Discussion.

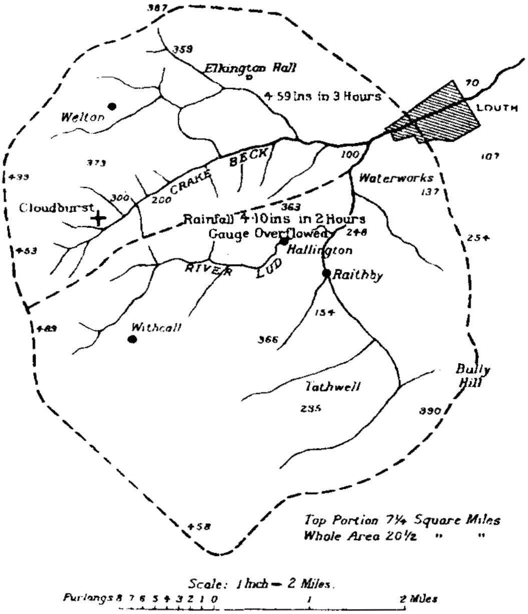
The President

The PRESIDENT, in moving a vote of thanks to the Authors, remarked that the Papers were interesting to engineers in Europe, though they did not have to provide for rainfalls such as were experienced in India. They were interesting also as showing the class of work necessary in the special circumstances described in the Papers.

Colonel Hearn.

Colonel HEARN observed that perhaps those who had not had an opportunity of studying the Louth storm of May, 1920, in "British Rainfall," would be interested in the main figures of that flood. The area was 22·2 square miles according to the Meteorological Office; but Mr. P. M. Crosthwaite, M. Inst. C.E., stated[1] that it was $20\frac{1}{2}$ square miles, and this agreed with the map (*Fig. 1*). The area which received more than 4 inches of that storm was 1·57 square

Fig. 1.



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[1] Trans. Inst. Water Engineers, vol. xxvi (1921), p. 204.

olonel Hearn. mile against 0·40 square mile in the London storm of the 16th June, 1917, analysed on p. 272. The total worked out at an average fall over the whole area of 1·23 inch against 0·76 inch in the London storm. *Fig. 1* was specially drawn to emphasize the shape of the catchment. The bulk of the rainfall occurred round Elkington Hall and Welton, where the cloudburst was shown, though that was not perhaps the correct point. The shape of the upper portion of that catchment was very significant indeed, whereas the lower portion was of quite a different physical aspect. Although the waterworks on the river Lud were flooded, there was, relatively, a very small flood coming down there—nothing like enough to submerge the town of Louth. Most of the water that caused the disaster fell over the northern portion of the area, about 7¼ square miles, to which might be added a few square miles round about Hallington, making up the 9 square miles which was his estimate when the Paper was written. On p. 275 there was a certain obscurity in the paragraph which commenced : " To two of the areas particular attention might be directed." The Rashidpur catchment had been included by him in those of high concentration, and, therefore, the words " other than the shape " should be introduced after " no apparent features " Turning in that connection to Appendix V (p. 292), had a higher soil-slope-protection factor been given, instead of a maximum of 0·66, the estimate of rainfall-intensity would have been reduced ; but on careful consideration he thought that some of those factors were perhaps too high—they were certainly as high as could well be given for such catchments. The estimation of this soil-slope-protection factor was perhaps a little obscure. Certainly his assistants on the Khyber Railway had found it rather obscure, so he had given them an alternative which took more account of the slope. For slopes up to 10 degrees he suggested 0·1 to 0·4 ; up to 20 degrees, 0·5, 0·6, or 0·7 ; and over 20 degrees, 0·8, 0·9, or 1. With regard to the shape factor, there appeared to be considerable corroboration, other factors being equal, in Mr. Lillie's diagram, *Fig. 7*, p. 313, where he gave for the type A catchment about twice the cross section that he gave for the type B catchment. As the type B catchment, which he took as unity, was an elliptical rather than a triangular shaped catchment, on the whole the factors proposed by himself did not seem to be exaggerated. Appendix IV had been compiled primarily to confirm the estimates of discharge made by the Upper Jhelum Canal engineers, and other inferences should not be made from the heading " Frequency of Downpour," because there were gaps in the discharges which he had not been able to complete. There was a very full report in 1917, but latterly only those discharges

Colonel Hearn

exceeding the maximum had been reported. On p. 280 he had stated that he hoped that the practical application of his rainfall curve might be tested on the Khyber Railway, and he was now able to give the results of one test. On the 21st April, 1923, his successor reported a storm which had occurred on the 7th of April, and expressed the opinion that his method and figures were quite correct for the small culverts but not for the larger areas, the waterways of which could have been reduced. (Colonel Hearn might say that that was his successor's previous opinion also.) On the 21st May, 1923, 1 month later, another storm was experienced. The maximum intensity was assumed to have been 2 inches per hour. For such an area as 4·9 square miles his curve gave $2\frac{1}{2}$ inches of rainfall. The resultant flood passed through a bridge designed for 7,600 cusecs, and was measured as being 6,900 cusecs. On another catchment a waterway designed for 3,960 cusecs passed a flood of 3,075 cusecs. This he thought was good corroboration.

Dr. Simpson.

Dr. G. C. Simpson remarked that he did not quite agree with Mr. Lillie's statement on p. 305: "The maximum rate of precipitation is a question of the maximum quantity of moisture that can be carried by a cloud, and this in turn is a question of the greatest possible vapour-tension of the air." The question of the amount of rainfall had practically nothing to do with the quantity of vapour in the air. Of course, everything else being equal, if there were an increase of water-vapour in the atmosphere, there would be an increase of rainfall. The cause which was responsible for the precipitation of rain was the adiabatic cooling of the air. The air must be raised in the atmosphere, and as it was raised it was cooled, and the water was condensed. Therefore, the determining factor almost entirely was the rate at which the air ascended. The reason for the ordinary depression—the rain common in England—was not exactly known; but it was certain that the air came in streams and was caused to rise slowly at a slope of probably 1 in 1,000. As it was cooling all the time, it dropped the moisture at a very low rate for some considerable time. In thunderstorms an entirely different effect took place. The air, instead of flowing slowly and rising on account of convergence, was elevated by convection, rising very rapidly over a limited area. Therefore a very much greater precipitation resulted. As the velocity of the ascending currents increased, two things happened: the deposition of moisture increased; but, in addition to that, a mechanical effect took place when the deposited water fell through the air. Every drop had a certain maximum velocity with which it could fall; and, if the air was ascending more rapidly than that, the drop was carried

Dr. Simpson. up. The maximum size of a drop was about $\frac{1}{2}$ centimetre in diameter: a bigger drop than that quickly broke up. That drop would be suspended in a vertical current of air of 8 metres per second. Therefore, an immense accumulation of water could take place in the atmosphere under certain conditions. When that vertical current suddenly stopped, the result was a cloudburst, in which the precipitation was quite irrespective of the quantity of moisture in the atmosphere as vapour, depending purely and simply on the rate at which the air-current had ascended. That was why some of the heaviest deposits of rain occurred in places which were generally arid, and where there was no relation between the annual rainfall and the maximum fall. In fact, the maximum fall depended on the instability of the air, which was very much greater over deserts than anywhere else. Before he left India the Meteorological Office was constantly receiving inquiries as to how often a heavy rainfall occurred in India. They had not the statistics of rainfall for shorter periods than a day; but he considered that it would be helpful if they could give engineers the statistics of the heavy falls even for single days. From the records of about 2,500 stations they counted the number of falls not exceeding 3 inches, 3–4 inches, 4–5 inches, and 5–6 inches. He observed that, when the frequency with which the rainfall occurred was plotted, in every case an almost identical curve was obtained, which appeared to be the ordinary curve of probability; thus the question whether rain of a certain intensity would fall or not was almost a question of chance. The mean was known, but any departure from that was governed entirely by the law of probability. Any such curve could, no doubt, be plotted logarithmically, representing an equation involving two constants; thus it would probably be easy to work out the chance of the occurrence of any given rainfall. That was rather interesting, but he had never followed it up to find out whether it was possible to calculate from the first part of the curve, where there were plenty of observations between rates of 3 and 6 inches, the constants for the rest of the curve. If that were possible, it would probably be found also that the volume of a flood discharge followed the same logarithmic curve. By making use of the few observations available, it would thus be feasible to calculate the probability with which a flood with a given discharge would occur.

Mr. Taylor. Mr. H. B. Taylor observed that as engineer-in-chief of the Nagda-Muttra Railway construction he had had the opportunity of seeing floods pass through some of the bridges which Mr. Lillie referred to in his Paper. He was quite in agreement with the suggestion that the factor of shape deserved considerable attention.

Mr. Taylor.

In his early days he used Dickens's formula, with simple variation of the constant in different parts of India. In 1908, soon after he went to Kotah, the Chambal river was in great flood. A rainfall of 20 inches occurred in 3 days, of which 10 inches fell in 1 day. Although the major openings carried the flood with credit, some little trouble occurred on the line generally. An amusing incident on the day of the 10-inch fall was the chasing and killing with sticks of some enormous fish trying to cross the main station road, over which some 3 or 4 inches of flood water was flowing. At Bharatpur, about 180 miles north of Kotah, an extraordinary flood took place in August, 1910, which no doubt was the one that Colonel Hearn referred to as being in 1900. A rainfall of 18 inches took place in 18 hours, with 19 inches in the 24 hours. The major bridges were undamaged, but the railway embankments suffered considerably. He could confirm the wisdom of making exhaustive inquiries of extraordinary floods, as Colonel Hearn recommended. When constructing the Goona Bara Railway, he had had pointed out to him, on the left bank of the Parbutti river, near the site of the bridge crossing, a flood mark on a fakir's tomb which it was said the water had reached in the Mutiny days. No other record showed any such flood, and the calculations from the catchment-area did not indicate its possibility; but, fortunately, it was decided to take notice of that mark. The very next year this extraordinary flood again arrived, and the water went right up to the fakir's tomb, as it had done 40 years before. That mark was 10 feet higher than the ordinary high flood level. On the same railway, at Goona, a year later 6 inches fell in 24 hours; the same fall took place at Kotah, about 120 miles to the west, whilst midway at Bara 14·9 inches fell in the same period. At Bara a serious wash-out followed this fall of 14·9 inches. The station-master who, putting his hands together, said the drops were as big as melons, and the permanent-way inspector, both certified that this fall practically occurred in just under 4 hours, giving an intensity of 3½ inches per hour for this period. The formation was on sidelong ground, the watershed being about 5 miles distant. The surrounding country was plain and open, and the excessive damage to the railway did not extend to more than about 4–5 miles of line. He decided not to increase the minor waterways, however, and found that a fellow engineer, whose works had suffered even more damage in a similar flood, agreed with him, their reason being that such a flood, the result practically of a water spout, would not recur within a century. There was one special point in his experience to which he wished to draw attention. In Central India he was once out trollying in a storm, which he calcu-

Mr. Taylor. lated as being of about a 2-inch intensity—6 inches of rain falling in 3 hours. The formation was on sidelong black soil in rocky country. When the rivulets were running full force and the country had become a solid mass of water, the surface water did not flow in its normal channels to the river, but in any direction it was driven by the wind. He realized that by careful surveying and running "cross bunds" as much as 200 or 300 yards up, it would be possible to prevent the flood water from thus leaving its proper channel and forcing its way through another opening which had not been calculated to pass it. He was afraid these rather discursive experiences had not dealt very closely with the subject of the Papers, which were to his mind very valuable: he only wished their contents had been available when he was dealing with actual works in India.

Mr Preston. Mr. SIDNEY PRESTON observed that he hardly felt competent to criticize the Papers verbally, but he desired to emphasize the following point. During the last few years of his service in India he had been engaged in constructing numerous irrigation-tanks in Central India. One scheme comprised two reservoirs, one containing up to full-supply level 4,600 million cubic feet and the other 5,000 million cubic feet. These were storage-reservoirs in the higher parts of the rivers, from which water passed down the rivers to pick-up weirs which fed the canals for irrigation. The only information he had to go on was Dickens's formula for flood-discharge and Binnie's coefficients for run-off. He altered the coefficient in Dickens's formula to the best of his judgment, according to the nature of the catchment-basin. But what was really more important to the irrigation engineer was the discharge—unless this could be estimated with some accuracy, it was extremely difficult to design a reservoir of the right capacity. Binnie's coefficient was very elementary, having been taken over an area of about 6 square miles in Nagpur; but still, so far as he knew, it was the best available, and he had to apply it. In the 7 years during which he was in Central India, he submitted estimates and schemes and had them all sanctioned for close upon £1,000,000. A large number of those had already been completed; but, unfortunately, having left, he had no record of them, and he did not know whether anything had been done to obtain statistics. In India, at the present moment, engineers had a unique opportunity for getting exact information about the discharge from catchments of all sizes and of various kinds. During the last 10 or 15 years a large number of storage-reservoirs for irrigation purposes had been made in Central India, in the Central Provinces, in Rajputana, Bundailkund, and other places. If there were an establishment to obtain the statistics, it would be possible to get valuable coefficients for determining the probable discharge for different rainfalls from all types of catchments. He had been relieved by a native engineer, who had since left; and the department which he had organized had been taken over by a Revenue official, who was now the chief Irrigation Engineer! The ordinary native had no idea of exact statistics: he neither understood them nor saw their use. He had known a case in India where a native magistrate of a small district was seen putting water into the rain-gauge, "because," he said, "the Commissioner Sahib is coming round to-morrow, and if he does not find a little water in the gauge he will get very angry." He instanced this as showing the unreliability of statistics obtained by petty native officials. The European senior officials were all too busy. They had charge of large districts. There were numerous works to maintain, new works to be started, projects to be got up, accounts to be rendered, and it was difficult for them to find time to collect the statistics which were really wanted; and in many cases there were not sufficient rain-gauges. If rain-gauges were installed in whatever catchments were selected for obtaining the coefficients, the subsequent calculation would be easy, since the catchment-areas had all been surveyed. The storage-basins had all been carefully cross-sectioned and contoured, so that it was possible to calculate, with great exactness, the volume which could be stored between the various levels, if only it were possible to get the observations. If that were done very valuable information would be obtained, from which absolutely correct coefficients of discharge would be obtained. The benefit to posterity would be enormous. Mr. Preston.

Mr. R. A. RYVES remarked that he had seen in England raindrops $\frac{1}{4}$ inch in diameter. He supposed that would be the result of an electrical phenomenon? [Dr. SIMPSON remarked that the drop had not fallen far enough to attain its final velocity.] The Papers by Colonel Hearn and Mr. Lillie gave the impression, to any person not a civil engineer, that civil engineers calculated the discharges from catchments by means of formulas for comparing the discharges of different catchments: but did engineers in these days calculate the discharge of a catchment, about which they had full information, by formulas? He would have thought it was calculated from the rainfall. But the formula had its place, and it was interesting to read these Papers and to see the endeavours which were made to arrive at a suitable formula. He did not think any of the formulas were much better than the simplest and the earliest, the reason Mr. Ryves.

Mr. Ryves. being that, with a formula which was so simple that it ignored everything but area, the discharge from some catchments was obtained by measurement and the coefficient was found by calculating back. All the variables were combined in one coefficient and, therefore, subject simply to judgment. When more was attempted, it was necessary to consider shape, vegetation, slope, etc.; and if that were possible, the discharge could be estimated very much better by direct deduction. A point he noticed particularly in Mr. Lillie's Paper on p. 295, with regard to the question of measurements, was the following sentence: "Taking a mean value of V for the locality and a measured value of S at the site, as is usually done, leads to most erratic results." He had experience of that a little while ago when a figure given to him as the discharge of a river was based upon simply measuring one cross section, taking a levelling-staff up and down the river for about 1,000 yards, and then calculating the discharge by a formula! That was useless. The slope which was arrived at was not even the mean slope of the river-bed, it was taken more or less by judgment, and varied according to whether the interval was 1,000, 500, or 200 yards. Scale readings, which were often taken laboriously day after day during the time a river was in flood, and were recorded, could be used to obtain the discharge by means of Kutter's formula, if the following procedure were afterwards adopted. Three sections were measured at suitable distances, the centre one being at the gauging-station. The true discharge for any given height on the scale in the middle section could be calculated by finding such levels at the upstream and the downstream sections as would give similar discharges in the upper and lower reaches. But that was not enough, because many levels would give equal discharges in the two reaches for the same gauge-depth in the middle section. If those levels, however, satisfied another condition—Bernoulli's theorem—then they were the true levels at which the stream must have been when it flowed on a given level in the middle section. It was a case of guessing in the first instance, but the true discharges could be obtained merely by continued approximations. But, having got three or four such calculations, it was then possible to draw the curve which would give the discharges of the stream for the different readings on the scale. With new gauging-stations, of course, it was much simpler to put scales in all three sections. He had had one or two put up with scales in such positions that they could be read by telescopes from one station. Mr. Lillie remarked that the subject of the discharge of catchments had been allowed to rest for 30 or 40 years and that an advance was now overdue. About 13 years

Mr. Ryves.

ago Mr. Ryves wrote a Paper[1] in which he laid down as of great importance two of the principles, which were also to be found, in a somewhat different form, in the present Papers. One of the principles was that the outlying portion of the catchment might be neglected in order to calculate the maximum discharge from the catchment, because the greater intensity of the rainfall in the shorter period sometimes produced a greater discharge. At that time he left the use of that principle to judgment, but he now introduced a calculation which would automatically decide whether the outlying portion should be included or not. The other element in any calculations of a discharge from a catchment was the time of total contribution, that was, the time taken for the water to flow from the farthest part of the watershed to the outlet. He maintained that instead of using distance in the formula, it was better to deduce the time of the flow of water from a catchment. In a catchment where a hill formed the barrier through which the river cut its way, a place might exist, 1 or 2 miles away from the outlet, whose discharge took an hour to reach the main stream. But from another place, say, 4 miles up the main stream the water might be delivered in $\frac{3}{4}$ hour. Time, not distance, was the criterion. For that reason he did not agree with the other contention on p. 297: "Put mathematically, the maximum rate of discharge from an element of area (dw) is inversely proportional to its distance (y) from the discharge-point." Then, on p. 298, Mr. Lillie said: "In short, in catchments which are larger than the crucial size, it is rather a question of the size of the maximum possible rain-clouds and the number that may occur simultaneously (or in the correct relative sequence) over the catchment. It is impossible, of course, to supply figures in answer to these questions, but it is not necessary to attempt to do so for the present purpose, which is merely to ascertain the rate of variation." He did not quite see why it was necessary to attempt to answer that question at all, because the best thing was either to know the actual rainfall records from gauges, or, if those were not available, to make deductions from a single heavy storm, reducing the intensity of rainfall to area in the usual way. For all comparisons of catchments in different parts of the world he preferred the simplest formulas—either the Ryves or the Dickens. The former seemed to him to be the more satisfactory, for the reason given by Mr. Lillie (p. 312). Mr. Lillie's method of dividing the catchment into elements in the form of triangles having their apexes at the outlet was a gesture, rather than a step, in the right direction. The real value of division

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[1] *Indian Engineering*, vol. xlix (1911), p. 259 *et seq.*

Mr. Ryves. into elements lay in the fact that the contribution of each element might be continuously plotted to a time base, and the amount and moment of maximum general contribution so found. Another important point was raised on p. 307. Mr. Lillie was undoubtedly right in his view that the maximum discharge of a catchment was not directly dependent on the annual rainfall. It was, however, difficult to follow him when he took annual rainfall into account, because it was related to the frequency of showers. This affected the general discharge for irrigation but, surely, not the maximum discharge; for what mattered in this case was not the average frequency of rain showers but the intensity of the wettest periods. The following figures supported Mr. Lillie's conclusion, stated at the bottom of p. 306, and bore also on the general proposition, here advanced, that, if a few specially-exposed situations were disregarded, falls exceeding 5 inches in 24 hours were not likely to be experienced except at intervals of several years, that many years might elapse between falls of 9 inches or so, and that the maximum fall was about 13 inches. In the records of stations in Southern India,[1] giving the ten heaviest falls on any same day in the year, the following figures occurred for different stations: In 40 years, maximum 8·81 inches, 6 inches exceeded once; in 40 years, maximum 6·61; in 26 years, maximum 5·70; in 26 years, maximum 8·33 inches, 5 inches exceeded once; in 26 years, maximum 10·07 inches, 4 inches exceeded once; in 18 years, maximum 13·10 inches, 5 inches exceeded twice; in 18 years, maximum 12·20 inches, 4 inches exceeded twice. From 40 years' records in Rio de Janeiro the maximum was 9 inches, the next largest fall 5·8 inches, while 4½ inches was exceeded four times. The fall of 9 inches occurred in 4 hours, and a fall of 5·1 inches in 6 hours.

In Colonel Hearn's suggestive and valuable Paper, one of the points which attracted special attention was his remark, p. 267, regarding the underestimation of discharges. In some cases it was difficult to believe that the discharges allowed for were really regarded as the greatest that were likely to occur. At all events, the waterways of some bridges (including some in the Madras Presidency which were adequate for 50 years and then suffered only partial destruction) had been designed, in effect, on a basis of the relations between "expectation of life," first cost, and compound interest. It seemed difficult to avoid the conclusion that real discharges could best be estimated in the case of small catchments

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[1] Papers regarding the Couvery Reservoir Project, vol. iii, 1910. Madras Government Publication.

Mr. Ryves.

by the deductions from spot rainfalls, reduced by curves of area-intensity when the catchment had a "period of total contribution" of one day or more, or intensified, for very small catchments, by curves such as those shown by Colonel Hearn in *Fig. 2*, p. 271. In the matter of the physical aspects of a catchment, Colonel Hearn was in a sense right when he stated, p. 269, that the simple formula took no account of physical aspects. But the engineer who applied the formula included a consideration of physical aspects in his choice of a coefficient. The simple formula was, in fact, a combination of a formula with judgment, and in many cases the judgment so exercised resulted in a computed discharge nearly the same as the discharge directly deduced from rainfall. Reverting to *Fig. 3* (p. 273), it might be noted that these intensity–time curves had another application, for they might be used to convert daily records of rainfall into the continuous curves which formed the basis of the direct deduction of discharge. On the important subject of shape of the catchment (p. 278), it might be remarked that these references to the great influence of shape showed how difficult it must be to incorporate this condition in a formula, the differences in the discharges being so very great, as shown in the Table on p. 279. But the effect of shape on discharge was fully taken into account if the discharge were deduced from rainfall maps of the catchment, by means of rainfall curves for a number of duly handicapped elements. Further, if the catchment were very large, a discharge might be deduced due to a rainfall of several days duration over the whole catchment, and another discharge of a last day for that part of the catchment, next to the outlet, comprised in a 1-day "period of contribution." The rainfall of the last day would not be the maximum 1-day fall for the locality, but some smaller fall, subject also to a deduction for the amount already found from the rainfall map of the last day of the series already computed for. The total discharge was the sum of the two so found. His own method of calculating maximum and other floods was the following:—There was first the preliminary operation of establishing a relation between rainfall and discharge by means of curves relating to dry, damp, and wet catchments. He used Strange's curves. He next selected a series of wet days which might be a real series, or a real series with the smaller falls increased by some likely amounts, or an imaginary series, which, for a small catchment of, say, 2 days' delay, would include the maximum fall and the highest falls known to precede and follow a very heavy day's rain, or, for a larger catchment, would include whatever was likely to be the series producing the maximum flood. Other series might be tried afterwards as a check. The series chosen should be 2 or 3 days longer

Mr. Ryves. than the period of total contribution of the catchment. From these records he plotted a rainfall map with isopluves, for each day. The next step was to introduce the time element, which made it needless to take shape, *qua* shape, into consideration. If records were available, he found the time of total contribution from records of daily rainfall and daily discharges. The discharges might be of no value in themselves—only scale readings; but they gave the intervals between the higher rainfall-curve peaks and the corresponding discharge-curve peaks, and these indicated the period of total contribution. If no records were available, he estimated the period of total contribution by comparisons with other catchments. The records, or estimates, might relate to an area somewhat smaller than the whole catchment. Next he estimated the rates of flow in the streams, working from the outlet upstream in several directions, marked the points corresponding to 1, 2, 3 days, etc. (or smaller intervals), and so proceeded to the part of the watershed farthest in time from the outlet. He repeated, if necessary, till these agreed with the period of total contribution previously found. He then joined the points in each series and so divided the catchment into zones, or—usually a better way—into elements, each of which approximated to a small catchment-area in itself. For each hour he then added up the ordinates of the discharge curves of the elements and so obtained the discharge curve of the catchment. This gave the hour and the volume of the maximum discharge. It was possible also to see from the diagram whether the elements most distant in space (usually also most distant in time) contributed to the maximum discharge. Also, any great difference might be noted between the period of contribution of the catchment (or that part of it which contributed to the result), and the period elapsing from zero hour to the moment of the maximum discharge. If the difference was important, the bases of the estimates of " delay " were examined, and recalculated with different stream-velocities if the data were at all doubtful. The differences in the result were usually small, and in a doubtful case the highest reasonable velocities which gave the greatest maximum discharges might be taken. If the data were sound, the diagram gave the maximum discharge, whether due to the rainfall over the whole catchment or to a more intense rainfall on a part of the catchment. A formula, however, was necessary in cases for which no reliable rainfall-records were available; it was also useful for preliminary calculations, and was necessary for general comparisons. For a number of cases in north-east Brazil he had found that his calculations from rainfall corresponded to values of the coefficient in the Ryves formula ranging from 900 to 1,000, usually

Mr. Ryves. about 1,000; and the use of the formula had enabled him to make comparisons with India, South Africa, and the United States. The data relating to catchments in other countries were usually only the area and the discharge; it was therefore necessary to have a formula which did not depend upon shape or physical features. As a general check on deduced discharges for the purpose of preliminary calculations, and for areas where no reliable rainfall data were available, the simple formula was of great value if the coefficients selected became more and more suitable as experience was accumulated. The coefficient in the simple formula served, then, as an element of comparison, linking up all the catchments in the world, generally, or in groups according to their areas; and it could not be dispensed with. Between the simple formula and the method of direct deduction lay the debatable country of the complicated formula.

Colonel Hearn. Colonel HEARN, in reply, observed that he feared Mr. Ryves was under a misapprehension in suggesting that he had endeavoured to arrive at a suitable formula. What he had done was to endeavour to establish a relation between intensity of rainfall and area. The only (and simple) formula given was an approximation to this relation. It was then necessary to discount the rainfall by some proportion depending on soil, slope, and protection, and, in his opinion, to increase the discharge (for a peak flood) by some factor depending on the shape. Mr. Ryves's methods were really more complicated and might be usefully applied to certain large catchments, but for very many small catchments no details were available, and time spent in detailed calculation would usually be unprofitable. A method applicable to a catchment whose "time" extended over days was hardly applicable to one whose "time" was limited to hours or minutes, and where the velocity of discharge was high. It happened that the simple formula given was a logarithmic formula. So also were Mr. Craig's and Mr. Lillie's. This suggested that Ryves's formula was not well founded, and Dickens's formula, in which the coefficient was invariable, could not be correct for all physical aspects. Mr. Preston was, perhaps, not aware that Mr. S. K. Gurtu, M. Inst. C.E., had contributed to "Indian Engineering" a series of articles based on results obtained in the Gwalior State. But he quite agreed with Mr. Preston's remarks about the importance of research in the earlier years of an engineer's career, and he hoped that several young engineers would take the matter up as their hobby. A certain gentleman, much interested in meteors, trained himself to estimate the time of flight by timing the flight of arrows shot from a bow. An engineer could train himself in time to estimate intensity of rainfall without a gauge, and perhaps also to estimate the velocity

Colonel Hearn. of flowing water. The rain-gauge recently described by Mr. J. W. Meares, C.I.E., M. Inst. C.E.,[1] would be of great assistance in training.

Mr. Lillie. Mr. LILLIE, in reply, remarked that his object in putting forward his Paper had been not merely to present a formula which might be useful, but rather to stimulate an investigation of the whole subject of rainfall and discharge generally. That such an investigation was necessary would be clear to any one who read the reports and writings of various engineers on the subject, for they showed how very different were their fundamental conceptions of the problems, of the way to deal with them, and of the information required. He wished it to be understood that he did not put forward this formula as an instrument which might be used in all circumstances, indiscriminately, and without modification. The subject was much too complicated for that; and indeed, he knew of nothing to which the principle, that the intelligence with which a formula was used was even more important than the formula, was more applicable than this subject of discharge. This, however, did not detract from the importance of the formula itself; and to be of any use whatever, a formula must be rational. He sympathized strongly with Mr. Ryves's wish for the simplest possible formula, which of course should be used in combination with the judgment of the engineer. This was what every one wanted. But a simple formula to be used as the basis of an estimate in this way must be rational. He did not think it could nowadays be seriously contended that the maximum rate of discharge bore any definite relation whatever to the value of M^a (M being the area of the catchment) no matter what value might be assigned to the constant a. Consequently, M^a could not be made the basis of a rational formula; and he had therefore looked about for a better, a rational, basis. In his opinion that basis was to be found in the expression $\Sigma(\theta L)$, and he believed that engineers would find that this expression was as easily calculated as M^a—more easily, in fact, unless a planimeter could be used for ascertaining the area of the catchment, when they were both equally simple. It would seem to be necessary, in view of Mr. Ryves's opening remarks, to say something regarding the need for, and the legitimate use of, a formula. Engineers on reconnaissance in India were generally without any information whatever on which to estimate the amount of bridging necessary, other than what could be obtained from the excellent topographical maps and other published information. From the former, a plan of the catchment could always be obtained,

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[1] Inst. C.E., Selected Engineering Paper, No. 2. 1923.

Mr. Lillie. (he had never experienced any difficulty about that), and from the latter the annual rainfall of the district could be found. Further, the engineer obtained some idea of the general character of the district from his own observation. The question then was, what could be done with these data? Engineers of surveys and even construction were little better off; and it was safe to say that, excluding the really big bridges, three-quarters of the bridges and culverts in India had been designed on information obtained merely in this way. The need, therefore, for the best formula that could be devised was obvious. With regard to the legitimate use of a formula, in applying his formula to catchments whose discharge was well known as the result of careful records and measurements, he was obviously merely testing and proving the formula. It had never occurred to him that he might be understood to imply that in such catchments the waterways of bridges should be determined by the formula rather than by the records and measurements, any more than it had occurred to him to disclaim any intention of suggesting that the waterway of the Sara bridge should be determined by the formula, because he included the case of the Ganges in *Fig.* 23 (p. 331). Had he had the information contained in Mr. Glass's very interesting Paper, he would undoubtedly have added the Damodar to the list of examples (much to his own satisfaction), but, if he were building a bridge over that river at Raniganj, he would not rely on the formula to fix the waterway. It seemed necessary to say this, in view of Mr. Ryves's remarks. Indeed, nearly all his remarks were based on the conception that observations and records existed, and could be amplified, in any catchment under consideration; and his mind was clearly directed towards the question how such information was to be applied. He evidently proceeded on the lines of following the actual happenings throughout the catchment on selected wet days, and plotting rainfall maps and isopluves. These interesting methods, of course, were not possible for the engineer on reconnaissance or survey, and were rather of the nature of research. But they failed, not only because the actual operation of discharge was not the same in all storms in the same catchment, but also because they were based on actual storms and not on the potential maxima, which maxima, as they only occurred in any one place once or twice in a century, were almost sure to escape observation, and certainly could not be waited for. His method of investigation was somewhat on the lines of the method used by American engineers of 20 years ago, an example of which was published[1]

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[1] *Railroad Gazette*, vol. xxxiv (1902), p. 976.

Mr. Lillie. in 1902. That was a rational method, but it led directly to the expression $\int \frac{dw}{y}$ which Mr. Ryves rejected on the grounds that the denominator should be time, not distance. No doubt the time taken by water to reach the discharge-point from the point of precipitation was the criterion, but the assumption that that time was proportional to the distance was always made in this connection, and there were good reasons for the assumption. It would seem, from the latter part of Mr. Ryves's remarks, that he regarded the matter in this light himself. Perhaps the chief difference between the opinions of Mr. Ryves and Mr. Lillie was that the former insisted on regarding each catchment as a study in itself, and refused to make deductions as between one catchment and another, at the same time not hesitating to make free deductions as between the effects of one storm and another in the same catchment. Mr. Lillie's view was that it was more reasonable to make deductions from one catchment to another than from one storm to another, for it was impossible really to follow all that happened in any particular storm, and the position of the points of most severe rain, the direction of movement of the clouds, the "time of full contribution" and the "time" from any particular element, all varied in different storms. Particularly was that so in the phenomenal storm which produced the maximum rate of discharge; in such storms rivers overflowed their banks, the whole country was more or less flooded, and water found its way to the discharge-point by more direct routes. It was impossible to deduce the action in a phenomenal storm from the observations made in an ordinary storm; and, as the phenomenal storms occurred but once or twice in a century, they were almost certain to escape observation and measurement. It was more reasonable to study the problem from the point of view of the maximum effects possible in any catchment, for Nature, like other things, had her limitations. A game of cards provided an analogy: it was impossible to foresee the fall of the cards in a single round, but it was possible to compute with certainty the maximum combinations. Mr. Ryves's methods seemed to be equivalent to the examination of the cards after a selected round, in an attempt to deduce what was likely to happen next round. He agreed with the remarks by Mr. Ryves and Mr. Taylor that it was unnecessary to increase the waterway of all bridges to meet the requirements of a flood which might only occur once in a century; but that question was rather outside the subject of the Papers. He had been very pleased to hear Dr. Simpson's explanation of the genesis of a rainstorm. It should form a valuable addition to the

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