Discussion

Mr R. C. S. Walters said that in Table 5 the Authors gave the average rainfall for various periods, and taking the three driest consecutive years, an average was obtained of 84·7 per cent, compared with the usually assumed 80 per cent. Mr Risbridger had said that it would be a bold man who would rely on 84·7 per cent, and Mr Walters said that he, and perhaps others, would like to keep to 80 per cent, notwithstanding the fact that the Authors had proved over the 42-year period that the average annual rainfall for 36 months was 84·7 per cent.

On p. 373 floods were referred to, and the Authors confirmed that the maximum flood had been 259 cusecs per 1,000 acres, and on the Claerwen part of the gathering ground 212 cusecs. That agreed with the Flood Committee's report for a gathering ground of 45,000 acres. He had seen figures for American gathering grounds where the floods had been double, and others half, but it was noteworthy that, from the information given in the Paper, during 44 years no suspicion of a flood greater than that referred to in the report of the Floods Committee had been recorded. There was nothing in the nature of a catastrophic flood of double the quantity; the Floods Committee had implied that their figures might be doubled for designing an overflow weir which might have to be made twice as long because the flood might be twice as heavy, but there was no suspicion that any flood had occurred on the gathering ground in question greater than the normal maximum flood; that was an interesting point to emphasize. It would be interesting if the Authors could give the computation for the figure 259 from 195 on *Fig. 15*.

On p. 374 the Authors computed a drought at 0·25 cusec per 1,000 acres for the lower gathering ground, and on p. 381, for the Claerwen gathering ground, a figure of 0·23 cusec per 1,000 acres. If he did not know (through lack of data) what the dry-weather flow was, he assumed 0·2 cusec per 1,000 acres for large gathering grounds, and it appealed to him very much that that figure was sustained by the Authors. Would they say how the figure of 0·06 cusec per 1,000 acres on p. 373, had been computed? That was the flow, he assumed, below the dam, and it would be interesting if the computation between that and 0·25 cusec per 1,000 acres was given; it would probably take into consideration the evaporation from the water surface of the reservoir, and other factors.

Mr Walters said that his remarks did not mean that, simply because certain facts seemed to be confirmed, all that information was known already. For instance, *Fig. 17* was a very interesting statement of the case that evaporation and other losses, when there was low rainfall, were less than they would otherwise be, because, as the Authors had stated on p. 378, there was not enough rain to evaporate, and therefore in years of low rainfall the evaporation was less. Similarly, in years of very high rainfall, on the right of the curve in *Fig. 17*, the run-off was so quick that there was no time for it to evaporate, and therefore the evaporation loss was less than it might be for normal average conditions about the middle of the curve. It was true that the spots were dotted about, but probably the curve gave a fair average.

Another very interesting point was that in Table 10 the average loss for the three driest consecutive years was 18·63 inches, but the average annual loss was 21·1 inches. He would compare that with the Ministry of Health's Compensation Report,[9] reprinted in 1946, for reservoir "C." The rainfall there was very similar to that at Elan, about 71 inches. In that report the average annual loss was given as 18·13 inches, and the average loss for the three driest consecutive years was 14·96 inches, so that it seemed necessary to add about 3 inches to both the figures in the report; that at any rate gave the sense of it.

Storage and yield was a big question, but he would say that if the actual storage, the actual proved evaporation given by the Authors, and the actual yield were considered, the average annual rainfall, less the evaporation, agreed on the Deacon diagram and more or less on the Lapworth chart, which was pessimistic.

In conclusion, he wished to draw attention to a sentence on p. 388 of the Paper, where the Authors said "For full economical utilization of the yield of a gathering ground . . ." In using the word "economical" there, he thought that the Authors meant with regard to the three consecutive driest years, because it so happened that the economical dam and reservoirs might coincide with the three driest consecutive years. It might, however, be that some more information was needed about what was meant by the word "economical" in that context.

Mr R. W. S. Thompson said that he had compared the Authors' figures with the figures which had been collected by his predecessors and himself for the catchment area of the River Derwent in Derbyshire down to Lady Bower Dam. Some data obtained there had been published a few years previously by the Institution of Water Engineers.[10] He had looked at the rainfall figures as well as the run-off figures up to date, and they tallied in a remarkable manner with those presented in the Paper. For instance, the average of the past 20 years was extraordinarily close to the estimated true long-average for the gathering ground.

He thought that the rainfall figures given by the Authors were probably as accurate as any which were available, and the way in which they had been obtained and dealt with was almost beyond criticism. There were difficulties, of course, in obtaining accurate rainfall data, particularly in

[9] Ministry of Health Report of Technical Sub-committee on the Assessment of Compensation Water. H.M.S.O., 1930.

[10] R. W. S. Thompson, "The Application of Statistical Methods in the Determination of the Yield of a Catchment from Run-off Data." J. Instn Wat. Engrs, vol. 4, p. 394 (Aug. 1950).

hilly country, but everything possible had been done in the case in question to obtain figures of extraordinary accuracy.

The run-off data were also, no doubt, very accurate, particularly as so many of them had been measured by gauges on the aqueduct and the compensation gauge, but he felt that the figures of discharge over the Caban Dam might be slightly under-estimated. Recently he had been at Claerwen, when there had been an exceptionally high wind, and tremendous waves had been coming down the Caban Reservoir and causing a very exciting-looking overflow over the spillway. That might have been an extreme case, but he knew that on a similar rock-faced dam it was possible to get quite a good discharge over the crest with the water-level 6 inches below the crest, and there was bound to be an under-estimate of the discharge when measured in that way. He would like to suggest to the Authors and to the Birmingham Corporation that it might be worth while to construct a gauge below the Caban Dam and a little way down the river, perhaps 200 yards, of the Venturi-flume type, to measure those big overflows independently of the crest of the dam and compare the results with the crest discharges for a few years in order to see whether, in fact, the Birmingham Corporation had a little more water in the catchment area than they seemed justified at present to think they had. He thought that that might be found to be so.

The evaporation loss of 21 inches seemed high. It might be that the explanation which had been given was correct, but if the run-off had been slightly under-recorded, the evaporation loss would be overestimated. In the Paper it was suggested that the accuracy of the Caban Dam measurements was borne out by the gaugings at Dol-y-Mynach, but Mr Thompson wondered whether wave action might not come in at Dol-y-Mynach also. He did not suggest that there was anything wrong with the calibration of the overflows, the sharp edge at Dol-y-Mynach, or the rock edge at Caban, but they might be affected by wind action and he would like the Authors to consider that point. He was sure that they would always get their 106 million gallons per day, and he thought that they had a much bigger margin than many water undertakings in Great Britain.

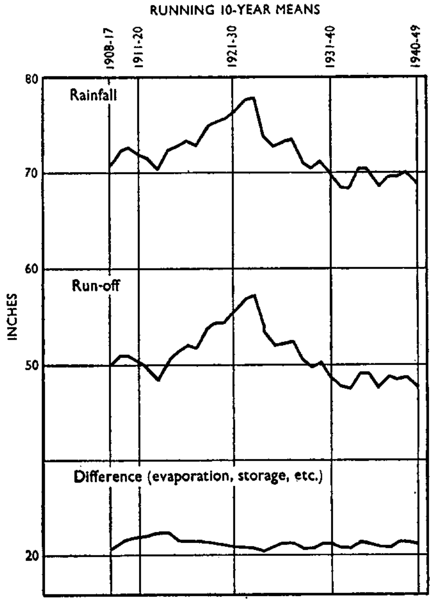
He had a slight criticism on a point of detail in the Paper. Taking Table 4, if the figures were added up it would be found that the 6 summer months produced 41 per cent of the rainfall; and in Table 6 the 6 summer months, April to September added up represented only 32 per cent of the mean annual run-off. The large difference between the 6 summer and the 6 winter months had an effect on the shape of the curves shown in *Figs 7* and *13*, and, with due respect to the Authors, he would like to suggest that possibly the smooth curves shown ought to be slightly corrugated. Dr Glasspoole was present and might contradict that, but the point which Mr Thompson wanted to make was that the average run-off in the 6 summer months was so much less, and had a slightly greater variability, so that one was almost bound to get the lowest 6 months including the summer months, whilst the lowest 12-month period would include both winter and summer and be disproportionately greater. In the case of rainfall the effect was not so pronounced, because the difference between summer and winter rainfall was not great, but with run-off, the summer accounted for only 32 per cent of the total and it had a bigger effect. The position of the spots on the graph rather suggested that. It was true that on that gathering ground the worst conditions had not been experienced, but if a line were drawn through the points for the Elan valley, it would be found that they suggested corrugated curves. In the case of a catchment area with as much storage as at Claerwen, he did not think that the smoothed curve introduced a great deal of error. But in dealing with an under-reservoired catchment, where it was necessary to get more water, and where an additional reservoir could not be built, but more water could be brought in, the question of the shape of the lower part of the curve would be of great importance, and the Authors' smooth curve, which was a sort of envelope, was not, perhaps, quite the limit of accuracy which was possible.

The lowest yield would be given by run-off in periods which were approximately multiples of 6 months—6, 18, or 30 months, according to whether there was little, normal, or excessive storage. It seemed to be an accident that the lowest run-off experienced in Birmingham had been in 16 months, because in the next 2 months in 1934, August and September, they had had 13 inches of rainfall which produced about 8 inches of run-off. That had been fortunate, because it just made the 18-month drought rather less severe than it might have been. The proper thing to do was to take 18 months as the period which in that sort of climate was likely to produce the most testing circumstances.

Dr J. Glasspoole observed that the residual mass curve, which was based on the cumulative excess or deficiency, depended on the starting point. If records covering earlier years had been available, *Fig. 3* might not have looked so convincing. The arguments for taking 1881 to 1915 as a standard for reference had been based on records covering 200 years, and the report on "Determining the General Rainfall over any Area,"[3] drew attention to the period 1887 to 1930, but recommended that 1881 to 1915 should be adopted for the present as a standard for reference. Mr Barnes had been a member of that Committee, but in Dr Glasspoole's view the Authors' policy of mentioning both periods was a reasonable one. The procedure of inspecting rainfall stations at least every 2 years, and of plotting rainfall maps monthly, was especially welcome, and it was to be hoped that other water engineers would adopt the procedure, as indeed a good many of them did, and that the Meteorological Office would be able to resume visits and inspections.

He had plotted the values of rainfall, run-off, and loss as running 10-year means, and the shape of those curves was quite different from that of the residual mass curve of rainfall, although plotted from exactly the same data. The trends of the rainfall and run-off curves appeared identical, but the loss curve was much more uniform and had the maximum and minimum at different times from the maximum and minimum of the rainfall and run-off. (See *Fig. 19.*)

Fig. 19



Elan and Claerwen Areas : Rainfall and Run-off

When wet years set in, the ground storage and stream storage made their demands, but with further wet years their capacity to absorb became smaller. The Paper showed that a series of wet years started in 1910, when the storage was made up, but after the wet years, the losses eventually decreased. He pointed out that the minimum in the loss curve was at about the time of the maximum of the rainfall and the run-off curves. He suggested, for the consideration of the Authors, that that arose from the fact that there had been dry years before that period, and the loss met that demand, but with the wet years the ground became saturated and satisfied, and the loss then became a minimum. It was interesting to note that the general trend of the loss in recent years had been to an increase where there was an indication that the run-off had decreased. That was very similar to what had happened in the Thames valley. In the Thames valley the range of loss in the 10-year means was about 3 inches for the period 1908–1950. The range in his curve of loss for the Elan and Claerwen area was 1·7 inches, which was the difference between the means of 10 years and therefore corresponded to 17 inches, which was of the order of the loss for any individual year.

He knew of no variation in temperature or sunshine which corresponded to that trend of loss. Similar running 10-year means of temperature and sunshine for the seasons of summer, autumn, winter, and spring had been prepared for England and Wales. None of the trends was similar to that trend of loss, nor was there any similarity in the trends of the winter rainfall as distinct from the summer rainfall. It was quite a distinct trend, and that suggested that the trend was a storage factor rather than a meteorological or evaporation factor.

Figs 8 and *9* showed that in some years the annual values of rainfall and run-off did not fit the curve precisely. It was noticeable that those years which were plotted above the curve—the years which had more run-off than would be expected from the rainfall—followed a wet October to December, whilst the years plotted below the line—the years which had less run-off than would be expected from the rainfall—followed a dry October to December. Taking the 6 years with the greatest departures above the line and the 6 with the greatest departures below the line, the difference in the mean rainfall during the preceding October to December had been of the order of 7 inches, so that storage again came into the picture. He thought that those two factors might be of interest in interpreting *Fig. 17*.

The Authors had dealt with three variables, namely, rainfall, run-off, and loss. The next step seemed to be to break down the loss into evaporation, absorption, and any other variables. It seemed from what he had already said that the storage was more variable year by year than the evaporation. Dr. Glasspoole was unable, as yet, to offer any suggestion why the loss was as much as 21 inches when 17 inches might have been expected, but it was clear that the figures did hang together extremely well.

Mr J. C. Dickinson stated that, recently, he had had occasion to deal with two catchments of comparable size, which he would call Catchments A and B. Catchment A was about 40,000 acres, rather long and narrow, being about 20 miles in length, largely cultivated, with limited surface soil over impervious rock. It was steep, and its climate was insular equatorial. The precipitation at the outlet of the valley was about 214 inches per annum, but such was the maldistribution of rainfall that the average over the catchment was only 124 inches, and there were records of intensities of 20 inches in 24 hours. It was interesting to compare that maldistribution with the comparatively regular distribution over the Caban catchment. Catchment B was about 90,000 acres, slightly elongated, generally covered with heavy jungle, again with underlying impervious rock, and the climate was insular tropical. The average rainfall was 106 inches. Catchment C (the one dealt with in the Paper) was 45,600 acres, with an average rainfall of 69½ inches.

It seemed to him that under the extremes of rainfall and sun found in the tropics any abnormalities would be emphasized, and it was therefore necessary to submit to critical examination anything which appeared to be a general rule in a catchment such as Caban. So far as long-term run-off was concerned, the figure for Catchment A was 71 per cent, and for Catchment B 63½ per cent, whilst he had taken the figure for Caban at 70 per cent. He did not place much value on that long-term average run-off as a yardstick to apply to shorter periods ; all that he would suggest was that those figures showed that heavy tropical jungle was a very greedy consumer of water. The average annual loss in the three cases was 36 inches, 38½ inches, and 21 inches respectively, and he fancied that it was the heavy vegetation which consumed the larger quantity of water.

The minimum recorded flows for the three catchments were : Catchment A, 1·1 cusec per 1,000 acres ; Catchment B, 2·16 cusecs per 1,000 acres ; and Catchment C, 0·06 cusec per 1,000 acres. Taking the relative sizes of those compared with the average daily precipitation gave figures of 70, 180, and 7½, so that he would suggest that the heavy jungle was compensating for its greed by smoothing out the low-flow periods, whereas the Authors were probably right in suggesting that the bog areas in their catchment had made the condition distinctly unfavourable. In the matter of maximum recorded flows, Catchment A showed a figure of 750 cusecs per 1,000 acres, Catchment B a figure of 131½, and Catchment C a figure of 259 cusecs per 1,000 acres. Having regard to the intensities of rainfall, the relationship between A and C was not unreasonable, and he thought that B was the odd one, because the heavy jungle had smoothed off the tops of the peaks.

Mr Dickinson said that, with certain general characteristics in mind, he thought that it would be interesting to investigate *Fig. 8*. The result was far from a grouping of points above a mean line, and he would suggest that *Fig. 8* should really be represented by a lenticular space bounded on the top by a straight line representing such conditions as gave the minimum losses, and on the lower part by a curve showing the conditions which gave rise to the highest losses. Under tropical conditions the width of that lenticular space between the two curves was so great that it was almost impossible to plot anything resembling *Fig. 9*.

The Authors made a plea for continuously-recording gauges. In the comparatively equable climate of Wales they had collected a mass of thoroughly reliable data by daily and monthly readings of rain gauges, but even there they failed completely in the case of their maximum flood, because their 3 inches of rain fell in two different days, when obviously it had occurred, as they said, in a short period which bracketed the division between the two days.

Further to illustrate that point, he would like to give a few figures giving the history of two floods which occurred in Catchment A. The precipitation had been recorded on more than 60 rain gauges scattered throughout the area. Both floods followed steady rain, so the catchment might be assumed to be thoroughly wet. The figures were for 5 days, and he would call the two floods (a) and (b).

TABLE 16.

Day	Flood (a): thousands of acre-feet	Flood (b): thousands of acre-feet
1	8·15	13·6
2	50·08	36·4
3	43·28	20·3
4	19·33	12·7
5	11·91	10·77
	132·75	93·8

It would be observed that in the case of the flood (a) there had been a total of 93,000 acre-feet precipitation in a period of 2 days, whereas in the case of the flood (b) there had been only about 56,000 acre-feet. It would be thought, therefore, that the flood in case (a) would be very much greater than in case (b), but as a matter of fact the peak of (a) had been, if anything, slightly less than that of (b), the reason being that the comparatively level top of the flood hydrolograph in (a) lasted for about 54 hours, and in (b) for only about 18. In the absence of continuously-recording gauges that point would not be made manifest. He made no apology for some degree of inaccuracy in observations of those big floods, because the physical conditions were so unpleasant that the attention of the observer was a little distracted, and he might be forgiven for not observing very closely, whereas a continuously-recording gauge, unless physical damage occurred, would record and provide the necessary data.

Mr A. G. McLellan asked the Authors whether he would be right in assuming that the observers in the Elan and Claerwen valleys, almost since the inception of the records, had been employees of the Corporation. He was at present concerned with the hydrological investigation of a gathering ground on which nineteen rain gauges had been established, and because his own undertaking had no organization in that area, and in the absence of volunteers, paid observers had to be used. It would probably be agreed that the enthusiastic amateur was the best rain-gauge observer, but they had had to use local farmers, etc., and he would not say that on the whole the result was always satisfactory.

Like Mr Thompson, he had imagined that the wind carry-over might have been appreciable, but assumed that the Authors would have considered that and decided that, like the evaporation from the water area, it could be neglected.

Mr McLellan would have liked the Paper to have dealt a little more with the readings of what might be called the " ratio station " at Nantgwillt which existed before the present gauges had been installed at Elan. He was trying, on a new gathering ground, to arrive as quickly as possible at a long-period average figure, and it would have been interesting to know how long it took to get a reasonable approximation to the average figure by the application of the readings of that ratio station to the readings from the four additional rain gauges installed by Symons in 1891. It would be reassuring to know that in a short time before formulating a scheme it was possible to arrive at an average figure with a certain degree of accuracy, so that it could be adopted with some degree of confidence.

For those who were starting to investigate a gathering ground, in his own case of some 30,000 acres, it was an object-lesson and an encouragement to learn the results of what Birmingham had done, but at the same time he wondered whether some of the practical results, apart from the academic interest, might not be more apparent than real. At the end of the Paper, for instance, the Authors advocated that 7 months' storage should be provided. That was after they had made the refinement in calculating the yield to be 106 rather than 104 million gallons a day. He took it that the 7 months' storage, which they suggested, in effect amounted to over-reservoiring the gathering ground—in fact, reservoiring it on the basis of more than 3 dry years. They had not got that storage, but had a condition of reservoiring for 3 dry years, and should therefore regard the safe yield as less than their calculated figure.

Mr McLellan thought that the paper was one of the most detailed hydrological analyses to have been published and he expressed the hope that other such analyses might be made available to those interested in the subject.

Mr C. F. Lapworth expressed his admiration for the very useful factual material contained in the Paper. Mr Thompson, he said, had made a point on *Fig. 14* which he wished to underline, regarding the use of a smooth curve for the minimum run-off diagram. He had himself investigated a very large number of these minimum run-off diagrams of various catchment areas, and he had invariably found that, in areas of high rainfall such as the Elan, there was a distinct cusp at 12 months, 24 months, and 36 months, and not, as shown in *Fig. 14*, a smooth curve. That was borne out by the fact that, if the actual figures for the Elan catchment were taken and put on that diagram, the period for 8 months was nearly 20 per cent, and the period for 12 months was nearly 40 per cent, of the long-average annual rainfall ; if those actual figures were plotted, a different sort of curve was obtained from that shown on the diagram. The practical effect in the case in question would have been negligible, because it so happened that the storage required for 16 months would be almost the same as that required for 14 months, but in other cases, where the catchment was not so fully reservoired, it would make a difference. From that point of view he thought that the method was not to be recommended.

On p. 386, the Authors gave Mr Mansergh's estimate of the yield of the catchment area, which, taking the present area, would be equivalent to 102 million gallons per day, which was very close to the figure of 106 million gallons per day given by the Authors. It is probable, however, that in those days, the figure which would have been used for storage would have been much less than the amount of storage which was now provided.

On the same page, reference was made to the fact that 180 days' storage had been, at one time at any rate, considered adequate to provide for the longest drought likely to occur in the British Isles. The amount of storage required for any particular catchment area depended, of course, on a number of factors. It depended on whether the rainfall was low, on the proportion of the average run-off which was required, and on whether the stream was flashy or not. In areas of low rainfall much more than 180 days was often provided. He knew of two cases of storage reservoirs which had amounts of storage of between 350 and 400 days.

Mr N. A. F. Rowntree thought that the term " 3 driest years " was an incorrect assumption. It had been interesting to note that the Authors, in introducing the Paper, had not used that expression but had said " 3 dry years," which was more accurate, and which had been used by Thomas Hawksley nearly 100 years ago.

Many of the calculations in the Paper were on a calendar year basis, notably Tables 5 and 7 and *Figs 7* and *10*. He wondered whether the Authors had considered using annual moving averages instead of taking arbitrarily January to December in each year. Was there any reason for not taking from 1 October to 30 September, and any or all of the other 12-month periods? For example, taking the extremely dry period referred to in the Paper from March 1933 to February 1934, the rainfall had been only 43·2 inches, the run-off 28·1 inches, and the losses 15·1 inches. Inserting those figures in *Fig. 8*, another point was obtained much lower down than the 33 marked as the lowest; it was, in fact, just off the chart. By taking many more of those " moving averages " it was possible to get quite a large number of points at that end of the curve, which might help to establish its position more accurately.

The same comment applied to *Fig. 17*, to which other speakers had referred. There was a very considerable scarcity of points at both ends of that curve. So far as the high rainfall end of the curve was concerned, looking at the scatter of the points marked, he would say that if they represented the information on which that line had been based, it would be just as logical to draw a horizontal line on the 22-inch loss line, or thereabouts. That did not mean, however, that the shape of the Authors' curve was not well reasoned, and one would tend to agree, but it would be good to see it confirmed by more data.

Another point which had occurred to him, and which had to some extent been raised by other speakers, was that instead of taking yearly figures for the purpose of computation it might be possible to take 6-monthly periods, or in other words to consider all the summers and all the winters and then match them together to produce years, not necessarily taking the lowest of each, but matching the figures to give a year or period of years corresponding to what might be expected in 3 dry years. In that way much of the scatter which was obtained in *Fig. 17* and other diagrams might disappear.

Now that such an excellent long period record had been published, it should be possible to establish the probability of occurrence of periods of drought, for example, the number of times in 100 years when a drought of 1933–34 dimensions might occur.

Mr W. N. McClean thought that the Paper was the most complete record yet produced of the rainfall over a definite area of about 70 square miles and of the run-off or draw-off over a period of 42 years, but there was no measure of loss.

Whilst monthly records could give useful information regarding water resources and the relation of storage to supply, they were insufficient for the water survey and record of the River Wye and for problems of control, usage, and flood. With regard to *Fig. 2* (rainfall distribution), Mr McClean said that in his opinion the Paper would gain by having a similar map showing the height contours, giving the positions of the rainfall gauges, and showing whether they were continuous recorders, or daily, or monthly gauges. That would be very informative, as the rainfall of a rain-period was admittedly orographical; and it would not alter the isopercental distribution of the month.

Taking the 42-year period 1908 to 1949, it had been pointed out that the annual rainfall average was 71·6, the run-off 50·5, and the loss 21·1. In Table 4 the Authors gave the assessment of "area" rainfall, and in Table 6 the volumetric measure of run-off, whilst in Table 10 they computed the loss by evaporation and absorption, which was rainfall less run-off. He felt that there was perhaps something missing there, in that the rainfall table, Table 4, did not give the summary for those 42 years. It might go very well at the bottom of Table 6, giving the resultant facts of run-off, rainfall, and remaining loss.

With regard to the dry periods, percentages were given in Table 5 which were percentages of the year's average rainfall. It seemed to him that those percentages should give the relative rates of rainfall. When it was said that the 3 dry years gave a figure of 254 per cent, that did not give the rate. The figure for the rate was 84·7 per cent. The same applied to the monthly periods; he thought that the percentages given were not the best which could be used there. Knowledge of the average rate of those different dry periods was needed, and it was a little disappointing that the periods in the rainfall table were all the months up to 12, and then 16, 20, 24, 30, and 36, giving quite a number of values; but in Table 8, which dealt with the run-off, the lowest run-off, under 12 months, was only given for 4 and 8 consecutive months. He missed having run-off values for all the driest periods and had extracted them from Table 6. It was remarkable to see how the period of 9 months in 1929 corresponded to the longer period in 1933–34. Those two dry periods seemed to be outstanding in the 42 years, and from certain mass diagrams which he had made, it seemed as though such extreme dry periods did not extend to much more than 18 months—that was a critical point.

Mr R. H. MacDonald, commenting on the residual mass curve shown in *Fig. 3* of the Paper, stated that the residual mass curve for the Nile for the same years was very similar to the Caban curve except that it was upside down, with the wet period at the beginning and the dry period at the end. It did not mean very much, he thought, except that those periods did occur, but whether they really occurred in cycles of that kind or not it was still very difficult to say.

On p. 349, the Authors said " Obviously the true long-average rainfall is the average of the longest possible period over which rainfall records can be obtained. . . ." Would the Authors qualify that ? If one had short rainfall records the true long-average would be the mathematical truth only for the time being.

In Table 10 the mean monthly evaporation figures were given. Those were slightly different from Dr Penman's figures for the British Isles. A few years previously Mr MacDonald had worked out, on a much shorter number of years, the figures for the River Shin, in Scotland. Those figures were very similar to those found at Caban. He was glad to see his figures for mean monthly losses thus justified.

Would the Authors state that where they dealt with the gathering ground, on p. 347, that there was no seepage into or out of their areas which affected the water-supply at all. It was well known that the Welsh hills were like that, but perhaps it should be mentioned for the record.

*** **Mr H. F. Wilmot** remarked that the use of isopercentals was particularly worthy of note, and the manner in which they were used to check suspect readings.

The residual mass curve of rainfall (*Fig. 3*) conformed very closely with the similar curve relating to the discharge for the River Thames, for which the periods of shortage and excess above the normal were 1883–1909 and 1910–41 respectively. That would indicate that the weather over the areas concerned was, on the broad outlook, relatively similar; since the records for the Thames could be considered very reliable Mr Wilmot was hesitant in raising the question of whether the earlier recordings for the Severn were accurate ; for instance, where heavy intense rain occurred, had the older rain gauges in the past been of adequate capacity, when recordings were taken at considerable intervals of time ?

The percentage errors in the two rain gauging records shown were + 6 and — 11, and some explanation how that might have occurred would

*** This and the following contribution were submitted in writing upon the closure of the oral discussion.—SEC. I.C.E.

be reassuring for the accuracy of the other readings; an excess should not be possible without interference by an unauthorized person. Were further errors confined in large measure to the same sites or were they widespread?

The presentation of the facts was so clear and straightforward that it tended to minimize the difficulties of the hydraulic engineer in assessing potentialities for water supplies where the data available were less adequate. It should be fully stressed that conclusions based on a period of less than 1887–1930 (48 years) in the case mentioned might be very badly out, for example, 1910–30 (20 years), 1887–1910 (24 years), or 1930–49 (19 years).

The assessment by Mr Mansergh in the first instance was really remarkable when taken over a long term. In 1910, however, there might well have been serious misgivings that he was too optimistic without wishing to belittle his sound conclusions; it had so happened that the years of data available to him were helpful in arriving at the conclusions he formed.

Mr Wilmot had had occasion to investigate flow conditions of the River Severn at Bewdley (1921–49), and had tried unsuccessfully to correlate the levels and discharges at Worcester (where levels alone were available from as far back as 1862) to extend the results and obtain greater validity for them. The period of build-up existed from 1921–32 and recession lasted until 1944; the average annual discharge between October 1921 and October 1949 was 2,190 cusecs. The trend to 1932 closely followed that of *Fig. 3*, but there was a marked difference for the succeeding years.

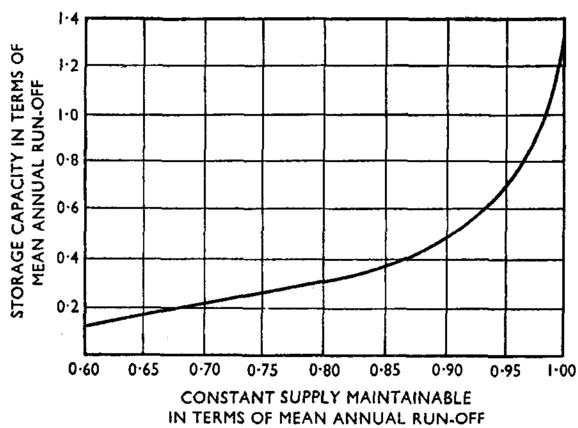
From the water-supply view point, *Fig. 14* giving the maximum deficiency which had, and which might, occur over varying periods of consecutive months was the all-important result which justified the long analysis preceding it.

Mr G. Bransby-Williams shared the Authors' regret that there had been no recording gauge on the catchment in 1946. Autographic records from an earlier date would have furnished useful information about the frequency and intensity of heavy falls in short periods and data for the construction of a basic hydrograph for the catchment.

The 42 years' record of run-offs seemed to be a more satisfactory basis for estimates of storage capacities and run-offs than the rainfall figures, which introduced an extra element of uncertainty into the calculations. There were factors affecting run-offs that did not influence rainfall. The extent to which they did so might be judged by the discrepancies in the proportional ratios between them in individual years. It might be added that, whereas the frequency distribution in a long series of records of annual rainfall in Britain was nearly symmetrical, and conformed closely to the normal curve of probability, such records of run-offs as it had been possible to construct from the data available showed distributions that were definitely askew.

The method of calculating storage by means of empirical formulae based on the assumed run-offs in a hypothetical series of dry years, which had been inherited from the Victorian engineers, ignored the economic aspect of the problem and also the relationship between the capacity of the reservoir and the quantity that could be supplied from it. The Figures in the Paper supplied data for a different form of calculation. A mass depletion curve could be plotted from the run-off records which would show the storage required to maintain a constant supply (for all purposes including losses from the reservoir) equal to 90 per cent, 80 per cent, 75 per cent, and so on, of the mean annual run-off throughout the 42-year period. That storage would be what Allen Hazen had called the " annual " storage; that was to say, the storage required to equalize the annual run-offs over a term of years. To that should be added what he had termed the " seasonal " storage that was needed to balance the excess run-offs in the wet seasons of the year with the deficiency in the dry seasons. That was obtained from records of monthly rainfall.

Fig. 20



CURVE SHOWING STORAGE/SUPPLY RATIOS

The curve in *Fig. 20* had been plotted to show the relationship between storage and supply on the Elan and Claerwen catchments, in terms of the mean annual run-off, obtained in the manner described. The total existing reservoir capacity was 21,136 million gallons. That was about 0·432 of the mean annual run-off, taken as 48,864 million gallons, which was sufficient for a constant supply of 0·88 of the mean run-off or about 116 million gallons per day. The figure of 106 million gallons per day in the Paper thus seemed to allow a substantial margin.

The form of analysis which Mr Bransby-Williams had briefly described should be applied to actual records of run-offs extending over a period of years. But the storage/supply-ratio curves obtained for a number of catchments, with varying characteristics, showed sufficient consistency to allow an appropriate curve to be selected for catchments on which no stream gaugings had been made, which would be sufficiently reliable, at all events for the initial stages of a storage-reservoir project.

Mr Risbridger, in reply, said that Mr Walters had stated that it was usually assumed that the average rainfall of the three driest years would be 80 per cent. The Authors had stated in the Paper that, although they had found hitherto that their average rainfall for each of the three driest years had been 84 per cent, they had based their deductions of the yield and the storage required on less than 84 per cent; in fact they had based them on 80 per cent, according to the rainfall curve developed by Dr Glasspoole from observations for the whole of Wales over a period of 74 years.

Mr Walters had referred also to the question of floods. Their maximum flood had been, of course, only the normal maximum flood, and they knew that they were as liable as any other upland gathering ground to be subjected one day to the "catastrophic flood" referred to in the report of the Flood Committee. If such a "catastrophic flood" did occur, however, Mr Risbridger was confident that a visitor to the district 2 days later would find the dams—both the old ones and the one recently built—still in position.

With regard to the reason for the difference between 0·06 cusec per 1,000 acres recorded at the Caban Dam and the figure which the Authors gave of 0·25 cusec per 1,000 acres for the lowest run-off, the difference arose because the 0·06 was measured at Caban after evaporation from the surfaces of the reservoirs had been deducted.

Mr Walters had asked for the computation of the figure, 259 cusecs per 1,000 acres, given as the maximum rate of run-off on p. 373, from the figure of 196 cusecs per 1,000 acres given in *Fig. 15.*

The latter figure represented only the maximum rate of flow over the crest of the Caban Dam. The maximum rate of run-off should include the maximum rate of increase of water stored in the reservoir itself, the rate of supply to Birmingham, and the rate of discharge of compensation water.

The rate of increase of storage was calculated by taking the greatest rate of increase in water level between 1 p.m. and 2 p.m. on the 20th September, which represented 4,200 cusecs. The rate of discharge to the aqueduct and to compensation was, together, 130 cusecs. Those figures, added to the rate of discharge over Caban Dam at 2 p.m., 7,450 cusecs, produced a total of nearly 11,800 cusecs or 259 cusecs per 1,000 acres. The peak rate of overflow at Caban Dam at about 3 p.m. on the same day was only 196 cusecs per 1,000 acres.

Mr Walters had requested some clarification of the term "full economical utilization of the yield." The Authors had had in mind, when using that expression, the storage capacity necessary to make the maximum use of the run-off of the three driest consecutive years, assuming that the rainfall of that period would be 240 per cent of the long-average annual rainfall.

Hence in *Fig. 14* the curve of actual minimum run-off in 36 consecutive months experienced in a period of 42 years had been amended as shown by the dotted line to represent the lower 3-year run-off which might be expected as a result of the 3-dry-year rainfall actually experienced in the same 42 years being more than the 3 driest years' rainfall in Wales during a period of 74 years as given by Glasspoole.

Whilst dealing with that point it might be an advantage to refer to the suggestion made by one or two other speakers that the storage provided erred on the side of safety. Mr Risbridger was of the opinion that, if such was the case, the margin was by no means extravagant when the supply to an important industrial city like Birmingham was at stake. *Fig. 16* showed that had the demand from the gathering ground in 1933–34 been 106 million gallons per day, 17,615 million gallons would have been drawn from storage, leaving only 3,520 million gallons in the reservoirs, or 33 days' supply at 106 million gallons per day. It should be remembered, however, that the capacity of the tunnel and cut-and-cover sections of the aqueduct was 75 million gallons per day which, with 29 million gallons per day compensation, produced 104 million gallons per day as the anticipated maximum demand from the gathering ground. Even so, with that demand, the reservoirs would have been depleted in 1933–34 by 16,621 million gallons, leaving only 4,514 million gallons or 43 days' supply.

When reservoirs, upon which the supply to a vast industrial area depended, contained only enough for a few weeks the position was already serious, and necessitated precautionary measures entailing great inconvenience to consumers and supplier alike. Complete failure of the supply would result in huge financial loss to industrial consumers. It was, therefore, considered a justifiable insurance to provide storage with a reasonable margin of safety.

The additional cost spread over the loan period was not of a serious order when weighed against the assurance provided and the total cost of the scheme. It would seem a little illogical for engineers—who, quite rightly and unashamedly, adopted factors of safety of 3 or 4 when dealing with structural materials—to endeavour to provide storage capacity to a factor of safety of unity, when the storage required depended upon a relatively unpredictable factor such as the incidence as well as the quantity of rainfall.

Mr Thompson had drawn a diagram corresponding to *Fig. 13* but with curves shown by " wobbling " instead of smooth lines. That would be correct if the curve represented run-off starting from January, but that was not the case; the Authors' curve represented the lowest run-off in 4 months starting in any month of the year, and the run-off in 8 months starting from any point in the year. If January were used as a starting point, " wobbles " would gradually diminish until after 3 or 4 years they disappeared altogether.

In reply to Mr Thompson's suggestion that a Venturi-flume gauge might be constructed below the Caban Dam, from the point of view of its practical usefulness, it would not now be worth while, since the gathering ground was now fully reservoired and the necessary expenditure could therefore hardly be justified.

There was the question of unmeasured loss over Caban Dam from wind action. It was true that some water was blown out but, in proportion to the total run-off from the gathering ground, it was almost negligible. Mr Risbridger had seen it blowing over and, with a gale in the right direction, a considerable amount did go over. From observations of river levels below the dam, however, and consideration of the aggregate duration of conditions leading to blow-out, the Authors had come to the conclusion that the total loss from that cause was not of such a magnitude as to affect appreciably the total-annual-run-off computations.

The only point in Dr Glasspoole's remarks to which Mr Risbridger felt able to reply without further consideration was the tendency to disagree with the aptness of choice of the particular 44-year period on which to base the assessment of the long average. Dr Glasspoole had expressed similar disagreement before, but the long-average rainfall deduced from the 35-year period, with which Dr Glasspoole agreed as a standard, differed from the Authors' 44-year period computation by only 0·1 inch in 69·4 inches, so that the averages of the particular periods were not far apart in any case.

Mr Risbridger thanked Dr Glasspoole for his very interesting curves in *Fig. 19*, which certainly demonstrated the trends of rainfall, run-off, and losses better than a plotting of those figures for individual years, but he did not attach the same importance to the effects of ground storage as did Dr Glasspoole because the comparatively close compact nature of the geological formation of the gathering ground did not provide much storage. It was true that there were considerable areas of absorbent peat bogs, but observations showed that, even when the preceding weather conditions had been wet, with the onset of dry conditions the run-off falls to dry-weather flow in a surprisingly short period.

Mr Dickinson had spoken of rainfall in tropical countries. Mr Risbridger knew from experience that rainfall in tropical countries could be great in a very short time, but he was not competent to discuss it from the point of view of hydrological statistics. He agreed, however, that the curve in *Fig. 8*, where run-off was plotted against rainfall, could be shown as a lenticular space, an observation which might apply equally to any curve derived from a series of plots having a degree of scatter. The line the Authors had used was merely a line through what they thought was the middle of that lenticular space.

Mr Dickinson had expressed regret that there had been no continuously recording gauge to amplify the information concerning the maximum flood. The Authors had experienced similar disappointment at the time the flood occurred and had subsequently installed an automatic gauge.

Mr McLellan had asked about the observers of their gauges. Observers were not employees of the Birmingham Corporation, except the observers of daily gauges which were reasonably accessible and were read by a man with a van. Gauges on tops of mountains, where access was difficult and, at times, dangerous, were read monthly, in some cases by local farmers, who had been instructed and took a very intelligent interest in the readings. It was possible, if the isopercental method of plotting was adopted, to find out very quickly if some observer had rung up a neighbour and substituted a reading.

On the question of length of time for establishment of rain gauges in order to make an assessment of the rainfall, Mr Risbridger said that when Mr Mansergh went to the area he had had the advantage of 20 years' records from one gauge and 1 year's record from four gauges, and he had arrived at what was now the accepted long average within 0·4 inch, which was remarkably accurate.

Mr Risbridger recommended reference to the Report of the Joint Committee on the Determination of the General Rainfall Over Any Area,[3] which included an extensive illustration of the method of deducing the long-average rainfall from the recordings of few gauges for a short period.

Regarding storage capacity of 210 days, Mr Risbridger said that from the mass curve of run-off which had actually occurred on their gathering ground, corrected to allow for the difference between their rainfall and the lowest rainfall which they might expect, the storage required was 20,780 million gallons; they had only 21,136 million gallons, and he still did not feel that they were at all extravagant. On the same point, raised by Mr Lapworth, the storage which Mr Mansergh intended to have was very little less than the Authors themselves had. Mr Mansergh had provided for three reservoirs in the Claerwen and three in the Elan; of those, he had constructed the three in the Elan, and their capacity, together with the capacity of the three which he had intended to have in the Claerwen valley, would have given very little less storage than was now available.

Mr Lapworth had pointed out that the curve of minimum run-off shown in *Fig. 14* should not be as smooth as was shown, but that there should be cusps at 12, 24, and 36 months. Mr Risbridger agreed that that was so, as could readily be appreciated if the plottings of minimum run-off on *Fig. 13* were actually connected instead of being enclosed in a smooth curve. The practical effect of doing so in *Fig. 14* was, however, not very marked because the smooth curve passed through the actual run-off plots for 16, 20, 30, and 36 months, and the point of actual greatest deficiency still remained at 16 months. The anticipated deficiency at 14 months would, however, be slightly less than the 29 per cent shown.

Mr Risbridger regretted that the definition of the true long-average was at fault, as pointed out by Mr McDonald. The intention was to point out that, given a sufficiently long period of annual records, then since that period extended, the effect of a departure of any 1 ensuing year's record from the previously computed long average would diminish with the number of years; namely, if the average of 49 years' recordings produced a long-average figure of 50 inches, the rainfall of the 50th year would have to depart from the computed long average by 50 inches or 100 per cent in order to produce a variation of 1 inch in that long average.

The adjustments to rain-gauging records referred to by Mr Wilmot were made to two monthly gauges and were the only adjustments made for that month.

It was not always possible to trace the cause of an isolated discrepancy in the reading of any gauge—particularly a monthly gauge. It might arise from incorrect measurement or recording by the observer, interference by an unauthorized person, drifting snow, or other reasons. The particular adjustments in question might have resulted from any of those causes, but since some snowfall occurred earlier in the month, that might have been a contributing factor to the apparent discrepancies brought out by the percentage map.

In the case of persistent discrepancies, however, an inspection was called for, particular attention being given in cases of undermeasurement, to ensure that the gauge was not leaking.

It might also be pointed out that, in the first place, adjustments were made provisionally and referred to the Meteorological Office for consideration and approval before final acceptance.

Mr Risbridger thanked Mr Bransby Williams for his interesting curve in *Fig. 20*.

Mr Godfrey, in reply,* dealt with the question of water blowing out, and said that that was a factor which they had always borne in mind, but he did not think that it had ever been very serious. One year, 1923, he believed, when there had been a rather heavier loss than usual, and they had been a little worried about it, they had gone through the records and found that during that year there had hardly been an occasion when the reservoir was near enough to top water level to permit water to be blown clear of the dam. When the reservoir was 6 to 18 inches below overflow, and a high wind was blowing down the valley, some water would be lost, but in that particular year there had hardly been a period when the water in the reservoir had been at that level. After that, they had taken some measurements in the valley below the dam during times of wind action, but wind action made so little difference that it had not been worth bothering about. Mr Godfrey did not think that the same thing had happened at Dol-y-Mynach, where there was a small lake of 26 acres continuously full behind it, and the condition of the water level below the sill did not occur.

With regard to what Mr McLellan had said about observers, some of the men in the Authors' area were mountain farmers, and the best way to keep

* Mr Godfrey has died since making this brief oral reply and has had no opportunity of approving it.

them up to the job was to pay regular visits and get them interested; then they would do the job equally well as the Corporation's men.

Mr Rowntree had raised the question of moving the average 6-monthly periods, taking the year from October to September, and so on. That involved a number of complications. The Authors had found during many years, and particularly in the drought years, that the maximum depletion of storage had occurred about the end of September, and they had not got out of their troubles then. There might be a very long dry spell, and the gathering ground would dry up, so that if the year were closed at the end of September the next year would start with depleted reservoirs. Commencing with the calendar year, the ground was normally saturated by then, and that appeared to be the more appropriate time to open the books for the ensuing year. That was a very strong point, and after giving the matter a great deal of consideration they had decided to adhere to that practice.

Mr McClean had suggested that other periods should be included in the maximum and minimum figures in Table 8. Such figures had been included in the original draft but the length of the Paper had had to be reduced considerably. The figures were available.

Mr MacDonald had raised the question of seepage in or out of the gathering ground. The Authors were convinced that it did not occur because of the characteristics of the geological formation of the gathering ground.

Correspondence on the foregoing Paper is now closed and no contributions other than those already received at the Institution will be accepted.—Sec. I.C.E.