Paper 6193

Investigation of rainfall, run-off, and yield on the Alwen and Brenig catchments†

by

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Discussion

The Author, introducing the Paper, emphasized that all figures obtained by the observation of natural phenomena were mere approximations and were not statistical facts.

96. He also drew attention to the reference in § 10 to the general deterioration of land drainage, and in this connexion it was useful to note that the Alwen land drainage had deteriorated first. Another significant factor in relation to the Alwen position was that following the 1933 drought conditions certain internal catchwaters had been constructed, which had materially contributed to the inflow from the catchment, although not technically increasing the catchment area.

97. Within the part of the Brenig catchment which had been taken over by the Corporation in 1911, notices to quit had been served on all the tenants in 1927 and, although tenancies had been renewed, from that date onwards less and less land had been cultivated until the outbreak of the war, when certain additional ploughing took place. Again from 1947 onwards, active steps, including the sinking of boreholes, had been taking place within the Brenig catchment, and the tenants had consequently reverted to their former practice of neglecting land drainage. Moreover, the projected afforestation had become a known fact from 1952 onwards; most of the tenants had left their holdings or had taken other farms and they used their holdings only for sheep grazings.

98. It should also be mentioned that there was an area on the Brenig catchment extending to 240 acres which was literally on the divide, and it greatly depended, therefore, on artificial ditching and on the surrounding water-table level whether drainage took place into the Brenig valley or northwards to the River Ystrad.

99. The major fault plane referred to in § 12 had been a contributory factor in causing an under-water landslip upstream of the main dam. This had occurred about 18 June, 1956, and had resulted in the main scour outlet pipe from the dam being completely blocked. In consequence the compensation flow had to be given temporarily from the supply pipe. The under-water remedial work had been of such magnitude that the scour had not been restored to operation until 26 November, 1956.

100. In § 88, some forecast was made about the possibility of the yield figures being tested for a second time within a period of 22 years. In fact, that had occurred, and had necessitated an Order being obtained (Birkenhead Water (Emergency) Order, 1956) for the reduction in compensation water. At the same time, drastic restrictions in supplies had been enforced, only to find that the exceptional rains of July and August restored the balance in a quite unpredictable manner.

101. The Author then showed a number of lantern slides.

Mr R. le G. Hetherington (Partner, Messrs Binnie, Deacon & Gourley, Consulting Engineers, London) hoped that the example set by Risbridger and Godfrey[2] in 1954 and now followed by the Author would be followed by others, and that the progressive

† Proc. Instn civ. Engrs, vol. 8, p. 17 (Sept. 1957).

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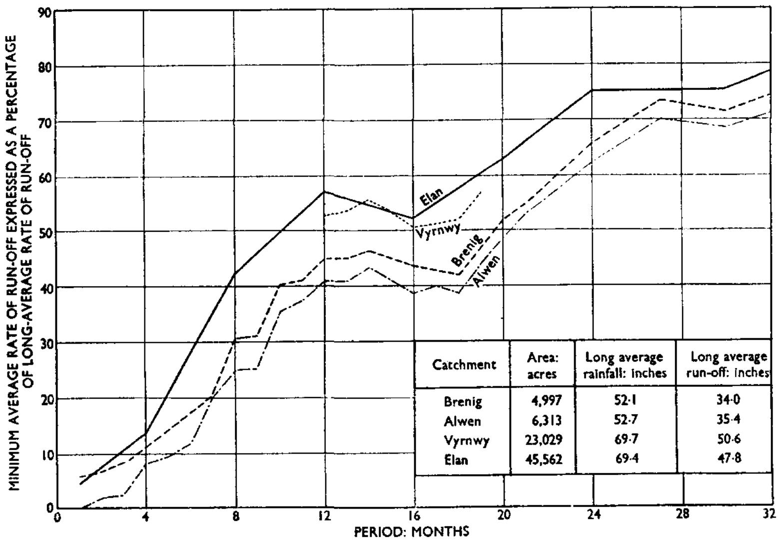
publication of data from more and more catchment areas would dispel the aura of secrecy which had tended to surround records of river flows and reservoir yields in the past.

103. The water engineer of Liverpool, Mr Stilgoe, had allowed Mr Hetherington to make use of some long-term records regarding Lake Vyrnwy. These records had been quoted in recent Parliamentary proceedings but had not previously been published. With these Vyrnwy records, the Elan Valley records,[2] and those given by the Author, it was possible to make a comparison between the yields of four catchments—Elan, Vyrnwy, Alwen, and Brenig, all of which were in central and North Wales and all of which were similar in many respects.

104. Fig. 11 showed the minimum average rate of run-off for periods of consecutive



Catchment	Area: acres	Long average rainfall: inches	Long average run-off: inches
Brenig	4,997	52·1	34·0
Alwen	6,313	52·7	35·4
Vyrnwy	23,029	69·7	50·6
Elan	45,562	69·4	47·8

FIG. 11.—MINIMUM RUN-OFF FOR VARIOUS PERIODS: BRENIG, ALWEN, VYRNWY, AND ELAN

months, expressed as a percentage of the long average rate of run-off. The four curves were thus comparable, in spite of the different areas and rainfalls in the four catchments. The plot for Vyrnwy was confined to the 12- to 18-month periods.

105. The sections of the four curves between the 12- and 18-month periods all related to the same period commencing April 1933. That correspondence did not apply elsewhere in the diagram, necessarily, but it applied over the critical period. The markedly lower rate of run-off obtained at Alwen and Brenig was striking in comparison with Elan and Vyrnwy. This was revealed when the recorded yields of the reservoirs in the four catchments during the period 1933–1935 were compared with a standard curve, such as the Lapworth or Deacon diagram for reservoir yield. Whereas the yields of Elan and Vyrnwy estimated from either the Lapworth or Deacon diagram were less than those which actually obtained in 1933–1935, this was not the case at Alwen and Brenig.

106. It was not easy to see why such relatively lower yields should have been obtained at Alwen and Brenig during the critical period. It had certainly not been because of a relatively lower rainfall, for a comparison of the actual rainfalls in the four catchments compared with the period minima given by Dr Glasspoole showed that the falls at Alwen and Brenig had been relatively higher than at Elan and Vyrnwy during this

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particular period. One possible factor was the difference in the size of the catchments, but while the flashiness associated with smaller catchments was likely to produce a lower flow over a short period, one would hardly expect it to affect the average over a period of 18 months.

107. Low yields at Alwen and Brenig in 1933–35 were attributable to exceptionally high evaporation losses. At Alwen in this period the loss was 19% greater than the long average loss and at Brenig 16% greater; whereas at Elan and Vyrnwy in the same period the losses approximated to the long average losses. He did not know if a study of the incidence of rainfall, air temperature, wind velocity, etc. during the critical period would reveal a reason for the high evaporation loss at Alwen and Brenig; could the Author throw some light on the matter?

108. Binnie and Lapworth,[16] in 1913, had described how the Deacon diagram had been derived from cumulative run-off curves. One of the earliest references to a cumulative run-off curve mentioned in the discussion on their Paper had been made by Turner as far back as 1891.[17] Turner had then produced a cumulative run-off curve for a three-dry-year period for a catchment which he had called Llyn Bran. This lake formed the source of the Brenig, and it was interesting to speculate whether there had been earlier gaugings on the Brenig and, further, if they formed, at any rate in part, the basic data on which Dr Deacon had compiled his diagram. Could the Author throw any light on that?

Dr John Glasspoole (Head of the British Climatology Branch, Meteorological Office) said that it might be inferred from Fig. 5 that 1881–1915 was a poor period to use as standard for reference in the Meteorological Office and also that the rainfall since 1931 had been reasonably normal and such as could be relied upon in the future. He would like to show the other side of the picture.

110. The rainfall over Wales had been defined in broad outline for about 60 years prior to 1881,[18] and the rainfall since 1931 in these areas was certainly above the average of the earlier 60 years. In 1921, the Azores high-pressure system extended northwards over the British Isles, giving a generally dry year, and since then there had been a definite increase in the atmospheric pressure, which would have been expected to result in generally dry years. Fortunately for the maintenance of water supply, two other quite separate factors came into operation. As pressure increased in the south, the Icelandic low-pressure system did not continue to retreat further northwards; and consequently there had been an increased pressure gradient over the country.[19] Thus there was an increased flow of air across the country from west to east and, consequently, there had been an increase in rainfall in the west rather than in the east. The Alwen and Brenig catchments lay in the the western part of the country. In the east, the rainfall since 1915 had been much nearer, and indeed in places below, the average of the period 1881–1915.

111. Another change had been the notable increase in the rainfall per rain-day.[20] This increase had been particularly notable in the spring and it had a marked similarity with the increase of temperature associated with the decline of the glaciers in the extreme north of Europe. Over England and Wales the mean temperature had increased by 2°F during the spring since about 1922–31, and the mean rainfall per rain-day had increased by about 20%. It might therefore be unwise to regard the rainfall since 1931 as normal, as suggested in Fig. 5 by the curve being reasonably horizontal, and certainly the period 1881–1955 did not cover all the variations which Nature could provide.

112. The residual mass curves of rainfall for the Alwen and Brenig catchments were similar and seemed to be similar to the corresponding curve of run-off for the Alwen. It was therefore curious that the run-off values given in Fig. 10 showed such differences for the Brenig. It had been suggested initially that the small run-off from the Alwen reflected the increased loss by evaporation from the reservoir surface, but the Brenig

[16] References 16 *et seq.* are given on pp. 302, 303.

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now gave less run-off than the Alwen. He was therefore glad to see that the Author planned to continue this investigation, which should provide the explanation of this puzzling change and account for the apparently increasing loss of water from the Brenig. The climatological trends related to rainfall were much more complicated than he had been able to explain, but he had dealt with those trends in greater detail elsewhere.[18, 19, 20]

Mr C. F. Lapworth (Partner, Herbert Lapworth and Partners, Consulting Engineers, London) referred to § 56 in which the Author, speaking of Alwen and Brenig, had stated: "the relatively large reservoir surface does not affect to any great extent the respective evaporation losses determined within the respective catchments." It should be remembered that one of these catchments was reservoired; the other was not. The explanation was then fairly simple. He would expect that the losses from a water surface in the Alwen catchment would be, say, 6 in. p.a. more than the loss over the land area surrounding the reservoir. Since the area of the water surface of the Alwen catchment was only 6% of the total, this would mean that there would be an increased loss, due to putting a reservoir there, of only 0·36 in., and that was negligible compared with the average run-off of 35 in.

114. In § 63 the Author had referred to the loss which occurred over the overflow due to wave action. This occurred on every reservoir. There was a considerable loss over the overflow, which meant, in effect, a loss of storage which might be vital in a drought period. Mr Lapworth did not think anyone had yet solved this problem. Possibly it might be useful to form some kind of baffle around the overflow to prevent this spillage, but one would have to be careful not to impede the overflow or to increase the liability to form ice. In this connexion, a siphon overflow, which had an inlet below water level, had certain advantages over a surface overflow.

115. In § 73 the Author had made a comparison between the yield of the Alwen catchment as given by the Lapworth diagram and the yield which would have been available during the 1933–34 drought. Fig. 12 illustrated this point; it was a probability

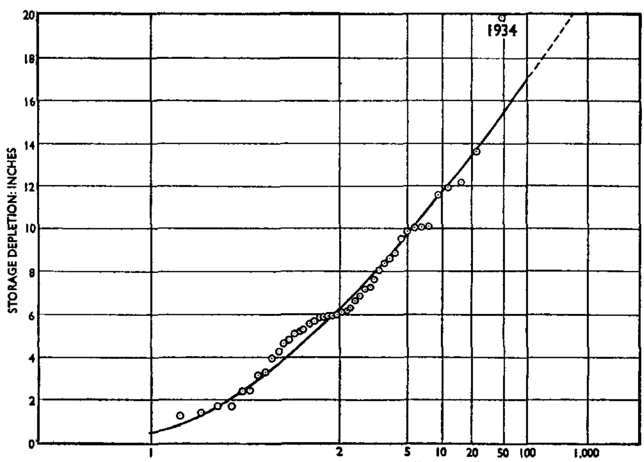

FIG. 12.—PROBABILITY DIAGRAM FOR ALWEN CATCHMENT. YIELD: 27 IN/YEAR

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diagram of the Alwen catchment, using data for the 44 years of run-off as given in the Paper. The vertical ordinates on the diagram represented the storage depletion in each year, for a constant yield of 27 in. p.a.; the figure given by the Lapworth diagram. For each year of record of 44 years he had taken a yield of 27 in. and had calculated what quantity of storage would have been necessary to maintain that yield. This led to 44 points, which were shown in Fig. 12. They had been placed in order of magnitude and then plotted on an arithmetic probability basis. The result showed the probability of various storages being required, according to the average length of time between the occurrences. Fig. 12 showed, for example, that every 2 years a storage of 6 in. was needed; every 5 years, a storage of 10 in.; and every 20 years, a storage of about 13 in.

116. Using the line on the diagram, it would be seen that the probability of a drought occurring once every 100 years meant that to maintain a yield of 27 in. a storage of about 17 in. was needed. This compared with the storage of 18·2 in. given by the Lapworth Chart. In other words, the Lapworth Chart provided sufficient storage on the basis of this probability diagram for a drought of such severity as would on an average occur once in 100 years.

117. On the line near 20 in. was a point marked "1934". This point was well above the curve. If that curve was projected upwards—it was doubtful if it was legitimate to do so—it gave the sort of drought which, according to the diagram, would occur only once every 500 years. This reinforced Mr Hetherington's comment that the conditions at Alwen during the 1933–34 drought had been very severe.

118. In § 87 was the statement: "The problem of reservoir yield is not yet answerable in terms of a definite figure but appears as a test of probability . . ." In fact, it never would be answerable in terms of a definite figure; it was simply one of probability, which the engineer has to answer on the basis of what is reasonable.

Mr P. O. Wolf (Reader in Hydrology, Department of Civil Engineering, Imperial College of Science and Technology, London) observed that hydrological theory could in practice be developed only on the basis of certain assumptions, and a theory so derived had to be tested against observations. By providing a large body of rainfall, run-off, and meteorological data, the Author had greatly assisted in the development of methods of assessment of the quantity and quality of water to be derived from various sources.

120. Would the Author comment further on a number of points in the Paper? For example, Dr Glasspoole had given the picture which preceded the information in Fig. 5 and had explained the most recent part of the diagram. Referring to the manner in which statistical theory could be applied to water-resources data of this kind, Mr Wolf pointed out that Hurst[21, 22] had shown that special statistical techniques were required in order to make full use of groups of data which, if their sequence was not taken into consideration, would appear to be statistically random but which, in fact, occurred in Nature in a peculiar order which had been known to man since Biblical times. Fig. 5 was yet another illustration that in statistical work in this field one must be exceedingly careful in the choice of techniques. In this connexion, Mr Wolf referred to Papers by R. W. S. Thompson[23] and D. Halton Thompson on statistical techniques to be used in the determination of yield from a catchment area, which provided extremely useful tools for use in cases such as this.

121. In § 39 the Author had stated that he had calculated the comparative minimum dry-weather flows of both streams from available records (Table 4). Exactly how had he done this and what exact conclusions had he drawn? Here also, Mr Wolf had in mind the frequency aspect and statistical theory, with which the Author had shown himself to be in sympathy.

122. In § 42 the Author had raised a matter which was of interest to the Institution at a time when they were obtaining the co-operation of water engineers throughout the country in the revision of the flood data published in 1933. The Author had written of "The highest flood discharge rate recorded". In a 24-hour period at Alwen he had recorded 91·1 cusecs per 1,000 acres in December 1936. Would he specify exactly the

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point to which he was referring? Was that the mean discharge for the day or the instantaneous peak? Had he taken into account that there was a reservoir in that area and could he estimate the peak discharge which would have occurred without any reservoirs?

123. Mr Wolf then suggested that § 70 and Table 13 might be a little misleading. In the fourth column of the Table there were a number of equations relating annual rainfall to run-off. Each might be valid in its own 11-year period, but what did each equation mean? What was its usefulness now, in the future, or in the analysis of past records? Was there any physical justification for putting forward expressions of this kind? It was known that the Author had himself initiated the study of wind speeds, wind directions, humidity, and various other meteorological factors, all contributing to a better knowledge of the rainfall/run-off relation; but to introduce this kind of expression was not a step for the advancement of science and he invited the Author to make a clear statement on this point in order to avoid any possible misunderstanding.

124. § 62 mentioned monthly temperature records taken at 10-ft intervals of depth, and Mr Wolf asked the Author to provide a diagram with two typical temperature profiles—for summer and winter.

125. The picture given in § 65, of water loss by overflow, was ratherdisturbing. The Author had himself, in §§ 71–78, given further thought to the problem of the adequacy of the storage volume required for best utilization, and with the 550 monthly run-off figures now available (extended Table 6) would be able to arrive at a closer estimate of the chances of failure with various rates of draw-off. The same data would also enable him to devise a policy of variable draw-off.

Professor Ray K. Linsley (Department of Civil Engineering, Stanford University, California) supported the Author's statement in § 55, in which he questioned the utility of empirical evaporation formulae, such as that cited in the Paper. The work of Peman[24] in Britain and of Harbeck[25] and others in America had shown clearly that they could not expect to get a good estimate of evaporation if they neglected such important factors as radiation, wind, and the vapour pressure differences involved.

127. It appeared from Fig. 9(a) that the reservoir temperatures were consistently higher than the screen temperatures. This might be attributable to the fact that two different periods were involved. One would expect that the mean reservoir temperature for the year would be very close to the air temperature for the year, with a difference from month to month due to heat storage and heat loss in the reservoir. If the water temperature ran consistently higher than the screen temperature, it might save a little water from evaporation by finding some way of extracting that excess heat.

128. Referring to Table 13, Mr Wolf had expressed the view that the relation between rainfall and run-off on a basin could not change from period to period unless there was a physical change. If there was a physical change, such as drainage, afforestation, reservoir construction, or change in measurement techniques, the apparent relation might change, but in the absence of these physical changes it must be assumed that the apparent change arose from the fact that the equations did not include all the necessary variables.

129. This type of variation throughout a long period had been observed in some cases in the United States, and the relation had been corrected in part by introducing a measure of the precipitation in the previous year. This, for example, would account for the changes in ground-water storage which might have occurred in the previous year from exceedingly heavy or exceedingly light rainfall. In this case, the equation would take the form:

$$r = a+bR+cR_{-1}$$

where c was a constant, R denoted the precipitation, and R_{-1} the precipitation in the previous year.

130. He had applied this to the data for Alwen and Brenig and thought he could detect that it would improve the relation somewhat. Undoubtedly, however, there

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were other factors which were present to cause these differences which this equation would not correct.

Mr Frank Law (Chief Engineer, Fylde Water Board) confined his remarks to the subject of evaporation losses. It would be seen in Tables 9 and 10 that the average losses were 17·3 in. on Alwen and 18·1 in. on Brenig. These were not unusual, nor were the fluctuations of the losses about the mean—namely, 11·0 in. to 23·1 in. at Alwen and 12·1 in. to 22·4 in. at Brenig. On the other hand, theoretical calculations using formulae such as those of Thornthwaite or Penman did not usually give such large variations from the mean. He had been interested to see if, by plotting one catchment against the other, there could be discerned a genuine correlation and, therefore, if the losses were genuinely attributable to weather conditions or, alternatively, if the differences were due to errors. The idea was that if the correlations were good the departures from theory must arise from some physical conditions not taken into consideration by the Penman and Thornthwaite formulae, while if the correlations were poor the cause must be errors in measurement of the rainfall and/or run-off.

132. Fig. 13 showed the result of plotting Brenig annual losses against Alwen annual losses. The scatter was wide and the correlation coefficient only 0·33, which was very bad. It looked as if the losses were due mainly to error, but while plotting it had been noticed that the points were grouped in three time periods and that for the largest of these periods, 1934–52, the correlation coefficient was 0·92 and the standard error of the estimate 1·05 in.

133. Fig. 14 showed the effect of taking only 1934–52. Much of the scatter was

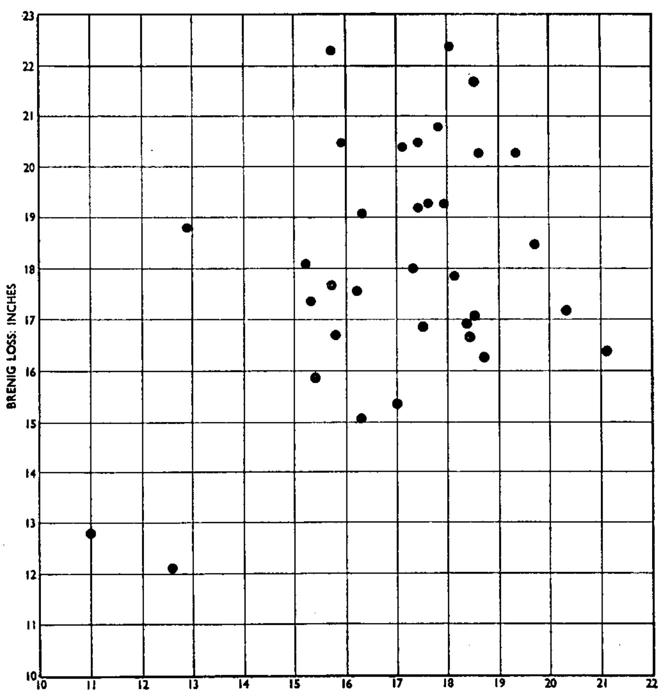

FIG. 13.—BRENIG *v.* ALWEN LOSSES FOR 1923–1956

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eliminated and the standard error of the estimate, 1·05 in., gave a band of 2·1 in. for the 95% confidence limits. All the points lay within these two confidence limits.

134. Fig. 15 showed the plots for the other periods superimposed on Fig. 14. Three of the last 4 years lay above the 95% limits and all eleven of the 1923–33 period lay below. These, therefore, seemed to be a different set of figures, while those for 1953–56 which lay above the previous 95% confidence limits again seemed to be a different family. It therefore appeared that there had been some change in the catchments or in the measurement.

135. The next question was, what was causing the difference? Fig. 16 showed rainfall on Brenig plotted against rainfall on Alwen. The correlation was good. At first the 1952 point appeared strange but this was attributable to a printing error in Table 2, where the Alwen figure had been given as 43·1 in. instead of 49·1 in.

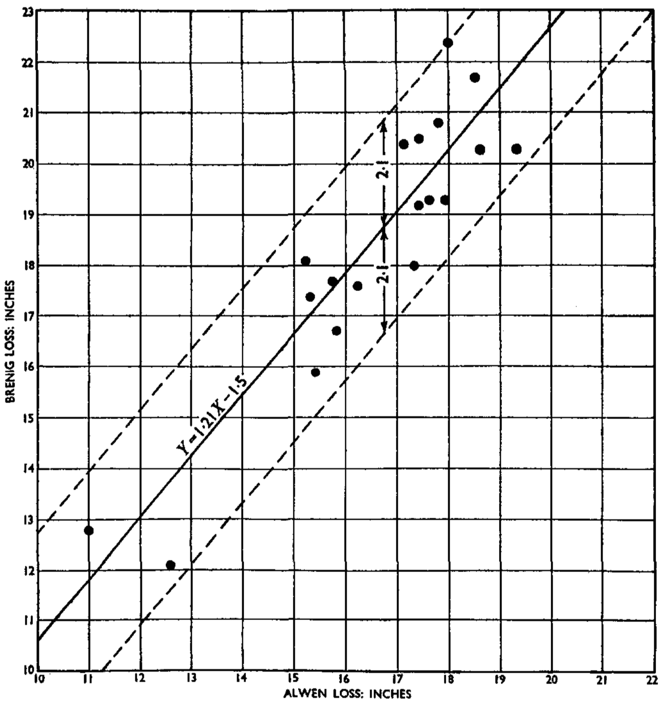

FIG. 14.—BRENIG *v.* ALWEN LOSSES FOR 1934–1952

136. Fig. 17 showed run-off on Brenig plotted against run-off on Alwen. The scatter was wider and the points fell into three groups with best-fitting lines approximately 3 in. apart. The correlation coefficients were all quite good, about 0·96 to 0·99, and the standard error of estimate was about 1·5 in. It looked as though the run-off figures fell into three families.

137. To find out what was causing the difference—whether it was Alwen or Brenig run-off measurements which were at fault—the losses on each catchment had been compared with those on the Elan catchment. Table 14 showed the results. It appeared that the run-off from Alwen had changed substantially about 1933. The Table also showed the

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TABLE 14.—CORRELATION COEFFICIENTS

	Period		
	1934–49	1923–49	1913–20 and 1934–49
Losses:			
Alwen on Elan . .	0·75	0·32	0·70
Brenig on Elan . .	0·67	0·64	

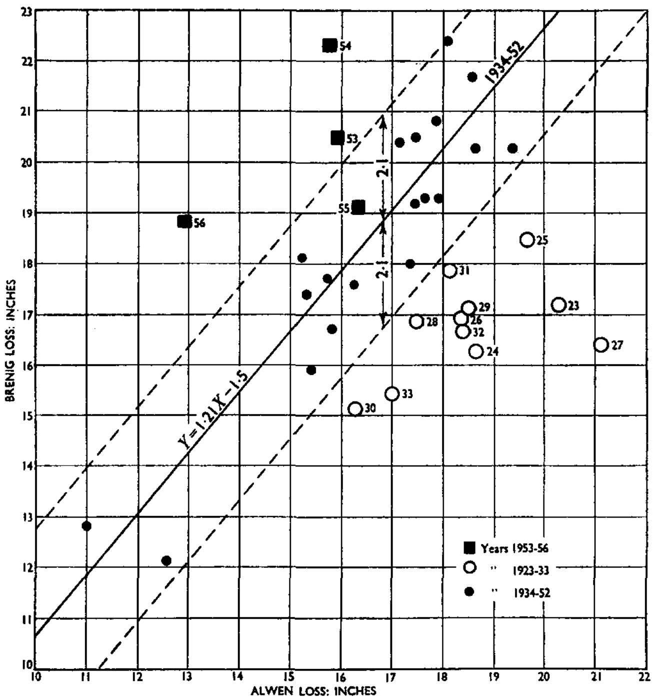

FIG. 15.—BRENIG *v.* ALWEN LOSSES FOR 1923–1956

the effect of adding the period 1913–20 to 1934–49. The correlation coefficient for Alwen on Elan dropped from 0·75 to 0·70. It looked as though the earlier figures, before the reservoir was filled, were of the same family as those after 1934.

138. Fig. 18 showed the result of plotting Alwen losses against Elan losses, with the best-fitting line for 1934–49 superimposed. Practically all of them lay outside the 95% confidence limits. It seemed as though the period 1921–33 was different in run-off from the rest of the period. In his opening remarks the Author had mentioned that certain catchwaters had been constructed in 1933. Was it possible that these might have caused the difference?

139. If these apparent errors occurred with unchanged catchments, what reliance

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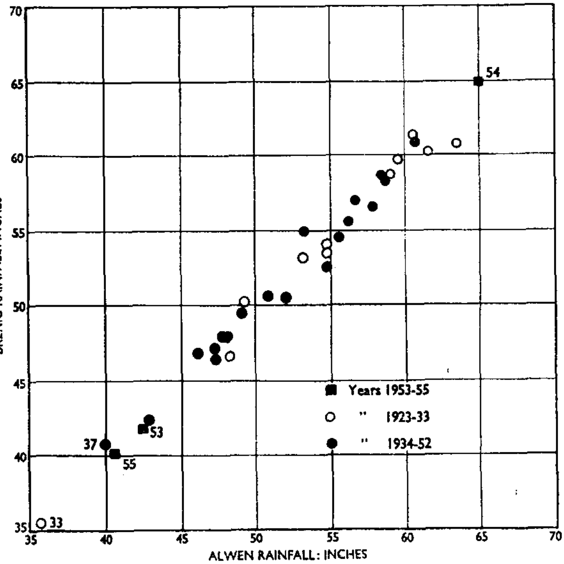

FIG. 16.—BRENIG *v.* ALWEN RAINFALL FOR 1923–1955

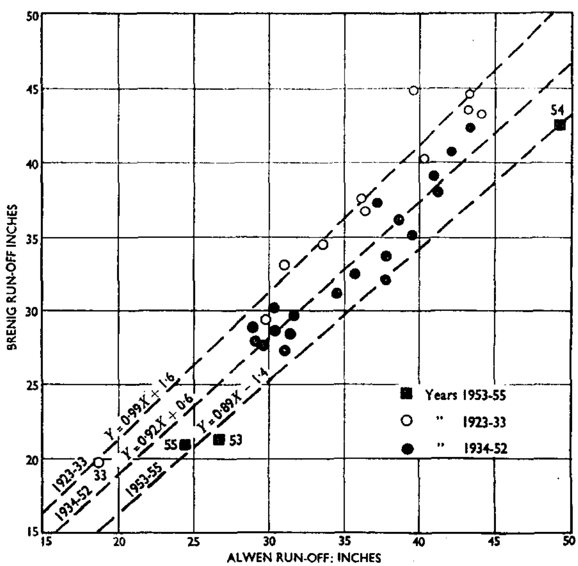

FIG. 17.—BRENIG *v.* ALWEN RUN-OFF FOR 1923–1955

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could be placed on the use of one catchment as a control when another catchment was receiving different treatment? It seemed necessary to check the control against a third catchment to make certain.

140. It would be seen from Table 14 that for the period 1934–49 the correlation coefficient of Alwen on Elan was better than that of Brenig on Elan, 0·75 against 0·67. It therefore seemed that during that period the Brenig run-off measurement was more erratic than the Alwen measurement. Could this difference be due to the weir on Brenig being subject to filling up with stones and silt behind the weir, whereas the similar weir on Alwen had a dam above which protected it from collecting so much stones and silt?

141. For the period 1934–52 the Brenig losses were approximately 2 in. more than the Alwen losses, 18·45 in. against 16·53 in. What caused these differences? Could they be explained by climatic differences or were they due to the collection of gravel

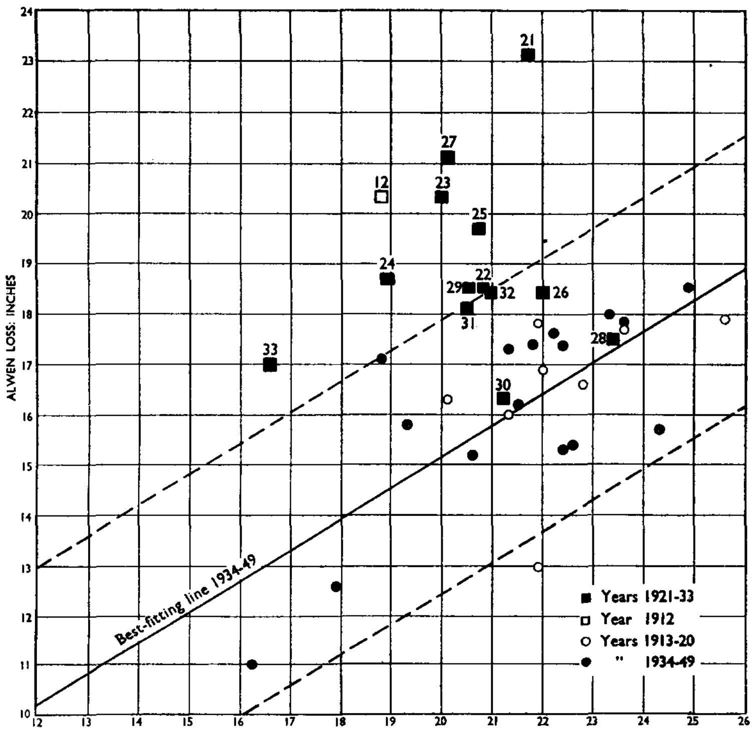

FIG. 18.—ALWEN *v.* ELAN LOSSES

behind the Brenig weir, causing the Brenig run-off to be underassessed? The collection of gravel behind a sharp-edged weir could cause the run-off to be underestimated.

142. Unfortunately, up to the present no run-off-measuring device had been produced which continued to function accurately in a debris-loaded stream. The Fylde Water Board had made one which kept free from gravel but they had not yet solved the problem of where was the best point for the level tapping. Two independent tappings

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and level recordings seemed to be desirable so that if at any time the two did not agree the error could be investigated.

143. Reverting to Fig. 15, during the past 4 years it seemed that the difference between the losses had grown. He understood from the Author that by 1956 the figures were: Alwen, 12·9 in.; Brenig, 18·8 in. The Author had suggested that this might be due to the Forestry Commission ploughing up land, but the 1956 difference was 5·9 in., compared with the 1934–52 mean difference of 1·9 in. In other words, during the past 4 years the losses difference had increased by 4 in. It seemed difficult to imagine that such a large change could be caused by ploughing up 28% of the land. The normal method of the Forestry Commission when planting was to cut a trench 15 in. wide at about every 5 ft, simply turning over the sods with the result that 50% was bare earth and 50% was turf. It was difficult to believe that doing that on 28% of the land could reduce the losses by 4 in. In proportion, if the whole of the land was to be ploughed up there would be no losses, which was absurd!

144. The value of the Paper was in the two sets of figures being side by side, and it was a pity if the Birkenhead Corporation and the Forestry Commission were to alter the two catchments almost simultaneously. He appealed to them to leave the Brenig catchment alone for another 10 years or so in order that they could see what happened to the Alwen catchment as compared with the Brenig.

Mr William Allard (Consulting Engineer) said that Professor Linsley had mentioned several factors as each capable of causing a change in results over a run of years and Mr Law had touched on the same point. These factors included run-off gauging technique. Mr Law had asked about the possibility of gravel collecting upstream of the Brenig weir. Mr Allard on the other hand wondered whether drowning could occur at times in the case of the Alwen weir, which, while it was only a short distance below the dam and hence unlikely to collect gravel, had, judging from a photograph shown by the Author, little drop in the stream bed downstream to help the channel carry away the larger discharges from the dam, without drowning of the weir occurring. The Brenig weir had been shown to be just above rapidly falling ground, so that there was a good get-away for the water there.

146. Had the Author any data about the major discharges and the corresponding heights of water above and below the Alwen weir? If drowning had at times occurred there, the Alwen run-off would tend to be exaggerated, whereas, as Mr Law had suggested, for Brenig it might, if collection of gravel occurred, be underestimated.

147. In § 47 the Author had referred to a Draft Report but this document was in fact adopted by the Institution of Water Engineers, whereas the Interim Report mentioned in § 75 had been discussed but never adopted by that same Institution.

The following contributions were received in writing:

Mr David Lloyd (Liverpool Corporation Water Works) remarked that it was appropriate to consider selectively what had been finally produced in the Paper, which had dealt with 44 years of daily observations and was a summary of a considerable quantity of data, carefully collected, compiled, and studied.

149. He thought that, on the one hand, a value of the safe yield from Alwen concomitant with the storage obtainable in a drought period had been proved. On the other hand, however, data of dry weather flow and peak floods were shown which indicated that floods had not been recorded as high as those at comparable areas; for 600 cusecs per 1,000 acres would be expected as compared with the stated 91 and 147 cusecs per 1,000 acres at Alwen and Brenig respectively.

150. The gauging had been by means of weirs having inadequate capacities, the so-called highest flood merely being their maximum capacity, and Mr Lloyd suggested that those weirs might have been overtopped and the peak floods unrecorded. The weirs should be enlarged.

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151. At Vyrnwy (23,290 acres) the run-off peak had topped 200 cusecs per 1,000 acres eight times in the past 20 years. In February 1945, the overflow alone spilled 3,939 cusecs or 169 cusecs per 1,000 acres at the peak.

152. Regarding such gauging, owing to the extreme range of river flow, a very difficult problem of recording by a single gauge was present. Mr Frank Law (Fylde Water Board) was experimenting with a trapezoidal standing-wave flume, but Mr Lloyd adopted two gauges—a small sharp-edged-notch weir at the entrance to a rectangular standing-wave flume—in similar circumstances.

153. The formula mentioned (Lloyd, 1938) for estimating evaporation-loss had been produced at a time when hydrologists were breaking away from acceptance of a usual value of 14 in. Since evaporation-loss was the effect of many weather factors, a formula could not be precise but certainly could indicate that values of loss ranging from 10 in/year in Scotland to 22 in/year in Southern England were quite rational; while, by extrapolation, values of 30 and 40 in/year could be expected in hotter areas.

154. There existed an excellent opportunity at Alwen of attempting an assessment of the effect of afforestation and it should be taken.

155. He thought Table 8 would have been enhanced by expressing the values in percentages of the average so as to make it comparable with other records.

156. Tables 9 and 10 of evaporation-loss showed a number of negative values indicating that the run-off was greater than rainfall in some months. He regarded these values as misleading and suggested that the general rainfall and the run-off had not been coincident. For example, at Brenig in 1937, in February there had been a loss of 2·35 in. and in March a gain of 2·60 in. Some explanation of these apparently absurd values was required, which would probably be the heavy snowfall which had swept North Wales at the end of February and had lain on the ground—recorded as precipitation but unavailable as run-off. Hydrologists should avoid leaving this target for incorrect criticism.

157. Mr Lloyd endorsed the Author's current assessment of safe yield, for an independent examination of his data indicated a value of 10 m.g.d. from Alwen in a drought. Additionally it should be mentioned that it would be difficult to empty the reservoir to the last drop, and too nerve-wracking in practice.

Mr A. R. B. Edgecombe (Head of Hydraulics Division, Central Laboratory, Geo. Wimpey and Co. Ltd) had recently been engaged on hydrographic surveys of the Rivers Taf, Cywyn, Tywi, Loughor in Carmarthenshire, and Tawe in the Swansea County Borough, Wales, in connexion with an oil-pipeline project. His main interest was in the section dealing with flood discharge, and the discussion offered a suitable opportunity to place on record his findings on the above rivers for comparison with those of the Afon Alwen and Afon Brenig.

159. There was great weight of evidence in support of Dickens's formula that the maximum flood discharge in topographically similar areas varied directly as the catchment area raised to the three-quarters power. The recording of floods on this basis formed a very valuable reference. The results were recorded in Table 15. In the cases of serial Nos 1 to 5 inclusive the maximum flood had been computed by observing a discharge, calculating Kutter's N, and applying flood levels and slopes as determined by local enquiry.

Mr H. W. Underhill (Department of Civil Engineering, Imperial College of Science and Technology) pointed out that when introducing the Paper the Author had said that drainage works would considerably increase the yield of the catchment. If he meant by increasing the catchment area the result was evident; but if he meant that drainage works would increase the run-off from the same catchment area it could only be, assuming negligible deep percolation loss from the basin, through a reduction in evaporation loss. (Total volume of run-off was here considered, not the rate of run-off immediately following rainfall.) It had been suggested in the discussion that drainage works could decrease the annual evaporation loss by 6 in. What figure did the Author have in

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TABLE 15

Serial No.	Name of river	Location	Catchment area: sq. miles	Maximum estimated flood: cusecs	Dickens's C
1	Taf	Carmarthenshire, Wales at St Clears	118·38	7,500	209
2	Cywyn	Carmarthenshire, Wales u/s Pont-ddu	20·75	1,249	128
3	Tywi	Carmarthenshire, Wales at Carmarthen	502·77	21,100	199
4	Loughor	Carmarthenshire, Wales near Caer-Coryn	57·90	4,320	206
5	Tawe	Swansea, Wales d/s Ynys-tanglas Bridge	87·90	7,980	278
6	Alwen	Denbighshire, N. Wales	9·86	575	103
7	Brenig	,, ,,	7·81	732	157

mind? The mechanism by which such a large decrease in evaporation loss (one-third of the whole) could occur was not clear. Penman and others had shown that plant transpiration was not significantly reduced until a moisture deficit of some inches (he suggested four for grass and more for deeper-rooted plants), had been built up in the soil. From Tables 2 and 3 in the Paper the average rainfall for May, June, July, and August (the 4 months of highest evaporation) was about 14·6 in. Assuming an annual evaporation loss of 17 or 18 in., the evaporation loss over these 4 months would be about 14 in. (see "The calculation of irrigation need", H.M.S.O., 1954). It was difficult to see how a soil-moisture deficit of 4 or more inches could be built up often enough and for long enough periods to cause so large a decrease in evaporation.

161. The effect of drainage works in such high rainfall moorland country was to increase the immediate run-off after rain. But if transpiration losses from the vegetation remained much the same, this increase in immediate surface run-off could only be at the expense of delayed surface- and ground-water run-off. The natural storage capacity of the catchment was being reduced to increase immediate run-off. On some occasions, for instance, when the reservoir was full at the start of a dry season, the natural storage capacity of the catchment would be of more value than the increase in immediate run-off.

162. The possibility of altering the complex rainfall-run-off relations to man's advantage was of great importance, and any comments from the Author's experience would be welcomed.

Mr R. W. Thompson (Engineer, Derwent Valley Water Board, Bamford) observed that the value of the Paper was increased by the relative scarcity of published records, of the type included in it, extending over 30 years or more, and by the increasing need for hydrological data of every kind. The importance of the length of the record, and its continuity and accuracy, could not be overstressed.

164. There was a special reason for hoping that these records of run-off—which at Alwen involved more than weir measurements—would be maintained at the highest possible accuracy for at least another 20 years. This was that arrangements had already been made with the Forestry Commission for the afforestation of the greater part of the two catchments. With the existing records for the two areas in their almost treeless condition, there were good prospects of obtaining a conclusive answer to the important and controversial question of the effect of large-scale afforestation on the yield of waterworks catchments. The greater the percentage of the area planted with trees, the more conclusive would be the answer.

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165. In view of that, it was extremely interesting to note the striking change since 1934 in the run-off from the Brenig catchment, as compared with that from the Alwen catchment.

166. The addition of figures in Tables 6 and 7 of the Paper gave comparisons set out in Table 16.

TABLE 16

Period: years	Aggregate run-off: inches		Difference: % Brenig/Alwen
	Alwen catchment	Brenig catchment	
1912–22	393·02	—	—
1923–33	393·80	408·59	+3·75
1934–44	381·72	362·01	−5·1
1945–55	387·83	350·51	−9·6

167. It was satisfactory to have the Author's assurance that the change in run-off disclosed by these figures could not be explained by faults or errors in the measurements, by abstraction from the Llyn Brân, or by afforestation of the Brenig catchment. Nor was it accounted for by supposition of leakage through the glacial material in the old river channel shown in Fig. 2, because even if there was such a leakage, it was unlikely that it had increased to the required extent. The Author's suggestion that change in run-off was caused by change in land use, with deterioration of drainage, might well be correct. However, more might become known about the decline of run-off from the Brenig catchment as the tree planting, now in progress, continued. Such planting would involve extensive ploughing and other drainage operations which should have had time to show their effect before the trees were large enough to affect evaporation losses. Mr Thompson thought that the value of that large-scale experiment would be enhanced if it became possible for the Forestry Commission to plant areas to the west and north of the Alwen catchment, these additional areas being largely "common land", at present in a highly unproductive condition.

168. A future analysis of the record from the catchments might therefore not only show whether or not the mean evaporation from the areas was altered, but also whether the run-off was made less "flashy", particularly in the case of the Alwen catchment.

169. Mr Thompson strongly endorsed the Author's conclusion in § 89 regarding the relative importance of run-off, as compared with rainfall, in the estimation of yield, but also agreed, nevertheless, that rainfall measurements should not be abandoned but rather that all possible steps should be taken to increase their accuracy. In the latter connexion, vigilance would be necessary to prevent excessive shelter of rain gauges as the trees grew.

Mr F. H. W. Green (Principal Scientific Officer, The Nature Conservancy, London) had not yet had time to work on the Tables given in the Paper as much as he would have liked, but appreciated the value of the figures of rainfall, run-off, and water loss in two catchments over a long period. To one concerned with evaporation, such factual data was most acceptable material to work on. He had only the criticism that Table 12 would have been far more useful had it contained the values of mean daily maxima and minima for each month instead of monthly maxima and minima. This meant that in estimating potential evaporation by formula, there had to be used the temperature of the nearest similarly situated station, Lake Vyrnwy, given in the Monthly Weather Report.

171. Using Crowe's formula[26] (which for first approximations was the most convenient to use, and gave results not very different from Penman's or Thornthwaite's, and was not obviously less reliable), Mr Green had calculated the monthly and annual

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potential evaporation values for the Brenig catchment, for 1952, 1953, 1954 and 1955, the results for the two last years being shown in Fig. 19. He had also plotted on this Figure the Author's corresponding figures for rainfall minus run-off, as well as the rainfall.

172. Some "smoothing" of the rainfall minus run-off figures seemed legitimate, where the month-to-month irregularities were explainable by short-period time-lags, such as freezing and thawing (the reason for the May/June oscillation in 1955 was not obvious, though it was probably caused by working in whole months instead of in shorter periods). When this was done, it could be seen that in a year such as 1953, when there was apparently no deficit of rainfall in any month, the curves were very similar. In 1955, there had been general similarity until the rainfall amounts decreased during the dry hot summer, to well below the potential evaporation levels; in fact, the

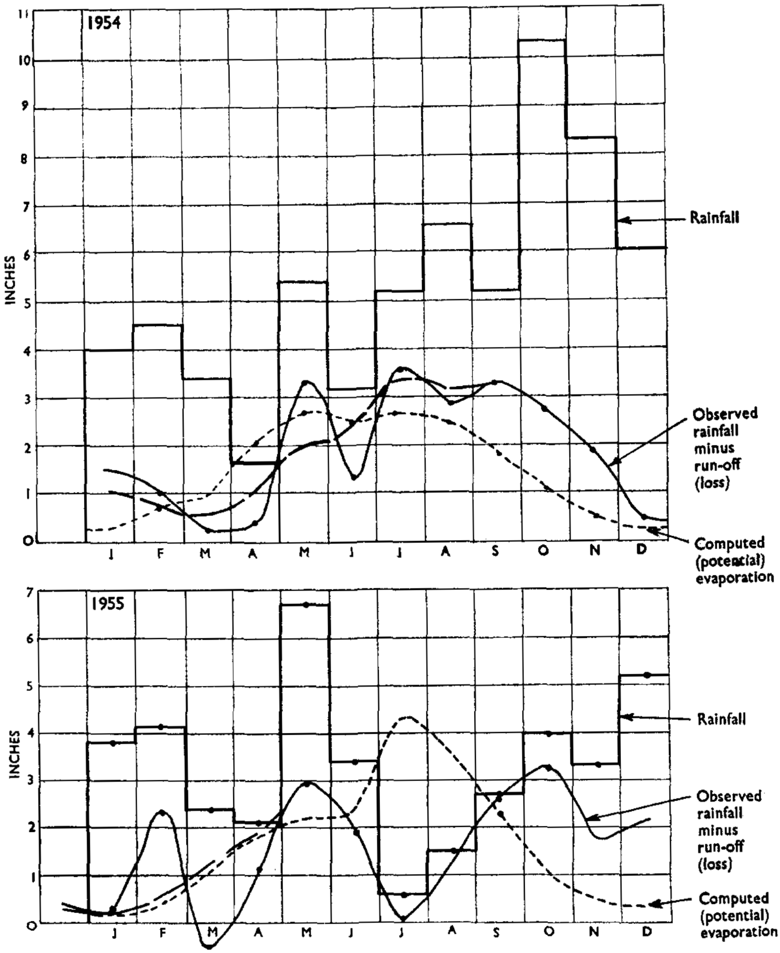

FIG. 19.—BRENIG CATCHMENT POTENTIAL EVAPORATION

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actual evaporation must have fallen far short of the potential, although water stored in the superficial deposits, above the solid rock, was being depleted. After September when the rainfall had again commenced to exceed the potential evaporation, the curve had not, by the end of the year, regained its normal shape, presumably because soil-water was still being restored, i.e., the loss due to absorption had been exceeding the loss due to evaporation. 1952 showed a somewhat similar state of affairs, though in much less degree. This might also in fact be the reason for the displacement in time of the rainfall-minus-run-off curve, as compared with that for potential evaporation, in 1954.

173. Of the three quantities (i) rainfall, (ii) loss by evaporation and absorption, and (iii) run-off, it was possible to obtain values of any one from known values of the other two. If (i) and (iii) had been studied long enough in comparison with (ii), it should be possible to use (ii) to replace measurements of either (i) or (iii). Before this could be done, means must be found of separating out the evaporation losses from those due to absorption, and to determine how much of the absorption represented percolation into the underlying rocks (and thus lost from the catchment area), and how much represented fluctuating amounts of storage in the soil and subsoil.

174. Mr Green thought that further study of the Author's Tables should go far, if not all the way, to elucidating this. Actual evaporation, for those periods when it differed from potential evaporation, ought then to be calculable with confidence, the potential evaporation being easily obtained by very simple apparatus such as had been set up at various places by The Nature Conservancy[27] (similar to that described in various places elsewhere, as for example by Lewis and Garnier[28]).

Mr W. H. R. Nimmo (Civil and Hydraulic Engineer, Brisbane, Australia) observed that in many parts of Australia and other countries were evaporation might exceed precipitation during most of the time, and measurements of stream flow had not been made, estimates of run-off might have to be based upon meteorological data alone. Consequently any relation which might exist between meteorological elements and losses from catchment areas became of great importance.

176. Although evaporation was a complex phenomenon dependent upon many variables, investigation showed that, over such large areas as catchments, there was a fairly close straight-line relation between losses and temperature. Moreover, potential transpiration loss—that was, the loss which would occur if there was always sufficient soil moisture to satisfy it—would, when averaged over long periods, be approximately the same as the evaporation loss from a natural water surface.

177. Mean monthly losses for 33 years (Tables 9 and 10) were plotted against mean monthly temperatures (Table 12) in Fig. 20, in which there were also plotted a line corresponding to a formula developed by Khosla[29] from data for rivers in India and other countries, and a trend line derived from an investigation by the U.S. Geological Survey of streams in the eastern portion of the United States.[30] Scattering of the points might be less if the period covered by Tables 9 and 10 had been the same as that for Table 12, and the mean of the mean daily temperatures had been taken as the mean monthly temperature. Nevertheless there was a definite trend which appeared to lie between the two lines drawn in Fig. 20. If, as had been suggested by the Author, there was leakage from the catchments, the apparent evapo-transpiration losses plotted were somewhat too large.

178. Since there was sufficient rainfall to satisfy the evapo-transpiration demand in almost all months, the water surface of the Alwen reservoir should not affect the relative losses of the catchment.

179. Mr Nimmo had studied 3-year moving averages of the annual run-off of a number of streams in Australia and agreed with the Author that run-off appeared to vary in an oscillatory manner. The average period was about 11 years, but investigation had not disclosed any regular variation that could be used for forecasting. The 3-year moving averages for the Alwen, Fig. 21, did perhaps indicate such an oscillation over the past 30 years but the results were hardly convincing.

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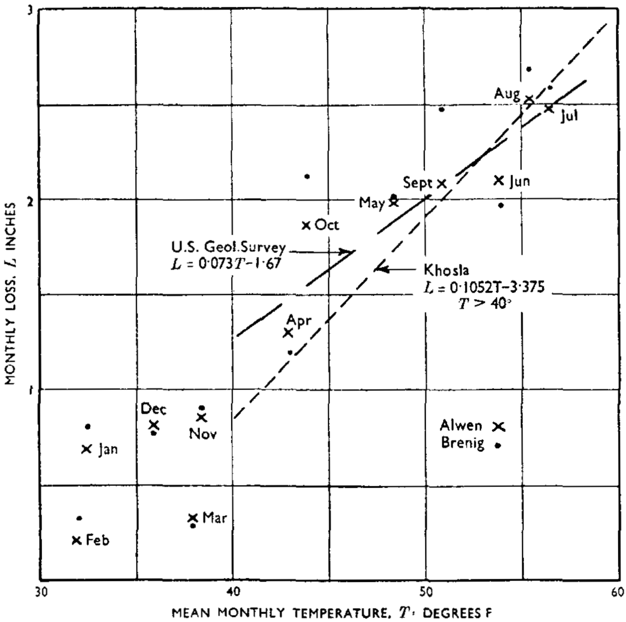

FIG. 20.—MONTHLY LOSS FOR ANY MEAN MONTHLY TEMPERATURE

Mr N. A. R. Rowntree (Partner, Messrs Rofe & Rafferty, Consulting Engineers), referring to the Author's doubts on whether or not enough of the losses factors had been allowed for in making estimates, said that in a climate where rainfall was substantial and reasonably frequent, rainfall might not be the only important factor in assessing the average loss from a catchment; equations in which rainfall was a dominant factor were unlikely to achieve more than rough estimates. Evaporation conditions were very different in the summer and winter months and it was to be hoped that by taking records of rainfall and losses over 6-month periods, April to September, and October to March, some more definite relation might be found.

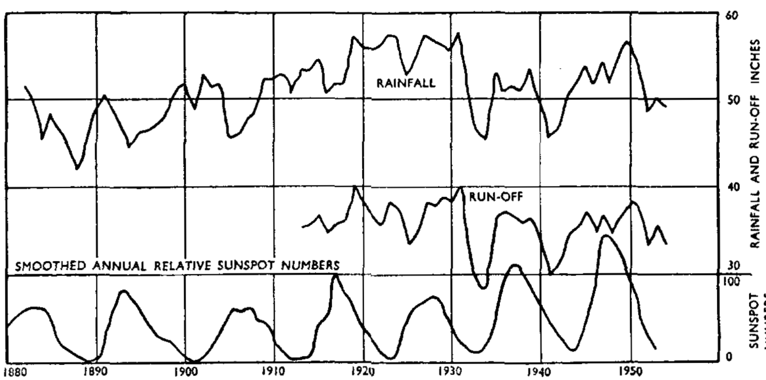

FIG. 21.—ALWEN CATCHMENT. 3-YEAR MOVING AVERAGES OF RAINFALL AND RUN-OFF COMPARED WITH THE CURVE OF SUNSPOTS

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181. An analysis of this type applied to other catchments in the drier eastern and southern counties indicated some relation between rainfall and losses during the summer months, but showed no relation at all in the winter months.

182. The application of this method to the Alwen data, however, showed not only that there was no relation in the winter months, but that there was only a negligible degree of correlation in summer.

183. This method of splitting the data into 6-month periods might give much more promising results if other meteorological factors could be introduced, and it would be interesting to discover in due course if an equation of the Lloyd type applied to 6-month records instead of annual values would be more consistent.

184. In the hope of obtaining some interesting relation, the values for rainfall and run-off in Tables 2, 3, 6, and 7 had been converted to moving averages. Nothing of great value had been shown until the annual moving averages for the losses on both catchments were calculated monthly and plotted on a time scale.

185. These values for 1932–35 were given in Table 17.

TABLE 17.—ANNUAL MOVING AVERAGES FOR LOSSES ON ALWEN AND BRENIG

Year	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
Alwen:												
1932 . .	17·4	16·6	19·1	18·3	17·2	17·2	19·9	18·4	17·6	18·6	18·7	18·4
1933 . .	19·3	20·5	17·6	17·3	17·9	19·9	17·2	17·5	17·2	18·2	16·9	17·0
1934 . .	16·5	15·4	17·2	17·6	17·4	15·9	15·7	18·5	19·7	18·4	16·6	17·8
1935 . .	16·7	17·7	16·2	16·3	16·0	17·9	16·2	13·9	17·0	16·0	18·2	16·2
Brenig:												
1932 . .	17·0	16·0	19·0	17·7	17·3	17·0	20·4	17·6	17·9	17·7	18·1	16·7
1933 . .	17·0	17·8	14·7	14·7	14·5	17·3	13·9	14·6	13·6	15·7	15·2	15·4
1934 . .	16·8	16·3	18·6	19·5	19·5	16·7	16·2	19·4	21·3	20·0	18·5	19·4
1935 . .	17·5	18·8	16·5	16·1	15·6	17·7	17·0	14·1	18·9	18·2	19·6	17·6

186. A plotting of the results showed that during 1932 until November of that year, the losses had been similar on both areas in that they increased and decreased together. In November 1932, there had been a sudden change and the losses on Brenig decreased while the losses on Alwen increased until, in the summer of 1933, the Brenig losses were running at an annual value of about 3 in. less than Alwen. However, in November 1933, the reverse effect had occurred, and thereafter the Brenig losses were slightly greater than Alwen.

187. It was notable from Tables 9 and 10 that from 1923 to 1933 the Brenig annual losses had been less than those on the Alwen catchment. From 1934 to 1955, with a slight exception in 1941, the Brenig annual losses had been greater than at Alwen.

188. The change of behaviour had been extremely sudden. Had there been a change in recording conditions in November 1932 and November 1933? A fuller analysis by plotting annual moving averages at monthly intervals for the whole period of the records including rainfall and run-off as well as losses might help to elucidate the anomaly.

The Author, in reply, thanked Mr Hetherington for his comparison of data from Elan (Birmingham) and Vyrnwy (Liverpool); he was particularly struck by the way in which the 16–18 months critical period was confirmed. He had always felt that the North Wales area must be considered as somewhat different from other parts of the country but it would appear that the area might be considered as extending farther south, at any rate, so far as the critical period is concerned.

190. The topography of the Alwen and Brenig valleys was another important factor. These valleys were saucerlike depressions in the Denbighshire plateau, the range of

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valleys being from top water level of 1,100 ft to about 1,700 ft; this fact and the associated wind and temperature conditions were therefore vital.

191. Referring to § 107, examination of the monthly rainfall occurrences during the critical 18 months period provided a possible clue to the relatively low yield obtained at Alwen and Brenig, bearing in mind that light rainfalls and hill mists were of little value for run-off purposes. This was illustrated in § 27 and by the fact that only 287 days showed 0·01 in. of rain or more, compared with the 44-year average of 324 days for a period of 18 months; and similarily only 228 days showed 0·04 in. of rain or more, compared with the normal 267 days for the same period.

192. The relatively higher maximum and minimum monthly temperatures recorded during the period provided another clue to the problem and the general wind direction during the 18 months showed almost double the normal proportion originating from the dry north-west-to-north-east quadrant.

193. The reference to the Paper given by Binnie and Lapworth[16] had been of great interest; the Author was pleased that attention had been drawn to it since the basic problem of rainfall and run-off depended on the study of cumulative diagrams. The suggestion in § 108 that Turner might have done some gauging of the Brenig as far back as 1891, from which he apparently produced his cumulative run-off curve, certainly tied up with the fact that the Hospital Commissioners had developed Llyn Brân about 1892 and rain gauges had been established in the area at that time. Unfortunately the Author could find no actual records of run-off gauging at Llyn Brân but Mr Hetherington had offered a new line of research for which he was grateful.

194. He was pleased that Dr Glasspoole had given the background of Fig. 5 and had reinforced the view that there were many more variables than were commonly considered. His reference to the increase in atmospheric pressure was along lines on which it was hoped some day to give figures for the Alwen area.

195. The reference in § 111 to the increase in rain per rain-day was also interesting. The original Paper had tabulated information on these matters but it seemed that a lot should and could be done on that side of research. In the Alwen and Brenig areas 0·01 in. of rainfall could occur persistently without producing any run-off, but if there was 0·5 in. of rainfall on one day followed by 1 in. the following day, a considerable flood came down.

196. Referring to § 112, the Author considered that lack of similarity between residual rainfall and run-off mass curves for Alwen and Brenig was not so curious when physical differences between orientation of catchments and changing characteristics of land were given their correct place in the problem of run-off. Moreover, the rainfall curves were the result of smoothing-out various records which covered contiguous areas, whereas the run-off curves were based on the actual records taken at two independent but fixed locations.

197. The Author was pleased that Mr Lapworth had agreed with some of his points, in particular with the fact that the differences due to reservoir surface area were negligible. Loss by wave action was, however, a problem which was very prevalent at Alwen. As indicated in § 65, there had been a considerable overflow in the early part of 1933. The drought conditions which had started in April 1933 had been preceded by high winds so that the reservoir had not been full to start with. He had himself recorded a spillage rate due to wind of upwards of 12 m.g.d. when the reservoir level was still 6 in. below overflow.

198. He did not know the answer to spillage but possible some form of siphon overflow might be advantageous. One could imagine that a reservoir might be designed with overflow sited so that the prevailing wind did not affect it, but there were physical limitations.

199. The Author was indebted to Mr Lapworth for deriving a probability diagram for the Alwen catchment and he agreed that, provided the yield could have been limited to 27 in. p.a. the conclusions were correct. Unfortunately the average rate of abstraction during the 11-year period 1945–1955 had been 28·87 in. p.a. and the degree

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of risk was therefore much worse than postulated. He fully agreed with the conclusions in § 118 on the reservoir yield.

200. Mr Wolf's references to the Papers by Hurst,[21, 22] R. W. S. Thompson,[23] and D. Halton Thomson were welcome because all of them had done a great deal on the statistical aspects. Unfortunately nature delighted in upsetting her "peculiar order" from time to time and even 44 years of study was an insignificant period in which to determine just how random the statistics were.

201. Referring to § 121, the comparison of minimum dry-weather flows were the actual recorded minimum figures for the periods concerned and had been based on check calculations of the actual discharges over the respective weirs. The figures for Alwen had been obtained from observations made in June 1915, whereas the figures for Brenig from 1 to 7 days had been based on records for July 1925, but the 28-days Brenig minimum occurred in July 1952. They supported the Author's contention that the dry-weather flow of Brenig was greater than that of Alwen.

202. In the case of Alwen, they had the benefit of gaugings done under the late Mr H. J. F. Gourley's direction for the period 1911–16 prior to any impounding on the reservoir. It was also significant that the figures for the lowest run-offs in Alwen had occurred in 1915. It was most unfortunate that there were no strictly comparable figures available for Brenig.

203. In reply to § 122 the flood-discharge figures were the estimated peak rates of flow occurring within a 24-hour period. Unfortunately the Author had insufficient data to make any reliable estimate of the effect of the reservoir on the run-off in that instance. In the case of the Brenig, however, a peak discharge rate of 146·6 cusecs/1,000 acres had been estimated as occurring during the course of the highest recorded flood of 84 cusecs/1,000 acres for a 24-hour period on 4 September, 1931.

204. As for the relation of rainfall to run-off in § 123, the Author was pleased that Mr Wolf had drawn attention to it, because attempts had often been made to draw a straight-line diagram which purported to relate rainfall and run-off. It was obvious from his investigation that there were differences in the 11-year periods considered and that this oscillated in some indeterminate way. He might not have proved to anyone's satisfaction—even his own—that there were physical reasons for these variations or that they were connected with other natural phenomena, but he had originally started out with the hope that they were linked in some way to the well-known sun-spot cycle.

205. Professor Linsley supported the Author's questioning the utility of empirical formulae. Some writers appeared to be very fond of producing such formulae for all types of natural phenomena and he was pleased that Professor Linsley was not in favour of that method of approach.

206. Replying to the comment in § 127 that the reservoir temperatures were consistently higher than the screen temperatures, the Author said that only 6 years of records were available for comparison. Originally 30 years of records had been available but no one had considered them of value and they had all been disposed of before he took up his appointment.

207. He would certainly see to it that all records were retained in fututre, but he was not sure that they could in any way extract excess heat from the reservoir.

208. It had been said that there could be no change without a physical change. The answer was that there had been physical changes at Alwen and Brenig. Alwen was a catchment populated by a few farmers who had been dispossessed of their land, which had then gone sterile. The drainage had therefore altered—and land drainage was a contributory factor to the whole question of run-off. Moreover, the vegetation had shown clearly changing characteristics, as illustrated by the gradual disappearance of heather.

209. Brenig had not yet been developed by impounding but there had been rumblings about development from 1923 onwards. There was therefore a background of a gradual tendency to curtail agricultural land drainage and this had been disturbed in the case of Brenig only by the intervention of the 1939–45 war, when certain land had been rehabilitated and some arable land brought into use again. Immediately after the war,

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with the need for water, investigations into possible development had again been undertaken and there was only limited grazing within the catchment and no real land cultivation above Brenig weir. At Alwen, on the other hand, active afforestation had taken place. This was illustrated in Fig. 22.

210. He was grateful for Professor Linsley's explanation in § 129 of the groundwater storage equation which took account of the previous year. This confirmed the point made by Gourley.[4]

211. The Author appreciated Mr Law's very careful and detailed statistical investigation of evaporation losses. The question of correlation of statistics would be sound if the basic data on which the investigations were done was used; but this was not the position. The Author was fairly satisfied with the reasonable accuracy of his own basic data but he was not so sure of the results obtained from evaluating them. This had been dealt with to some extent in reply to Dr Glasspoole. Mr Law, however, had not so much thrown bricks as raised pointers, and for this the Author was grateful. Even after he had produced the present Paper there had been times when he could hardly see the wood for the trees!

212. Dealing with evaporation losses, Mr Law had suggested that the formulae of Thornthwaite or Penman seldom gave such large differences. He had asked whether the troubles arose from weather conditions or errors. In fact the investigations had been done as well as possible in the circumstances—a statement which the Author made with all humility. Unfortunately, he had no information about the method by which the original gauging was done, other than the records left by his predecessors. There had been changes of personnel both at the reservoir and among those who looked after the Brenig weir, but he had questioned the present personnel about the period with which they were concerned and believed that there had been no significant changes in measurement methods over the weirs.

213. The catchwaters referred to in § 138 were within the catchment area as already defined and they would certainly increase the rate of run-off from the catchment. That was indeed the very purpose for which they had been formed during the difficult 1933–34 period.

214. The fundamental error in § 139, however, was in believing that any catchment remained unchanged. The Author had probably been at fault in § 8 in not emphasizing the extent of bog and peat covering the catchments. This fact was self-evident in the highly coloured soft acid nature of the water.

215. The Author had mentioned the decline of the land in § 10 and it was significant that not only had heather continued to disappear but the occurrence of bogmoss appeared to have increased. This moss is well known for its very highly absorbent properties and it was in fact now harvested at Alwen as a secondary result of the forestry operations. Information on the characteristics of peat bogs had been given by Rivett[31] in dealing with the practice of moorland gripping which was in effect a form of open drainage similar to that employed at Alwen in connexion with the afforestation.

216. He agreed with Mr Law's comments in § 141 about possible errors due to gravel; that trouble did not occur, however, at Alwen because it was screened by the dam. A small amount of silt gathered from time to time, but that was rapidly and easily dealt with. On the Brenig weir, which was in an isolated place—and particularly during the war period when manpower was scarce, it was conceivable that there had been some neglect, but inquiries showed that at most about 6 cu. yd of debris from 1½ in. downwards in size was removed from above the weir in each year. Unfortunately he had no data to show where that had collected most. Any he had seen in the past 6 years had been in a position where it would not affect the gauging very much.

217. He thought that Mr Law's statistical analyses had shown that there were distinct periods and discrepancies, but he thought he had the physical answers to these and he was not prepared at this stage to concede that his gaugings had been wrong, just as he was prepared to concede that the Meteorological Office had been correct in their average rainfall determination. The answer was to be sought in other changes, and he knew that the results of the afforestation drainage had been astonishing. Mr Law

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FIG. 22.—AERIAL VIEW OF DAM AND AFFORESTATION OF ALWEN CATCHMENT, 1956

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had spoken of the normal method of drainage but at Alwen deep ploughing had been used employing a Cuthbertson double-mould-board plough with a special heavy crawler tractor. This threw a sod on both sides and the ditching had therefore been deeper and wider than suggested in § 143.

218. It was also wrong to consider that the results of land drainage were limited to the extent to which the surface of the land was disturbed. Land drainage certainly provided a more rapid rate of run-off into the reservoir at Alwen thereby reducing evaporation losses which occurred over the 94% of land catchment area. There were of course other vital reasons why such a method could not be carried out *ad infinitum*, but so long as storage was available and subject to losses by spillage not occurring, it was more valuable to have "live" storage than "hidden" storage. He had set up a gauge on one small catchwater; he had not yet sufficient data, but he thought that when it was collated it would show that the deep drainage done prior to afforestation materially increased the available run-off from the catchment area. How long this increase would last was a matter for conjecture.

219. With the likely advent of afforestation no agricultural drainage work had been done within the Brenig catchment in the past 5 years and it was noticeably very much wetter.

220. Dealing with § 143, it was true that for 1956 the figures had been 12·9 in. for Alwen and 18·8 in. for Brenig, but no one year should be taken out of context. Given a correct answer, 12·9 in. might easily have been 14 in. and 18·8 in. might have been 17 in. These were approximations done with the best will in the world and with the instruments at their disposal—but they nevertheless remained only approximations. One had to look at the whole family of losses and use discretion.

221. Referring to § 144, the Author could not stem the tide of afforestation in the Alwen and Brenig catchments nor indeed did he feel that such a policy would be more advantageous to the country as a whole. Surely the sooner some data was available from catchments of this size the better it would be for the protagonists of afforestation or otherwise? The trouble at present was that such data as was available was very limited in scope and liable to misinterpretation. In any event, the Author considered that catchments for water supplies should not be sterile zones, and in this particular area he felt that afforestation as laid down in the White Paper on Rural Wales[32] was the best possible land use consistent with a dual water and agricultural policy.

222. Mr Allard had mentioned an important aspect regarding the weirs themselves. On Brenig, the Author did not think that any difficulty arose. Downstream of the Brenig weir there was a natural waterfall and even if the weir was almost surcharged he thought that no significant backing-up could occur.

223. On the other hand, on Alwen it was not what he would have regarded as the best site for a weir. Nevertheless, it was the best on that stream at the point required and it had been there from the commencement of gauging. It was important that the measurements were taken at one point over the whole period. He had recently set up gauge posts at both weirs with the intention of checking the conditions but so far there had not been a flood of sufficient significance to record.

224. Referring to § 147, the Author was indebted to Mr Allard for drawing attention to the position regarding the Interim Report of the Hydrological Committee.

225. The Author agreed with Mr Lloyd that the recorded floods appeared low. On the other hand, it must be borne in mind that any decision regarding what formed a comparable catchment area was open to dispute. Moreover, the evidence put forward in § 35 might indicate that an error in determination of catchment area of $\pm 5\%$ was a serious underestimate, at least in the case of Alwen. An error of -10% in the Llyn Alwen area was in fact easy to envisage and it might easily be higher. This might in fact also explain the apparently very low dry-weather run-off figures and the extremely flashy nature of the whole catchment.

226. Regarding § 150 he agreed that larger measuring weirs would have been useful. The Author agreed with the suggestion in § 155 but he did not agree with the suggestion

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in § 156 that negative values were misleading. He agreed, however, that snow-fall and ground storage could be the probable explanations.

227. In reply to Mr Edgecombe, he was glad to have the information tabulated in Table 15 although he was not now so sure that areas could in fact be topographically similar.

228. Mr Underhill was correct in assuming that he considered evaporation losses within a catchment could be reduced by drainage. The resultant increase in yield would only normally be available, however, if the reservoir storage was made adequate or the increased degree of risk during a drought period was accepted. The Author suggested, however, that the apparently higher losses now being ascertained for catchments was often in fact the direct result of sterilization of land use—not of improved assessments—and he believed that the older (and apparently empirical) assessment of a loss of 14 in. might in fact have real justification.

229. Referring to § 161 he would suggest that it was during the dry periods when in most cases the level was low that it was most essential to divert all precipitation into the reservoir. As mentioned in § 39, the natural storage of Alwen catchment had already been written down as negligible.

230. Mr Thompson had emphasized in Table 16 the point made on the effect of land deterioration and the Author shared the view that the effects of ploughing and planting would become apparent before the trees were large enough to affect evaporation losses. His suggestion regarding planting the areas to the west and north was unfortunately outside the scope of the present Forestry Commission scheme although the Author agreed it was desirable to complete the full-scale experiment and he hoped this would become possible.

231. In reply to Mr Rowntree, the Author appreciated the significance of his remarks on splitting the summer and winter months and he was greatly indebted to him for Table 17 which, however, showed an apparent set of circumstances for which, he could offer no real explanation. On the other hand, he had already drawn attention to certain peculiarities of rainfall occurrences, temperature, and wind direction during this period in his reply to Mr Hetherington. He also thought that the orientation of the Brenig catchment was of significance.

232. The Author was extremely interested in Mr Green's analyses for the years 1954 and 1955 as illustrated by Fig. 19. In view of this he regretted that Table 12 had not given the mean daily maximum and minimum temperatures for each month but of course there was a limit to the amount of work which one could tabulate. He would not refute the use of Lake Vyrnwy in the circumstances but he would have preferred himself to use Llandudno after adjustment.

233. Mr Nimmo had brought some refreshing new thoughts from the other side of the world and his relationship between losses and temperature in Fig. 20 were striking. The Author was even more indebted to him, however, for supporting his view on the variation of run-off in an oscillatory manner and it was satisfying to learn that the average period for a number of Australian streams also appeared to be about 11 years.

234. The Author had already alluded to the sunspot cycle and Fig. 21 was at least interesting, even if not convincing.

The Author drew attention to two errors in the Paper: on p. 25, Table 2, the rainfall for 1952 should be 49·1 in., not 43·1 in. as printed; on p. 32, § 48, line 5, 462 cusecs should read 465 cusecs.

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