was generally no more indication of curvature in one direction than in the other. He therefore used for his discharge investigations the squared paper shown in *Fig. 6*, on which an ordinary scale was used for gauges, and a square-root scale for discharges. To illustrate the application of the method, the estimate of maximum flood-discharge was shown for Haveli, on the Chenab below the confluence of the Jhelum and above the Ravi, the site for the headworks of a proposed feeder canal of the future. The data available were: daily discharge observations (with surface floats) for 2 years

Fig. 6.



Note: Full lines show the limit of observations, and dotted lines are extrapolated.

Mr. Lindley.

past; for 6 years before that fewer observations, but still sufficient to yield curves for the year; and for 12 years before that, only one to five observations a year. The last 2 years' data yielded a satisfactory straight line for each year, with no indication of curvature in one direction more than the other, and no indication of regular departure from the curve during the year beginning and ending with a flood season; of the 6 years before that, four similarly yielded straight lines, while two indicated curvature (which more observations might have shown to be erroneous). On plotting these on a single form, all lay within a strip bounded by parallel lines, though one line was diagonal to the strip, and some of the curves, when produced, came outside the produced bounding lines. In *Fig. 6* were shown these bounding lines, and such of the curves as would indicate a greater maximum flood by their extrapolation. It would be seen that by extrapolation the parallel strip covering the observations gave a maximum flood of 190,000 to 220,000 cusecs, while single curves gave 260,000 and 295,000. For the 12 years of few observations, lines were then drawn through the mean of the data of each year, with the inclination of the strip, and the gauge-readings that these gave for zero discharge were noted; these indicated that at the beginning of the period, when the maximum gauge also occurred, the river-bed was about that corresponding to the upper edge of the strip. The maximum possible flood at the site was therefore most unlikely to exceed 300,000 cusecs, might be as little as 190,000, and was most probably about 250,000. An estimate of maximum flood-discharge had been made when the canal project was drawn up, in 1915, just before the first set of data which yielded a discharge-curve for the year. The framer of the project managed to find data of a recent flood which led to estimates of 141,335 to 329,422 cusecs; he considered as nearest the mark the estimate which gave 286,151 cusecs; he extrapolated by an ordinary curve framed from the few local observations and some at a site below the Ravi confluence, and estimated the flood due to the maximum gauge as 744,000 cusecs. The Chief Engineer who reviewed the project, estimated for the full quantity of the Jhelum maximum flood at Rasul, 600,000, plus half the Chenab maximum flood at Khanki, 713,000, thus arriving at 956,000 cusecs at Haveli. The plot showed that all these estimates were utterly impossible. The figures incidentally showed how very greatly flood waves flattened out as they passed down such a river. Even allowing for the fact that the Rasul maximum was too great (he had calculated 25 per cent. less), and that the Khanki maximum possibly called for similar reduction, a flood of (say) 600,000 cusecs at Khanki joining a normal Jhelum monsoon flow of 25,000 would be

Mr. Lindley. expected to yield more than 300,000 cusecs at Haveli. But again, while the maximum flood of the Sutlej below the Beas confluence was estimated at 300,000 cusecs, just above the Chenab confluence he found it most improbably more than 220,000.

In Mr. Glass's Paper, on p. 334, "gaugings" were mentioned, which appeared to mean readings of water-level on a gauge; the term was frequently, if not generally, used for an observation of discharge. It would appear that no observations of discharge had been used in the investigation, the foundation for all discharge figures being calculations "from observed surface slopes with the use of Kutter's formula, due allowance being made for . . . scouring . . . during high floods." It would be interesting to have more detail of the observation of surface slopes, of the choice of Kutter's coefficient, and of the allowance for scour. The resulting estimate might be accurate enough for local purposes, but Mr. Lindley's experience did not lead to confidence in such observations and allowances. The surface slope of a river in flood varied greatly in short distances along its course, and from side to side. If the slope were observed on a distance long enough to cover such variations, the cross section must similarly be averaged for the same length; this point was raised by Mr. Lillie. Mr. Lindley once analysed for a flood estimate the observations of a site for 20 years; the averages of coefficients for even 5-year periods varied by about 10 per cent. Allowance for scour was even more doubtful. The investigation was most sound in estimating not merely an absolute maximum, without regard to its possible frequency, but the maxima likely to occur with different frequencies. Comparatively seldom was provision against an absolute maximum worth the cost; in many cases it was sufficient to secure, for example, that a road should not be flooded more than a few times in a year, or more than a few hours at a time, nor be damaged.

Mr. Lillie's formula contained functions only of mean annual rainfall, size, and shape of catchment; it gave a "standard" area of flood cross section, leaving discharge to be calculated from this and average river-gradient. Colonel Hearn showed that maximum rainfall-intensities of short duration were the same in dry and wet parts of the world; dealing only with small areas, he therefore ignored variation of rainfall. Mr. Beale had proposed similarly to ignore variation of rainfall, and had not confined himself to small catchments; he had dealt only with the tract on the eastern slopes of the Western Ghats near Bombay, but there the annual rainfall ranged from 300 inches at the crests to 30 inches farther down the valleys. He argued that annual rainfall did not affect the volume of maximum

Mr. Lindley.

floods, but only their frequency. The assumption appeared to be correct for quite small catchments; it would again be correct at the upper limit of area, since such a catchment would include zones of all degrees of dryness. Examination of any considerable collection of data showed that between the limits there was variation; this could probably be related roughly with the annual rainfall, and perhaps more accurately with the rainfall of a shorter period.

Colonel Hearn divided catchments into four classes according to their shape, and assigned to each a shape factor by rough estimate; Mr. Lillie provided a way of measuring the shape factor, his measure being in effect the perimeter resolved normally to radii through the point of discharge and integrated. To make this truly a measure of shape, independent of size, it required to be divided by the square-root of the area. When greater exactness in estimating floods from catchments became feasible, allowance would have to be made also for the "internal shape" of the catchment, namely, the degree to which it diverged from the tacit assumption that flow from all points was straight to the point of discharge. Mr. Lillie measured size by the greatest length; thus this factor made a difference, which it should not, between two areas of the same size but of different shape. Shape having been taken into account, the only measure of size that was independent of shape was area. The connection of the function of size given with the Craig formula was not understood.

Colonel Hearn's curve of "rainfall intensity," *Fig. 3* (p. 273), was his measure of the effect of variation of size alone, derived from data. In the following brief tabulation were given values read from his Table, and values according to Mr. Lillie's function made to agree at 1 square mile:—

Area.	½	1	2	3	4	6	8	10
Hearn . .	4·8	4·0	3·3	2·9	2·7	2·25	1·95	1·75
Lillie . .	5·8	4·0	2·55	1·9	1·55	1·14	0·91	0·76

Mr. Lillie's function, moreover, would give negative results for areas less than about 10 acres. One of Mr. Lillie's conclusions from theory was that the discharges from small catchments varied directly as the area, and from big catchments as the square-root of the area. Mr. Lindley's plotting of data in *Fig. 5* (p. 400) showed a much lower rate of variation of discharge with big areas; in fact the curve seemed asymptotic to constant discharge independent of area.

Mr. Lindley. The following brief tabulation gave rough figures for run-off in inches, of different areas, according to a curve embracing Mr. Lindley's data, and corresponding figures by Mr. Lillie's function, made to agree at 1 square mile :—

Area.	10^{-2}	10^{-1}	10^{0}	10^{1}	10^{2}	10^{3}	10^{4}	10^{5}	10^{6}
Lillie . .	3·65	6·9	4·0	1·85	0·76	0·30	0·11	0·04	0·015
Lindley . .	5·0	5·0	4·0	3·0	1·5	0·6	0·15	0·025	0·003

A factor that neither of the Papers had taken into account was the flattening of the wave of a flood as it passed down the river, through the variation of its surface slopes from the mean, and through storage in the increased section. In dealing with the discharge at Haveli Mr. Lindley had cited two instances of actual decrease of this nature. In the investigation of Punjab river-discharges which was under his direction, he hoped during the coming flood-season to secure more precise and fuller data of the flattening of flood-waves at four stations on the Sutlej, between the Beas and Chenab confluences.

Colonel Hearn's curve of rainfall-intensity (of run-off) might be compared with the curves in a Paper by Mr. F. A. Marston, published for discussion in the Proceedings of the American Society of Civil Engineers for January, 1924 ; these curves showed, for storms of different intensities and duration, the way in which average intensity decreased as a greater area about the storm-centre was taken. The curves were of the same nature as Colonel Hearn's, but less steep ; this was to be expected, as his curve was in effect one in which, with increasing area, increasing duration had also to be allowed.

The series of Mississippi formulas, of which Mr. Lillie quoted one, was not even to be found in many reference-books.

Mr. Ockerson. Mr. J. A. OCKERSON, Member of the Mississippi River Commission, remarked that very careful consideration had evidently been given to the subjects discussed, and, being unacquainted with the physiography of the localities described, he necessarily hesitated to take up the discussion where the details bore evidence of much study by the respective Authors. Mr. Glass's reference to the use of retarding-basins suggested the propriety of offering a few remarks from Mr. Ockerson's own experience, although the difference in the magnitude of the problems was great. The Damodar had a catchment-area of 8,200 square miles, while the

Mr. Ockersón.

Mississippi river watershed measured 1,240,000 square miles. The flood-discharge of the latter at the mouth of the Ohio, 1,074 miles above the mouth of the Mississippi, was 2 million cusecs as against the 400,000 to 650,000 cusecs of the Damodar. The two rivers were similar in this respect, that both streams had excessive floods in 1913. The great floods of the lower Mississippi occurred from February to April, and came largely from the Ohio basin. On the delta portion of the Mississippi the increase in the height of flood stages had been progressive since 1882, when active flood-control work began. The area subject to overflow measured some 29,000 square miles, the basins being in places 65 miles wide. Levees (earthen embankments) built along and near the river-banks, reduced this width to a mile or two, which was the direct cause of increasing the flood height. These levees, about 1,800 miles in length, contained about 415 million cubic yards of earthwork. The expenditure on this work since 1882 had been $193,364,295, and there remained about 86 million cubic yards of earthwork to be done to complete the controlling-levee line. Mr. Glass was correct in his claim that in a sedimentary stream flowing in a shifting bed of its own formation, with banks of friable material, the relations between stage and discharge were variable, and gauge relations were far from constant. The character of the floods themselves, and the rate at which they rose, affected the velocity and volume of discharge. Stage was only an approximate measure of the volume of discharge. The work in the Miami Conservancy District, Ohio, was a good example of the use of retarding-basins for the prevention of floods. The watershed covered an area of 3,800 square miles. The storm of March 23rd to 27th, 1913, was the greatest on record in this region, the average rainfall for the entire basin being 8·8 inches. Over 400 persons lost their lives, and the loss of property exceeded 67 million dollars. After thorough inspection and study of the situation, the Board of Consulting Engineers, of which Mr. Ockerson was a member, recommended the construction of five detention-basins for the prevention of destructive floods in that district in the future. These recommendations were adopted, and the work—largely carried on throughout the war period—had been completed at a cost of about 32 million dollars. The use of detention-basins was a very attractive means of controlling floods, but it had seldom been applied to purposes of flood-control, because the catchment-areas were rarely adapted to such use. In the case of the immense drainage-area of the Mississippi river, the popular mind demanded the use of reservoirs for flood-control. Reservoir-sites were few and not well situated for storage of flood-waters; then, too, the locus of great

Mr. Ockerson. rainstorms was not the same, but changed from time to time, which would require reservoirs at different sites to meet these conditions, rather than sites fitted by natural configuration of the ground for such use. It was estimated that the Mississippi river flood of 1922 would have required a reservoir, at or near the mouth of the Ohio river, with an area of 4,235 square miles, 15 feet in depth, in order to lower the flood-level 2 feet at New Orleans. So the consideration of reservoirs in the scheme of flood-control on the Mississippi river had virtually been rejected, and control by means of levees adopted. These few remarks were not offered as discussion of the Papers, but might be acceptable as coming from experiences in a vastly greater field.

Mr. Olive. Mr. W. T. Olive considered that such formulas as that proposed by Colonel Hearn depended on too many uncertain elements, some of which must be guessed at. It was not possible to determine either the total rainfall or its intensity in any given flood; and the discharge was affected by many local and climatic conditions, ranging from total absorption of the rainfall in arid country to the waterproofing effects of frost and ice.

He was entirely in accord with Mr. Lillie on the impossibility of obtaining the flood-discharge from a large area, either by highest flood-marks or by a discharge-formula. As to the latter, how was it possible to synchronize the many factors involved in the consideration of all the elements of the problem? For very small areas, such as in urban districts, it was possible, under good conditions, to arrive at a fair approximation to the discharge by treating the area in sections, especially should rainfall-intensity observations be available; for time was one of the most important factors. He concurred that rivers rarely had anything like a constant slope. Mr. Lillie admitted that the statistics in India were only of daily rainfall and did not indicate intensity; also, the important matters—intensity and duration of phenomenal downpour—were independent of the annual rainfall: in fact, the conclusion was that engineers could not generalize on these matters.

The excellent Paper by Mr. Glass endorsed Mr. Olive's own view that the only reliable gaugings of flow were actual observations, scientifically made, and extending over a considerable period of time.

Sir Francis Spring. Sir Francis Spring observed that the profession, and more particularly those members of it who practised in India and the East, must be grateful to the Authors. He found special interest in their Papers because of his own acquaintance with many of the localities referred to, which enabled him clearly to visualize the characters of the average surfaces of many of the areas dealt with

Sir Francis Spring.

in the Papers. Having frequently, during a long engineering career in India, had to calculate, or to satisfy himself in regard to others' calculations of, the waterways of bridges and culverts, large and small, chiefly under railways, and having been brought in contact with many cases where the inadequacy of such works, due to the calculations for them being based on what was not, and was incapable of becoming, an exact science, had led to disastrous breaches of communications, he welcomed any intelligent analysis likely to render such calculations less unreliable than they most certainly were now under the usual formulas. In confirmation of some of the heavy rainfalls recorded in the Papers, he would like to mention a case that came to his official notice in or about the year 1896. It was a case of proved inadequacy of some openings on the Assam–Bengal Railway, south of the Barak river. The area concerned just there was a great tea-growing district, and the presence of intelligent tea-planters at a few miles intervals, all round the breach, made it possible to get hold of the fact that three independent rain-gauges, located more or less at the angles of an equilateral triangle 5 miles on a side, showed 36 inches of rain to have fallen in 36 hours. He remembered having known of a 4-inch fall in 1 hour on another occasion.

Mr. Glass offered to the profession a mass of valuable information about a certain much-gauged river—information which, but for his industry in bringing it forward into accessible shape, might have remained buried in the record rooms and useless for all scientific purposes. He presented his studies with a view rather to the information of engineers concerned with floods as affecting cultivation than, as in the other two Papers, as affecting the designs of waterways under roads and railways.

Colonel Hearn was right in drawing special attention to three of the factors influencing flood-discharge, namely, soil, slope, and protection. He made certain suggestions as to the collection and record of facts relating to actual floods. In Sir Francis Spring's experience it was extremely difficult, in ordinary routine working, to get hold of such facts. The engineer in charge of a section of railway containing, perhaps, hundreds of openings, would seldom find it feasible, at the critical moment of flood-peak, to be on the spot, equipped with adequate current-meters as well as with gear for holding them in position in the strong current. And yet, in the absence of large numbers of such measurements, there was not much hope of arriving at a reliable formula. The number of close coincidences between rainfall per hour, as given in Colonel Hearn's curve in Appendix V, and those given in the penultimate column as

Sir Francis Spring.

"Established Rainfall," as deduced, presumably, from rain-gauge observations, was, to say the least of it, very remarkable, affording good evidence in favour of his formula. In Sir Francis Spring's opinion, engineers owed a debt of gratitude to Colonel Hearn for the industry with which he had collected figures of rainfall and put them on record where they could be found when needed for waterway calculations.

Whether Mr. Lillie's reasoning were judged to be sound or unsound, it seemed advisable to look into the elements of his formula $D = VR\lambda\Sigma(\theta L)$ in order to be satisfied that they were such as would be ready to hand when needed. First of all $\Sigma(\theta L)$ was merely a matter of the drawing-board, and λ, or $1{\cdot}1 + \log L$, was also, of course, at once got off the drawing-board. R, or $2 + \frac{\text{annual rainfall}}{15}$, was obtainable from the data that must have been collected. Lastly came V, the velocity dependent on the slope element, and even if Mr. Lillie's arguments were accepted and it was agreed that the other three elements of the formula correctly represented the influences, on maximum discharges, of size, shape, and rainfall, a doubt must still remain as to the value to be attached to V. And, moreover, this doubt was particularly difficult of solution. Usually—in great parts of India at least—fully half or three-quarters of the waterways to be bridged, in a given section of railway, had to be designed for the passing through them of floods from catchments having no very defined channel of discharge; and it was difficult in such cases to estimate a probable value for V. For small and well-defined rivers Kutter's formula, and for the larger class of rivers the Mississippi formula, would probably prove to be quite near enough, considering the possibility of permissible bed-scour, and always provided that the necessary data were forthcoming. When it was at all practicable, as had been the case, for example, when the Ganges was being gauged in anticipation of Sir Robert Gales's bridging of it at Sara, velocities ought to be taken, scientifically, right across the river, at depths deliberately chosen.[1] But, for one cause or another, all that might prove practicable would be to estimate the velocity from the general inclination of the river-bed, by some chosen formula. Should it so happen that, when searching for a representative maximum mean velocity, the observer was unable to hit off the moment of maximum flood-rate

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[1] Sir F. Spring. "River Training and Control," chap. xxv, Figs. 2 and 3, Plate xlix. Simla, 1903.

Sir Francis Spring.

—a maximum that might not occur more than twice or thrice in a century, though its height might be known nearly enough from local evidence—it could be seen from the Plate referred to in the footnote to p. 410, how a reasoned estimate might be made of what the maximum discharge was likely to be when the critical flood arrived. With regard to the difficulty of estimating probable velocities in the very numerous cases where there was no well-defined channel, and where perhaps the cross slope of the country was either almost level or very ill-defined, all that could be done was to decide, from observation, what kind of velocities the soil could stand at the site of the waterway without being unduly scoured—"undue scour" being of course dependent on foundation design. Thus, when the bridge or culvert bed was rock, there might be no harm in allowing an afflux giving anything up to 20 feet per second through the opening; whereas, if it was sand, no more than 5 feet per second might be safe for shallow, but of course more for deeper, foundations. Permissible height of afflux would be a matter for decision in accordance with the engineer's judgment and experience. Next he must see to the design of the height of his embankments, so that the upstream afflux, over and above the water-level due merely to S, should neither result in the topping of the bank nor in the washing of the underside of the arch or girders. Then, with regard to the actual scouring effect due to the allowed velocity, he must use his judgment in fixing the depth of the foundations, as well as in the design of the flooring, if any, and of the downstream loose-stone pitching, or apron, and especially the last, so that the permitting of an afflux should not result in such scour as would undermine the structure. The ideal conditions would be that the water, at the time of worst flood, should pass through the opening provided for it, devoid of afflux, at the velocity strictly due to the slope and other factors on which it depended, and without any deepening whatever of the bed by scour. In practice, however, the structure of the bridge or of the culvert ought to have been so designed and built that a certain amount of scour would not do any harm, or, as concerned the banks, a certain amount of afflux either. Such considerations as these seemed to lead to the conclusion that it did not really matter very much if the calculation of waterways was not an exact science. For, if he chose to use them, the engineer had at his command practical alternatives for structural design which, provided he exercised sound judgment, might be trusted to safeguard him from the effects of under-calculation—within reason.

None of the Papers made mention of a potent cause of certain disastrous breaches of communications that were quite common in

Sir Francis Spring. parts of India, and especially on the Eastern side. This class of disaster being, from its nature, outside the scope of all formulas, it was not to be expected that Papers on the subject of discharge formulas should refer to it. But as the subject to the fore was the design of waterways and the effect of their design on communications—the latter indeed being the essential point of the whole discussion—it seemed permissible to mention a class of occurrence that was a source of continual danger to roads and railways in certain parts of India—say, of an area equal to that of the British Isles. In the parts referred to it had been the immemorial custom for the farmers to throw light earthen embankments across the valleys—often nearly imperceptible valleys—of what, to the eye, seemed perhaps a level and valleyless country. The consequence was that, after the rainy season, there was to be found a shallow and more or less extensive lake at the upstream side of each such embankment. These shallow lakes, locally called "tanks," were furnished with primitive sluices for drawing off the water for the use of the crops below them, as well as with more or less—oftener less—effective waste weirs for surplus rainfall. Usually there was to be found in each valley a series of these tanks, each taking the overflow of the tank next above it, as well as its own proper rainfall. Many of these tanks had an area of several square miles, and at one time of the year there might be, in a district the size of Yorkshire, more water visible than land, whereas 3 or 4 months later, when the tanks had been drained for irrigation, the conditions were reversed. The breaching of a chain of these tanks was often the cause of disastrous washaways on the railways.

In Mr. Lillie's reference to Mr. W. A. Buyers's report on certain washaways on the East Indian Railway, notice was taken of a very frequent cause of breaches, in large tracts of unfenced and comparatively level parts of India, namely, that a river, having overflowed its banks, ran along parallel to a railway-bank, perhaps for a mile or so, and cut into the bank before finding its way into the bridge-opening designed for it. This particular trouble was very fully handled in Sir Francis Spring's book already referred to. The cure, now in everyday use in India, lay in the provision of suitably designed "Bell bunds" a pair of which, at right angles to and upstream from the bridge, would keep the flood approach current at a safe distance from the main railway-banks.

In India the usual conditions that an engineer had to face, in the application of such formulas as were under discussion, were either a breach of existing communications due to exceptional rainfall or the design of an entirely new group of waterways, later

Sir Francis Spring.

to become a reality. In the former case he usually would have plenty of data. In the latter he might or might not have the benefit of adequate Ordnance maps and rain-gaugings, and at least he could get surveys made of catchments and slopes. Then, for the guidance of his staff, he must choose some formula, for application perhaps to several hundred catchments of varying sizes, shapes, slopes, rainfall, and capacity for absorption, or facility for discharge; and he would have to see that the chosen formula was not applied as if it were a law of the Medes and Persians, but with discretion and judgment.

The Papers would have served a good purpose and have led to the saving of much money—in India practically all public money—if they led to further intelligent investigation and the unearthing of some of the masses of valuable evidence now hidden and accessible only with difficulty in public record rooms. It could hardly be expected that a formula would be found that would be applicable to all cases. But at least such information might be made available as would enable engineers to make more intelligent use of their chosen formulas, because of a better knowledge of the factors and principles involved. The following comparison, between what were given as measured discharges off four of the many catchments cited by Mr. Lillie and the discharges calculated by his formula, made for confidence in the formula :—

Rivers.	Measured *S*.	Formula *S*.
Irrawaddy . . .	205,617	219,000
Chambal	50,000	44,920
Kala Nadi . . .	23,323	23,100
Amjar	7,500	7,580

In Sir Francis Spring's opinion, Mr. Lillie's Paper constituted a valuable contribution to the intelligent treatment of a difficult and, in the past, much-discussed subject. It now remained to be seen whether a general use of his method would result in its gaining the confidence of engineers working in India and the East. The test, in the long run, would be whether its coming into general use, in lieu of older formulas, was found to have the effect of reducing the number of small and large breaches of communications that, during the monsoon seasons, were so common and so disastrous.

Sir Francis Spring. It was much to be desired that the Railway Board, who had the power, presumably, to initiate anything of the sort, if they thought well of it, or perhaps the Institution of Engineers, India, should organize the collection of data, for type catchments, in various climates, through the engineers of the several Railway-Working Agencies. Such an inquiry ought to have the effect not only of saving much of the cost now incurred in the rebuilding of damaged works, but also of reducing the loss of earnings—in India mostly public revenue—to say nothing of public inconvenience, caused by one railway or another, almost every year, having to refuse, or to delay the transit of, traffic offering. Work of the sort suggested was not too easy; but much might be done by the use of self-registering upstream and downstream gauges. Moreover, if discharges less than the highest were measured fairly accurately with current-meters, curves could be drawn that might be relied on, if intelligently used, to give probable discharges during what were judged, for local reasons, to be periods of maxima.

Mr. Temple. Mr. F. C. TEMPLE remarked that, having worked for the last 15 years in a country liable to heavy floods, and having during that period been in charge of the construction and maintenance of roads and their bridges, and of drains and sewers, he had read the Papers with particular interest. They added appreciably to the information available to the engineer engaged on such work in India, and might help him in deciding how far he was justified in spending money in constructing works to take care of the abnormal flood, which could be expected at any time in the tropics, and which yet was not to be expected, apparently, more than perhaps once in 50 years. A handicap generally was occasioned by the extreme scarcity of funds available, as well as by the lack of precise data on which to base calculations. His own practice had been, wherever possible, to provide breaching-sections of road-banks at the approaches to important bridges, at points where the breach could easily be repaired; to cut down long lengths of road in moderately high country, which was only subject to submergence of 12 to 18 inches in high floods, so that water would flow over the road almost unobstructed; to keep storm-water out of sewers as far as possible and to make the sewers only large enough to take the minimum quantity that could not be prevented from entering; and to make surface drains on a rule-of-thumb method to deal with all but an exceptional downfall. This was an unscientific method, but one certainly followed by a good many engineers; and these Papers should help to eliminate some of the uncertain factors.

Mr. Thrupp.

Mr. Edgar C. Thrupp observed that it might be interesting to give a few particulars and figures with regard to the Fraser and Thompson rivers in British Columbia, to compare with the data contained in the three Papers under discussion. In these watersheds the flood-discharges of small areas of 20 square miles or less were caused by cloudbursts as in other parts of the world, but the flood-discharges of large areas were caused mainly by melting snow, and only to a limited extent by heavy rainfall. The usual period of maximum flood was the end of May and the beginning of June, and the greatest flood on record occurred at that time in 1894, when certain flood-levels were noted, but no actual river-gaugings were taken. Since then the Government hydrographic service had been established, and a very valuable stock of data was being accumulated, although no flood approaching that of 1894 had yet been measured. He had, however, studied the gaugings and the flood-levels recorded, and had arrived at a figure for the 1894 flood-discharge of the combined Fraser and Thompson rivers at Lytton which might be taken as reasonably accurate. The Government gaugings had established discharge-rates up to a rise of 38·5 feet, with a discharge of 182,000 cusecs from the Fraser and 110,000 cusecs from the Thompson, or a combined flow of 292,000 cusecs. Extending the discharge-curve up to the 63·5-foot level reached in 1894 showed a discharge of 600,000 cusecs. This great rise was due to the restriction of the Fraser at the Kanaka gorge, where the sides were solid rock and practically vertical, so there was no risk of serious error due to irregular expanding sectional areas at the higher levels. The discharge-curve was similar to that of one gigantic sluiceway. The contributing areas at that point were 63,000 square miles on the Fraser and 21,000 square miles on the Thompson, or 84,000 square miles in all. Comparison of these figures with the case of the Damodar showed that the Indian river gave a greater flood-discharge with less than one-tenth of the area, namely, 650,000 cusecs from 7,200 square miles. The exceptional conditions of the 1894 flood were, a heavy snowfall in the previous winter, a late spring, and a sudden change to hot weather in May. These conditions seemed to have extended over the whole area and the adjoining watershed of the Columbia river, and the hot spell to have lasted long enough to wipe out the usual effect of shape and size of the areas. Subject to the fact that the normal annual discharge of the Fraser was 14 inches and of the Thompson 18 inches, the ordinary high-water discharges did show the influences of shape and size. The Fraser had a maximum run of about 500 miles to Lytton and the Thompson less than 250 miles. It would be seen that, while the areas were in the

Mr. Thrupp. ratio of 3 to 1 (or 75 per cent. and 25 per cent. of the whole) the ordinary high-water discharges were in the ratio of 62·5 to 37·5; but during the winter months the Fraser generally yielded more than double the flow of the Thompson. In India the chief motives for study of this subject were economy in railway construction and embankment of low-lying lands, with comparatively little interest in the possibility of hydro-electric developments by dams built across the rivers. In British Columbia the latter question would become very prominent in the future, for although there was a wide fluctuation in the flow of these rivers, it was quite within reason to handle the flood-discharges and to regulate the low-water flow sufficiently to make all-the-year-round power a commercial possibility. The two rivers, Fraser and Thompson, had in their water-sheds lakes aggregating over 1,250 square miles in area and situated at elevations between 1,100 and more than 2,500 feet above sea-level, and it would be a simple engineering feat to construct regulating-dams at the outlets of those lakes to give a general average low-water flow of one-tenth of the 1894 flood-discharge or 60,000 cusecs at Lytton, which was itself 700 feet above sea-level. When this problem had been seriously worked out in British Columbia it would be found that about 12 million HP. could be economically developed in the southern half of the province alone, and probably well over 20 million HP. in the whole province, which would place it in the front rank as a great prospective industrial country.

Mr. Wadley. Mr. A. J. **Wadley** remarked that it was not often that an engineer had at his command the rainfall records for more than a quarter of a century of no less than twenty-five rain-gauge stations situated in and around the catchment-area—also the river-gaugings for 62 years. More usually he had to compile the hydrography of the rainfall and the catchments during the periods of surveying, designing, and construction of works. Mr. Glass was to be congratulated, however, on the ingenious method by which the available information had been collated and analysed. As often happened, the records were far more complete for the unsatisfactory Edilpur site than for the more stable Raniganj site. The disadvantage of depending upon the readings of a gauge at the margin of a river was, that it did not record the flood-hump or piling-up which took place wherever the maximum velocities occurred. It had been stated[1] that the flood-hump of the Colorado River had been 50 feet higher than the water at the margins. Such a hump might well amount to 2 or 3 feet even in a navigable river like the Damodar. Mr. Glass was to be

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[1] *The Sketch*, 31st July, 1907.

Mr. Wadley.

congratulated on the adroitness with which the desired hydrographic information had been extracted by means of the rainfall contours and tabulated areas given in Figs. 7–10, Plate 4. The Hooghly skirted the base of the Damodar's deltaic cone, and the dangerous "James and Mary" quicksands lay just below the junction of the two rivers. The Author mentioned the sand-carrying proclivities of the Damodar floods, and in that connection the flood-detention scheme, if constructed, should rob the quicksands of their terrors, and render the Damodar easy and safe to embank, assuming that the life of the reservoirs would be duly conserved by proper attention to afforestation in the catchment. The Bengal engineers had ascertained that the bed of the Damodar had been slowly rising at the rate of 1 foot 2 inches per decade since 1888. The tendency of silt-bearing rivers to swing across their deltas in the process of advancing them was well known. The rising of the bed was one of the earliest premonitions of an impending change of course. As the hydrology of the Damodar was linked with that of the Hooghly, the contemplated flood-detention scheme would improve the regime of both rivers, since the tendency would be for both of them to deepen their beds to a small extent, owing to the reduction of the silt-charge in the Damodar. This silt-charge was so enormous during floods, under existing conditions, that a vessel was quickly overturned and buried by waves of rolling sand, if she unfortunately touched the river-bed in the "James and Mary."

Colonel Hearn's Paper was of especial technical interest. He showed how much easier it was for the storm-centre to lie in the middle of small than of large catchments. Few would disagree with his conclusion that it was safe to allow for a high intensity of downpour in the case of small catchments. Two other important questions were raised by Colonel Hearn: What influence had slope upon the synchronism or "time" of the catchment, and what was the effect of bare slopes as compared with covered slopes? He might have gone further by studying the volume of silt borne in floods from bare, sandy catchments, as perhaps palpably increasing the flow; also the further question of the condition of saturation in which the high-intensity downpour was likely to find the catchment, as indicated by the monsoon rainfall. All of these were absorbing questions. Colonel Hearn would perhaps find it helpful to tap the information collected and the methods adopted in arriving at the waterways of the masonry works on the Upper and Lower Swat River Canals, N.W.F. Province.[1] The discharges

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[1] Proceedings Punjab P.W.D. Congress, vol. iii (1915), p. 103.

Mr. Wadley. observed in the hilly region near Malakand might be especially serviceable for the Khyber. Three factors were taken into consideration, namely :—

(1) The size of the catchment;
(2) Whether it was in the hills, i.e., a steep catchment;
(3) Its distance from the hills, i.e., a catchment becoming flatter as the hills receded.

Under (1) catchments were graded into seven sizes, namely, 0 to $2\frac{1}{2}$ square miles, $2\frac{1}{2}$ to 5, 5 to $7\frac{1}{2}$, $7\frac{1}{2}$ to 10, 10 to 15, 15 to 50, and above 50 square miles. Under (2) the discharge allowed (in cusecs per square mile) was 2,400, 2,000, 1,750, 1,500, 1,250, 1,000 and 800, respectively, according to the size of catchment. Under (3) these figures were reduced, as the hills receded, to two-thirds of the discharge allowance for catchments within a zone distant 5 to 10 miles from the hills, and to one-half the discharge allowance for catchments 10 to 15 miles from the hills. A more recent summary regarding the Pabbi Hill torrents would be found at p. 306 of Buckley's "Irrigation Pocket Book," third edition, 1920.

He congratulated Mr. Lillie on the able and thorough manner in which he had dealt with the subject. The inclusion of one-fifteenth of the rainfall with the phenomenal downpour, constituted what might be called the saturation factor for the district and made the formula as comprehensive as possible. He presumed that Mr. Lillie would provide diagrams from which the values of $\Sigma\ (\theta L)$ could be taken and the values of S, the standard cross section, if possible. He was unable to follow the method for determining V, the standard velocity, unless a value for the hydraulic mean depth was assumed; and as far as he could see there was nothing to guide an engineer in assuming such a value except the wetted perimeter of the observed cross section S', at the discharge-point. He wished the Author had given a fully-worked example. But having assumed the hydraulic mean depth, it was understood that V could be calculated with the aid of the general slope, ascertained from the levels given on the map. Another point he could not follow was the need for deducting the Chulis falls, as was done in the case of the Chambal river. If all falls were to be deducted from the "general slope," matters became complicated. It would mean an expedition up the river-bed to its source to measure them. He was inclined to think Mr. Lillie did not intend that. The "general slope," as determined from map contours, etc., could not be an exact figure requiring such elaboration.

What surprised him was that, as far as he was aware, no hydraulician had yet attempted to determine the velocity at a discharge-site from a mechanical analysis of the detritus found on and in the bed at the site. These materials wrote all the bed velocities with the utmost persistence. It was merely because engineers were unable to read what was written, that they did not make use of their records. Mr. Wadley.

Sir T. R. J. Ward remarked that he had had unusual opportunities to recover flood-discharges by direct calculation from marks pointed out by the dwellers on the banks of the rivers. This experience might be of use, and might not be out of place in the discussion on these three interesting and valuable Papers. Unfortunately, he was not able to consult notes, and could only give the broad results. Early in 1903 he was in Seistan, the terminal basin of the Helmand and several other rivers, that drained a very large area in Afghanistan, British Baluchistan, and Persia. Reliable information about the flood volume of the Helmand was required. The rivers had dried up below Rudbar during the previous summer—this occurred periodically about once in 30 years; the terminal lake of Hamun, too, had practically dried up; but the winter and spring floods of 1902–1903 had refilled the Hamun so that it overflowed into the terminal basin, the Gaud-i-Zirreh, which only happened about once in a decade. He was away when the maximum flood came down, but Khan Sahib Ghulum Qadir, Assistant Engineer, Punjab Irrigation Service, took the discharges with the help of some boatmen from the Punjab, a class renowned for their skill, using an 8-foot Berthon boat and a Cooke level with stadia points. The volume worked out to be about 70,000 cusecs. Discussing the season's floods with the people, he learned that in the spring of 1885 an unprecedented flood occurred; and in the course of a journey of about 100 miles up the river to Rudbar, the flock-owners living on its banks showed him marks on to which he levelled and in this way obtained the volume of that flood at several places. The agreement was good, and the volume was some four or five times that of the flood actually measured in 1903. In the year of the 1885 flood, military and political parties passed along this part of the Helmand on their way to and from the Russo-Afghan Boundary Delimitation Commission, about the time of the Panjdeh incident; and one of their surveyors, Khan Bahadur Sheikh Mohiuddin, who mapped this country in 1885, accompanied his levelling party; a few years later he perished of thirst, and his glorious death in the cause of his profession had been often Sir T. Ward.

Sir T. Ward. described[1]. The flood was thus authenticated, but no information from which its volume could be calculated was obtainable from the maps or diaries. People the world over, who lived by herding animals, seemed to be very observant and to have reliable memories, but in addition to the points obtained from men who showed the place to which they had driven their flocks, or moved their camps for safety during the flood, was the mark of the water delicately pencilled in fine silt on the cliff, as if laid on with a brush. The Helmand had here cut for itself a gorge in the compact clay 200–300 feet deep and of widths ranging from 1 mile to 3 miles. This flood had overtopped the wind and weather line often found on vertical clay banks about 3 feet or so above the normal high river, and the people, to his astonishment, were able to show him, at places where the cliff was favourably placed, the actual mark of the water traceable for yards and easily found by any one whose attention had been attracted to it. On his return to the Punjab canals in 1906, he was able to utilize this experience to obtain data for the design of cross-drainage works on the Upper Jhelum Canal Project. The preparation of working-drawings had just been started, but the monsoon rainfall had shown that the provision for maximum flood-discharge made in the project estimates was insufficient, and it was necessary to obtain reliable information of the maximum flood-volume. Some 10 or 15 years before, a great flood had occurred in the Jhelum river, which carried away the bridge at Baramulla, in Kashmir. The returns showed that the rainfall on the catchment of these torrents had also been very heavy. Among the marks of the flood shown to him were the fir-cones brought down by it which could still be found in places where they had been protected from wind and weather; also the platform of a water-mill in the river, on which its terrified owners had climbed to escape drowning. In this way a comparison of the flood-marks of the monsoon of 1906 with those of previous great floods was obtained. Again, in 1916 Sardar Bahadur Amir Singh, Deputy Collector, Punjab Irrigation Service, who had worked with him on the Helmand, was employed to trace flood-marks on the Indus at Kalabagh in connection with a project to build a barrage. He was also employed by the Military Works Service in 1918 across the frontier in enemy country, to obtain flood-marks from which to calculate volumes required for the design of an important bridge. In 1921 Sir Thomas Ward employed the same method at Delhi, but the level showed that the memories of town dwellers were not as reliable as those of people in desert places: the agreement

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[1] See Journal of the Royal Geographical Society, vol. xxviii (1906), p. 336.

Sir T. Ward.

was not satisfactory. A word might be useful on the technique of obtaining such information. The people he had referred to had the gift of narration. Their fancy having been kindled by a sympathetic interest in their experiences, the description ran on with the fidelity of a gramophone. If this was interrupted by a question, or the narrator's attention was distracted by a note-book, the spell was broken, and his information was apt to become unreliable. Conversation should tell whether the memory of the narrator was still good. The level was an invaluable aid in testing the information obtained at different places and from different sources at the same place. Discussion among the people usually elicited reliable information of the persons who had had experiences in a flood, who had lost animals, who were nearly drowned, or what not. The craftsmanship of tracing flood-marks could be improved by practice; this could be got by pegging-out floods whenever opportunity offered, and, when they had subsided, levelling over any marks found and comparing the result with those obtained from the readings on the pegs.

Mr. Williams.

Mr. G. Bransby Williams remarked that Mr. Glass's Paper was of great interest to engineers who had to deal with questions of discharges from catchments in India, and both the physical and the meteorological conditions in the area covered by his observations were typical of a large portion of that country. In an article on flood-discharge and dimensions of spillways in India,[1] Mr. Williams had shown that—accepting as correct Mr. Chamier's hypothesis that the maximum flood would generally be produced by the greatest possible rainfall of a duration corresponding to the length of time taken for the water to reach the point of discharge from the most distant point of the watershed—it was only necessary to know three things in order to discover the maximum possible flood from any catchment-area, namely: (1) The period of concentration of flow from the land within the watershed line, (2) the maximum possible rainfall during that period, and (3) the percentage of the rainfall to be allowed for as discharge before the peak of the discharge-curve. In his investigations he had confined himself to comparatively small watersheds, less than 100 square miles in extent, and it was interesting to observe how far the results arrived at in such cases were applicable to the very much larger area dealt with in Mr. Glass's Paper. The formula he used for the time of concentration was $t = \sqrt[5]{\frac{A^2}{h} + \frac{1}{D}}$ where t was the time of

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[1] *The Engineer*, vol. cxxxiv (1922), p. 321.

Mr. Williams. concentration in hours, A the area of the catchment in square miles, h the average fall in feet per 100 feet in the longest direction of the watershed, l the length of the watershed measured in that direction, and D the diameter of a circle of the same area as the watershed. In the case of the catchment of the Damodar above Raniganj these factors might be taken as $A = 7{,}000$, $h = 0{\cdot}25$, $l = 150$, and $D = 94$. If these values were inserted in the equation, the value of t found was 64 hours, which seemed to agree fairly well with Mr. Glass's curve for the critical period of rise of the probable maximum abnormal flood. The flood of August, 1913, reached its peak from the datum line in 35 hours, but the datum was 50,000 cusecs, and it might be presumed that the discharge of the Damodar was less than that when the flood commenced to rise. Assuming 64 hours as the theoretical time of concentration, his own figure for the maximum rate of rainfall that could be continuous throughout that period in a country with a mean annual rainfall of 60 inches would be $\frac{1}{3}$ inch per hour, or $21\frac{1}{3}$ inches total for the 64 hours; and the maximum percentage of this that would be expected to run off during the period of concentration, from undulating laterite land and wooded hill-slopes, would be about 45 per cent. At that rate the maximum possible discharge would work out to 672,000 cusecs, which was in excess of Mr. Glass's figure for the average extremely abnormal peak discharge, but appeared to be less than he considered possible in the maximum abnormal flood. Mr. Williams's figure for a mean annual rainfall of 50 inches would be lower than this, but he admitted that his estimate of the maximum discharge that could be expected, in a country with a mean rainfall of less than 60 inches, had probably been hitherto somewhat on the low side.

Most engineers concerned with questions of discharge would agree with Colonel Hearn that the existing formulas were unsatisfactory, and that no formula for maximum discharge could have anything but a limited application. The Tables at the end of Colonel Hearn's Paper were extremely interesting. The figures in Appendix II, many of which were new to Mr. Williams, certainly showed some remarkable downpours. The accuracy of some of the figures might, however, possibly be open to question, and in any case it might safely be assumed that the very intense rates of rainfall recorded were not likely to have extended very far, and that a rain-gauge even a few miles away would have recorded a very different quantity. Colonel Hearn's opinion, that any attempt to gauge the intensity of downpour on small areas by consideration of annual or monthly averages was not justified, was probably correct within

Mr. Williams. certain limits. It was true that storms occasionally occurred in the driest countries that equalled in intensity, for a short period, anything that could be expected even in places in a tropical country where the annual rainfall was over 100 inches. But there must obviously be a point beyond which this statement ceased to be correct, and for dealing with practical engineering problems it appeared to require qualification. No one, for instance, in designing a sewerage system for an English town would make sewers of a capacity to take a discharge of 4 inches of rain per hour, such as had been found necessary in the drains at Kurseong—a hill station in Bengal. Nor did the inhabitants of London expect to find the streets flooded to the depth of a foot or more several times in the course of one season, as was the common experience of the dweller in Calcutta, although the sewers in the latter city could carry many times the discharge for which the London sewers were designed. It was also impossible to imagine that Cairo could receive the whole of its average rainfall for 10 years in 1 day, whereas at Mahableshwar or Cherrapunji such a rate of rainfall would be a more or less ordinary occurrence. For ordinary engineering calculations the practice of making the estimate of the maximum flow depend to a certain extent upon the average annual or seasonal rainfall seemed to be justified, but of course this statement was subject to the proviso that, in cases where an underestimate of the discharge might result in a serious disaster, the calculated figure must be on the safe side.

Mr. Lillie was mainly concerned to arrive at a safe formula for the waterways of railway-bridges, which was a matter of the greatest importance. His formula seemed, in most of the examples he gave, to have produced results within the limits of safety; but in the important case of the flood on the Adjai in 1913 the waterway calculated by his formula would appear to be much too small. The method by which he had arrived at his formula was not at all convincing. It was, in fact, very difficult to follow, and the Paper seemed to suffer from some confusion of thought. He referred to the period of a "shower" as being something definite, and where the area of a catchment extended to that of the hypothetical shower a crucial size was supposed to be reached beyond which there was apparently expected to be some discontinuity of the curve of discharge. He omitted, however, to explain what he meant by a shower, and in the absence of such a definition it was not easy to understand why he expected to find any such marked change in the curve, of which, in fact, there seemed to be no evidence. Altogether his Paper appeared to be more interesting as an academical study than valuable as

Mr. Williams. a practical contribution to the solution of the engineering problems involved.

Colonel Hearn. Colonel HEARN, in reply, considered that the arguments in his Paper had been on the whole endorsed by the valuable communications elicited. He would like, however, to emphasize that the formula suggested by him represented an attempt to arrive at a relation between average rainfall-intensity and area, but that it was applicable only within limits. It was the equation for a curve which represented as nearly as possible that relation, as deduced from the discharge observations set forth in the Paper, those observations being "weighted" by factors which had necessarily been estimated. Further research was certainly necessary to confirm this formula, and the extraordinary interest displayed by the Correspondence was a hopeful sign that such research would be undertaken or continued.

He thought it possible that the rainfall on the Pabbi hills might be increased by the local action of the Jhelum river. The rain-clouds crossing the river might be condensed by the cooler air above the river, and thus discharged abnormally. It had been suggested that similar condensation over the heights to the west of Louth occurred, due to the action of a cool wind blowing from the sea. In the Khyber, on the other hand, intense heating of the bare rocky country probably caused ascending currents with the same effect. Major Anderson's Table (p. 364) showed heavier discharges from the storm in May than from those of August, when the air-temperature was lower, although at that time of year the highest in India. It would be noticed that among the points suggested at the end of the Paper for record were the direction, rate of travel, and height of clouds.

Mr Lillie. Mr. LILLIE, in reply, remarked that the following explanation might make clearer the conception of a standard section and a standard velocity, and answer Mr. Buyers's question as to what was to be the standard value of V in maximum flood for rivers that overflowed their banks.

All rivers were irregular as regarded slope of bed and area of cross section, but a river could be imagined to be canalized down to the point of discharge, or replaced by an artificial river, such that the slope of its bed was constant and equal to the average slope of the real river, and the area of cross section at each point was equal to the *standard* section of the real river. It was not imagined that the rugosity of the banks was in any way changed; and the contention was that the imaginary river would have the same discharge as the real river. The standard values of S and V of the Paper were the

Mr. Lillie.

actual S' and V' in the canalized or imaginary river. With this explanation, the statement that there would be no great change in the standard value of V throughout the course of the river would be more readily accepted. The objections were based on the misconception that he referred to V', the actual maximum mean velocity of the real river at various points, which was a different thing.

The canalized river would not overflow its banks, for they were, by hypothesis, high enough to prevent that. The question of the moderating effect of floods was thus excluded from the scope of the formula, and must be taken into consideration, along with other things, separately. This point would be referred to again later. The moderating effects of lakes on floods were no doubt very great indeed in some cases, but not in all. If the water at the moment of peak discharge was overflowing into lakes and hollows, instead of passing through the bridge, the rate of discharge might be greatly reduced; but if the river had already overflowed its banks, and the whole catchment was under a flood moving gradually towards the discharge-point, there might be no moderating effect. The river was then running through banks of water, so to speak, and the values of S' and V' were quite indeterminate; hence the advantage of the conception of standard values of S and V. This latter case represented the state of affairs usually found when the country was not absolutely flat.

Returning to the subject of determining the value of V, Sir Francis Spring raised the general question of the difficulty of determining the velocity. Mr. Lillie had always felt that slope and velocity were the most perplexing part of the whole problem; but it would be a mistake to let this throw doubts on the validity of the formula, which was a formula for the determination of S, and was independent of V. The value of V was wanted for two purposes, both subsidiary and really outside the main purpose of the formula: (i) to convert S into a rate of discharge in cusecs, and (ii) to enable the engineer to decide whether or no there would be danger of scour if a waterway of S square feet merely (namely, that sectional area proper to the river itself) were provided. With regard to (ii), Sir Francis Spring's remarks gave a succinct explanation as to how the information provided by the formula (or otherwise obtained) should be used in fixing the waterway of the bridge, but the point was that they indicated that V need only be estimated approximately for this purpose.

With regard to (i), there was no need to convert S into D for the purpose of determining the waterway required. If D were given, Mr. Lillie. it would be forthwith converted back into S. The only useful purpose of ascertaining D was in order to compare results with those of other engineers and other places, for hitherto engineers had unfortunately presented results in the form of rates of discharge instead of flood sections. Not only so, but they frequently omitted any mention of the velocity of discharge—thus giving no means of ascertaining S, the one thing that was really comparable. If the catchment in question happened to be steep (and V therefore high) the rate of discharge to be expected might be twice as much as if it had been flat, so the information given was robbed of most of its value, except in the case of very small catchments, which would be referred to in connection with Colonel Hearn's Paper.

The fact was that, for nearly all culverts and most bridges (other than very large ones), if the proposed formula was used there was no necessity whatever to calculate V or evaluate D. Only when scour was likely to be crucial need V be gone into. For large rivers, however, especially near the outlet into the sea, the whole problem was different and much more difficult. There the velocity became the most important consideration : but no one would rely on any discharge-formula for such cases.

He would like to disclaim any intention of belittling Kutter's formula, as Mr. Bellasis suggested. He had far too great a respect for the research work of the authors of that formula to do that. Similar comment as to the applicability of the formula to very large rivers had been made years ago, e.g., in the article in the *Encyclopædia Britannica* which was used as the text-book on the subject at Coopers Hill 35 years ago. He had never before heard that comment, or the substitution of the Mississippi formula in the case of very large rivers in flat country, objected to.

Some of the correspondents had deprecated any attempt to work out a formula "for universal application." If they meant one that could be used in all cases without judgment, and without regard to circumstances, everyone would agree. His own idea of a formula was one that was absolutely hard and fast, and that did not, like Dickens's, include a constant that could be manipulated ; a formula that gave something absolutely definite. That something should be the standard flood section of the river, but if there were any special circumstances about the river, the engineer must use his judgment in applying the results of the formula. It might be that the moderating effects of flood-water were to be expected ; in that case the waterway to be provided might be less than was indicated by the formula. On the other hand, there might be danger of accumulations of water above the bridge coming down suddenly

Mr. Lillie.

in the manner indicated by Sir Francis Spring and others, or the soil might be peculiarly susceptible to scour; in either of these cases a larger waterway than the S given by the formula must be provided. But there should be no juggling with the formula itself. Judgment must always be used; that was what engineers were employed for; and the exercise of judgment would sometimes indicate that the formula was altogether inapplicable to the case under consideration. In many minds there was an instinctive dislike of any formula, however rational it might be; and, curiously, the most ardent disbelievers in formulas would be found to be regular users of them. Mr. Gurtu's remarks would seem to class him among these disbelievers, but he admitted using extensively one of the least reliable of formulas in the Gwalior catchments. Mr. Lillie only asked that his formula should be given a fair trial with the others (it was very simple to apply): he had no doubt as to the results.

Mr. Glass's Paper afforded an excellent opportunity for a test. If anyone who was interested would take Mr. Glass's plan (Plate 4), of the Damodar catchment down to Raniganj (the Edilpur figures were inapplicable because of the moderating effects of the flooded country below Raniganj) and with compass, set square, and protractor, divide the area up into sectors and read the angles, he would find that four sectors would approximately account for the whole area, namely, working from south to north, 68 miles × 12°, 146 × 17°, 116 × 35°, and 15 × 52°. These gave 8,138 as the value of $\Sigma(\theta L)$. R (for an annual rainfall of 50 inches) was 5·33 (*Fig. 5*), and λ for a catchment 146 miles long was 1·37 (*Fig. 6*), and $8{,}138 \times 5{\cdot}33 \times 1{\cdot}37 = 59{,}460$ square feet. Now Mr. Glass gave the maximum recorded discharge as 650,000 cusecs, which, he had informed Mr. Lillie, was made up of sectional area about 55,000 square feet and velocity about 12 feet per second, and with this the foregoing was in fair agreement. Working this out, however, on a larger scale plan (16 miles to the inch), Mr. Lillie got $S = 56{,}500$ square feet.

Mr. Williams suggested that the formula gave figures which proved to be a good deal too small for the Adjai river. On the contrary, there was reason to believe that they had disclosed a case where the waterway provided was unnecessarily large. He asked Mr. Lillie to define what he meant by a "shower" and to explain why he should put a period to such a shower. Clearly a shower (or rainstorm, if that expression were preferred) could not go on for ever, and it was for engineers to ascertain what Nature's limitation was in that respect (it was not a "man-made" limit as Mr. Gurtu

Mr. Lillie. suggested). This had been attempted by many writers, and a vast amount of observations and statistics had come under review for the purpose. The Papers under discussion alone gave a great deal. Mr. Lillie did not feel that he had erred in accepting Dr. Gilbert Walker's figure (3 inches or 4 inches per hour, lasting 2 to 3 hours) as representing Nature's limit, and there was good reason for believing that this maximum shower might occur anywhere in India (but not, Mr. Lillie thought, in other continents) whatever the annual rainfall. Mr. Gurtu's remarks showed that he had not grasped this fact, for he regarded the Sind record as a vagary rather than an evidence of a law of Nature.

It was not suggested that these heavy downpours commenced and ended suddenly, nor that they were of the same intensity all over the area covered; but each shower was the equivalent of one that was evenly distributed, and the arguments in Mr. Lillie's Paper might be taken as referring to such a hypothetical storm, with a uniform intensity of 3 inches to 4 inches per hour and lasting 2 to 3 hours. Such a storm was the most severe that a catchment might be subjected to, and the contention was that it was the storm that would produce the highest rate of discharge. In some cases, with a larger catchment, a less intense storm of longer duration might actually produce a higher rate of discharge, but this did not affect the argument; neither did the fact that the storm might end gradually instead of suddenly: for the Paper did not attempt to calculate by mathematical analysis what the rate of discharge from that storm was; that was arrived at by observation and records, as was indicated in the Paper. The arguments in question were directed towards an analysis of the effect which an increase in the size of the catchment had on the rate of discharge. The whole scheme of the part of the Paper in question was an analysis of rates of variation, and one of the points that clearly emerged was that under the operation of the maximum storm there was a crucial size of catchment that just came within the ambit of that storm, so that even the remote elements of area would be contributing their full quota to the discharge before the storm ceased, or appreciably abated, when the nearest elements began to cease to contribute, and the peak discharge had therefore been reached. This size was what was called in the Paper the crucial size of catchment. In any larger catchment than that, the remote elements could not contribute fully to the maximum rate of discharge. There would hardly seem to be any possibility of error or confusion in this statement, nor was it easy to see any possibility of error in the deductions made from it on p. 298.

Mr. Lillie.

Of Mr. Horton's sixteen causes which he said affected the maximum rate of discharge, Mr. Lillie had dealt specifically with Nos. 1, 2, 6, 7, 13, and 16, and had referred to 10, 11 and 14. Nos. 3, 4, 5 and probably 10 and 11, although they would affect the rate of discharge in moderate rain-storms, were irrelevant in times of phenomenal flood, which were contemplated in the Paper. Nos. 12 and 15 did not affect India, where the floods always occurred in the summer with a very high temperature, and Nos. 8 and 9 concerned the question of the modifying effects of reservoirs, and were outside the scope of any formula.

A more serious criticism by Mr. Horton was that it was incorrect to take the rate of discharge as inversely proportional to the distance of the element of area from the discharge-point. Other writers had also challenged the accuracy of this step. The reply was this:—The expression in question was introduced when comparing two catchments of the same size but different shapes. In this connection the assumption was unexceptionable, but in comparing catchments of widely different sizes the objection was valid. For these, however, no such assumption was made. It was admitted that the variation in question did not account for variations of size, and a factor λ was accordingly introduced, which had been determined (as was stated) on an experimental basis. As an objection to the formula, the criticism fell to the ground.

Mr. Glass considered that, even for the purpose of comparing catchments of the same size, the discharge from an element of area was not inversely proportional to y, and that, even in the case of two catchments of the same size and shape, the reticulation of the catchment by the streams was of such importance as to make a great difference in the peak discharge. Mr. Lillie's contention throughout was that although this reticulation might make a difference in moderate showers, it was not of importance in the phenomenal storm (with which alone this discussion was concerned) when the whole catchment was composed of freshly formed streams making short cuts and flowing with considerable velocity. Sir Francis Spring's remarks on the difficulty of assessing velocity lent point to this contention. Long experience of the application of the formula could alone decide the point in question, and it was such experience that had prompted Mr. Lillie to put the formula forward. No doubt in the cases of such rivers as the Indus, which doubled back on itself in the folds of the Greater Himalayas, the arguments as to shape did not apply without modification; but who wanted to apply a formula to such cases?

He could not agree with Mr. Glass that conditions might easily

Mr. Lillie. be conceived under which the areas nearest to the discharge-point contributed least to the peak flood, the bulk of the flow of which might be due to a fortuitous concurrence of flood peaks from tributaries situated at the far end of the catchment—unless Mr. Glass referred merely to minor peaks. That such concurrence did occur, and that it took an important part in the formation of the peak discharge, was admitted, and constituted one of the leading arguments as to the variations in discharge due to differences in size (see the bottom of p. 298 and p. 307 and other places). But that the real maximum peak discharge could occur without the nearer parts contributing, might well be doubted, seeing how much greater chance the nearer parts of the catchment had to contribute in full than had the remote parts. Mr. Lindley's remarks as to the flattening of the flood-wave as it ran downstream would make this point more evident, and greatly reinforce the argument in the Paper that the contribution from an element of area was inversely proportional to its distance from the discharge-point, subject, of course, to the modification implied by the use of the factor λ.

Colonel Hearn's very interesting Paper brought out excellently the difference in the phenomenon of discharge in catchments under the "crucial size." It referred to very small catchments, and Colonel Hearn gave his figures for the maximum discharge as functions of the total quantity of precipitation on the catchment per unit of time, independent of slope and velocity. So long as the areas were very small this was reasonable, for manifestly more rain could not run off the catchment than fell on it, no matter how steep the slope; hence he was free to ignore the velocity of discharge for such small catchments, in a way that was out of the question for areas of more than a square mile or two, above which the maximum rate of discharge was less than the aggregate precipitation.

Mr. Lindley's communication was of exceptional interest, and presented a great wealth of information, but it was to be regretted that he had not given fuller explanations and details, for it was impossible to grasp the exact meaning of some of the information. It was true that "the shape factor" (by which he meant $\int \frac{dw}{y}$, or $\Sigma(\theta L)$, which was the same thing) must be divided by $\sqrt{\text{area}}$ to make it truly a measure. It did not, however, profess to be a mere shape factor, but, as stated on p. 299, it included L. $\Sigma(\theta L)$ was, in fact, not a factor at all, but a linear dimension. It might, if more convenient, be written 57·3 (area/$\bar{y}$), the 57·3 being necessary because θ was in degrees.

Mr. Lindley also, apparently, implied that Mr. Lillie's size factor

Mr. Lillie.

should be a function of the area, but that was not necessarily the case. The size factor was[1] $L\ (1{\cdot}1 + \log L)$, of which the L was included in the $\int \frac{dw}{y}$ (see pp. 299 and 300). There was no obvious reason why the size factor (that was, the rate of variation of discharge resulting from a variation in the size of the catchment) should not be in accordance with that expression. There was nothing inherently irrational in it.

With regard to Mr. Lindley's remark that Mr. Lillie's size function would give negative results for areas less than 10 acres, it must be remembered that this function λ was $1{\cdot}0$ for all catchments of less than 20 miles in length. The phenomenon was different in small areas up to the "crucial size."

The two comparisons which Mr. Lindley gave, between his figures and Colonel Hearn's, and between Mr. Lillie's and his own, respectively, called for comment. Colonel Hearn's figures showed the quantity of rain falling on the catchment, and Mr. Lillie's the maximum rate of discharge from it, and they were therefore hardly comparable. It is not to be expected that they could be the same, except in very small areas. At 10 square miles it was impossible for the whole of the water to run off at the same rate as it fell, and it was not unreasonable that Colonel Hearn's figure for that area was nearly two and a half times Mr. Lillie's.

With regard to the comparison between Mr. Lindley's figures for "the run-off in inches" and the "corresponding figures by Mr. Lillie's function," here again the figures were not comparable, for they did not represent the same thing. The "run-off in inches" was another name for the *total* discharge, whereas Mr. Lillie's function related to the maximum rate of discharge, and there was no reason why the variation should be at all the same. Incidentally, Mr. Lillie did not get the same figures for the variation of his function as Mr. Lindley showed.

Figures showing the variation in the total discharge from catchments of different sizes were of exceptional interest, but they were irrelevant to the subject of Mr. Lillie's Paper. Mr. Lindley's view that the variation of the maximum rate of discharge in the case of very large catchments was not in proportion to the square root of the area, but became nearly constant, would, on the face of it, hardly appear to be reasonable, and would have to

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[1] Mr. Granville has communicated the explanation as to how this expression was arrived at (p. 379).—G. E. L.

Mr. Lillie. be supported by very clear reasons and records. It seemed that a possible explanation of his having arrived at this conclusion lay in the fact that his records included a number of large catchments in other countries; there were no rivers in India with catchments of even half a million square miles. Mr. Lillie had contemplated nothing bigger than that, for it was not, in his opinion, reasonable to compare the records of the discharges of Indian rivers with those of other countries. This might account for the pulling down of the end of Mr. Lindley's variation curve to a nearly horizontal position, as it was probable that all American rivers fell short of Indian rivers, comparing like with like, in the matter of discharges.

One more point in Mr. Lindley's remarks called for comment, namely, the flattening of the wave of a flood as it passed down the river, which Mr. Lillie also had noticed. An excellent example of it was shown in *Figs. 2* (p. 304) between mile 50 and Kotah on the Chambal river. The fact that y appeared in the denominator of the expression $\int \frac{dw}{y}$ resulted in a decrease in the figure for the rate of discharge as the point of discharge was moved down the river, unless there was an increase in the numerator to compensate. The formula thus showed in many cases such a flattening of the wave as Mr Lindley referred to. If Mr. Lindley applied the formula to the catchments he mentioned in this connection, he would find the results interesting. Drawing the catchments from the 16-inch map the figures were :—

Catchment.	$\Sigma(\theta L)$	R	λ	S	V	D
				Sq. Ft.		Cusecs.
Sutlej and Beas at their junction .	16,800	3·00	1·50	75,600	4½ (?)	340,000
Ditto just above their junction with the Chenab	11,000	2·66	1·60	47,000	4½ (?)	211,000
Jhelum and Chenab at Haveli . .	14,900	3·00	1·50	67,050	4½ (?)	302,000

It was not possible to estimate accurately the standard velocity due to the average slope of the river above the point of discharge, but from such information as was available the figures given seemed probable. They showed the flattening of the wave Mr. Lindley indicated for the Sutlej, and also just the discharge at Haveli he gave. It was not easy to see why the discharges at Rasul and Khanki were as high as 600,000 and 713,000, unless there were some local conditions of importance. They would seem to be fully twice the normal. Mr. Lillie would not expect such a marked flattening of the wave at Haveli as that on the Sutlej. Mr. Lillie.

The answer to Mr. Granville's question why, in evaluating λ, *L* was taken as the length of the whole catchment, instead of calculating it separately for each sector, was that the arguments under which λ was deduced referred to the catchment as a whole. Reference to those arguments would make it clear that it would not do to treat each sector as a separate catchment.

In conclusion it was perhaps permissible to say a word in criticism of the methods of the "practical man" who, eschewing the pitfalls of a theoretical analysis, set himself to collect statistics of actual records, and on them based tables or diagrams for guidance in future works. Such methods, on the principle that an ounce of practice was worth a pound of theory, met with almost universal approval, and the results were received very uncritically. But the shortcomings and failure to account for all Nature's actions, which were alleged against the theoretical analysis, were just as truly pitfalls for these practical people. Every item of their records needed as critical an analysis as did the result of a formula. First of all, with the great confusion of nomenclature and the different methods of tackling discharge problems, what guarantee was there that the record was a rate of discharge at all? It might be a total quantity of discharge, for many engineers presented their figures in that way. If it was a maximum rate of discharge, what guarantee was there that it was that of the phenomenal storm? On this ground alone most records fell under very grave suspicion. Further, how many of the various irregular actions of Nature, that had been cited in this correspondence as an argument against a formula, had had an effect on the discharge recorded? It might be that flood-moderation had reduced the record to but a fraction of what it otherwise would be, or that one or other of the phenomena had greatly exaggerated it. In any case, there was almost sure to be no mention of the velocity of discharge, and hence the record might be almost meaningless—might, in fact, be of the nature of a very abnormal figure. In his opinion the drawing of deductions from abnormal figures was worse than the most extreme errors arising from the use of a good formula. After all, a formula did at least pretend to give normal results, leaving abnormal circumstances to be separately accounted for; and the very analysis on which the formula depended made it abundantly clear what was, and what was not, taken into account. All these essential facts were concealed in the method of tabulated statistics.

Mr. Glass. Mr. GLASS, in reply, remarked that no velocity-measurements had been made at the Raniganj gauge-site, and, as stated in the Paper, the discharges corresponding to the various gauge-readings were calculated from the observed surface-slope and river cross section at the gauge-site, using Kutter's formula. He could not now recall the value of n adopted, but this could be ascertained by reference to the Chief Engineer, Irrigation, Calcutta. The surface-slopes were observed by simultaneous readings on three gauges (with corresponding zeros) placed at a sufficient distance apart. The river section was obtained after the flood of 1913 by a level survey across the bed, and it was found that this section agreed remarkably well with one taken at the same site in 1863.

The accepted flood section (S') of the 1913 flood was 55,000 square feet, and the calculated mean velocity (V') was 12 feet per second. Mr. Lillie had arrived at a standard flood section (S) of 56,500 square feet, a result which was a further proof of the reliability of his formula, seeing that the 1913 flood was very considerably larger than any other experienced during 62 years of record. It was chiefly for checking doubtful high flood-marks and accepted flood-sections, in discharge-estimates for sites on large rivers, that Mr. Lillie's formula should prove useful. As it did not dispense with local river surveys for calculating the standard velocity, it could hardly be used for numerous project calculations made in the office in cases where the value of D rather than of S was required.

He regretted that he was unable to give Mr. Buyers the information he asked for regarding mean velocities at Raniganj and the maximum recorded 2-day fall on the catchment, but he thought that could be obtained from the Chief Engineer, Irrigation, at Calcutta.

Mr. Lacey was not correct in attributing to Mr. Glass the statement that since the removal of the Damodar right embankment the proportion of flood volumes spilled over the entire right bank had been reduced by silting of the land. As a matter of fact, the spills had not been reduced, but the flood-levels had been continuously raised, as shown on Fig. 2, Plate 5. The effect on the Hooghly of constructing flood-moderating reservoirs in the basin of the Damodar had been considered.

Mr. Lindley remarked on the use of the term "gaugings" to mean readings on a gauge, whereas, as he stated, it was generally used for observations of the discharge. Mr. Glass might similarly remark that the term discharge was used sometimes when rate of flow was meant and often also where volume of flow was under consideration. He agreed that the ambiguity of such terms was objectionable.