*Discussion on Paper No. 6568**

Some aspects of the hydrology of the Thames basin

by

Francis Murray Andrews, M.B.E., M.A., M.I.C.E.

Mr H. F. Cronin (Past-President) said he spoke as a recipient of the Thames flows in a responsible position for about twenty years and in a less responsible position for twenty years before that. He was most grateful to the Author for presenting the Paper at such an appropriate time, because River Boards and the control of rivers were expected to be the subject of legislation in the near future.

137. Concern was being expressed that many of the rivers in this country were so extensively used for water supply and for other purposes, and he believed that already there had been hydrological surveys of three river catchment areas to assess their ultimate resources. No doubt in the near future there would be a hydrological survey of the River Thames and its basin to ascertain its potentialities for meeting the demands for water supply and other essential uses. Mr Cronin sincerely hoped that this task would be entrusted to the Author, and that, when it was, the Author would present a paper and deal with the questions which Mr Cronin wished to put to him.

138. Mr Cronin said he had a small grumble about the water year; he did not like the period October to September, and he noted that when the Author dealt with rainfall he used the calendar year. Mr Cronin would like to suggest the use of the Waterworks year, viz. April to March, and then there would be uniformity, with the water supply, rainfall and river flows all covered by the same period.

139. Mr Cronin's next grumble was a very much bigger one, and he hoped the Author would bear it in mind for his next paper: the Author had said very little about low flows. Catchment engineers, naturally, were worried mainly about floods, and for good reasons, but from the water supply aspect the low flows exercised the most important influence on the availability of the supply from a river and on the works necessary to maintain that supply.

140. Mr Cronin would like to give a few figures relating to the Thames and so put this matter in perspective so far as that river and the water supply taken from it were concerned. For that purpose he would refer to Fig. 16 where quantities were plotted against time, the river flows being for 1921. The Metropolitan Water Board were required by statute to allow 170 m.g.d. to pass over Teddington Weir. At the present time the abstraction by the Board and by two adjacent water companies, was steadily increasing, the latest figure being about 280 m.g.d. So long, therefore, as the flow did not fall below about 450 m.g.d. there was sufficient to permit the statutory obligation to be fulfilled and for the water undertakings to abstract all the water they required. On the figure the full line represented the standard average flow and this enabled these conditions to be met. But in some years, notably 1921, the flow had been very much lower as represented by the dotted line. If these flows were repeated, as they probably would be, it would be necessary to make up the deficiency by drawing heavily on the storage reservoirs, the deficiency being represented by the area between the 450 m.g.d. line and the dotted curve below that line.

141. Fig. 16 represented the state of affairs for an isolated dry summer. But on two

* *Proc. Instn. civ. Engrs.*, vol. 21, January 1962, pp. 55-90.

recent occasions the position had been more serious, when in 1933-34 and again in 1943-44 there had occurred a cycle consisting of a hot and dry summer, a dry winter, followed by a second hot and dry summer. The effect of this was shown by the dotted line in Fig. 17 which represented the 1943-44 flows, the standard average flows being shown for sake of comparison. For such a cycle it would be noted that there was not a great surplus of water in the winter for refilling the reservoirs and if this cycle, or something like it, occurred when the demand line became greater than 450 m.g.d. it might not be possible in the winter, to replace completely the volume of water drawn out of the reservoirs in the first summer.

FIG. 16: THAMES FLOWS FOR A SINGLE DRY SUMMER (1921)

142. By observing the rainfall and the river flow during the winter and spring of 1943-44 it became evident that, unless the following summer were extremely wet, low flows would be experienced in the summer of 1944, but the winter flows of 1920-21 gave no indication of what was to follow. The summer flows of 1921 were peculiar and after the fairly normal rainfall of the preceding winter the discharges from the springs might have been expected to maintain the river flows. However they did not, and one uncharitable explanation of the low flows was that the weir at Teddington was not watertight and that more water passed under it than over it. He would leave the Author to answer that, but he had met other engineers who, like himself, were puzzled by the small amount of water available from other sources during that summer. All this was leading up to a question which he wished to put to the Author, and it was this: could the Author provide a simple and reliable formula, which, based on his observations, would enable very low flow conditions in the summer to be forecast, say in the previous January. If he could do this Mr Cronin felt sure that he would earn the gratitude of the Metropolitan Water Board engineers.

143. There was another curious phenomenon connected with drought years to which

he would like to draw attention. The table below showed the average daily flows in the Thames during the five consecutive months of lowest flow in years when the discharge had been abnormally low. The figures were divided into two groups, pre 1907 and post 1907, for a reason which would appear later.

TABLE 14: AVERAGE DAILY FLOW OF THAMES IN M.G.D. DURING FIVE CONSECUTIVE MONTHS

Pre-1907		Post-1907	
Year	Average Flow	Year	Average Flow
1899	312	1934	264
1898	353	1921	266
1906	375	1944	275
1901	379	1929	359
1893	395	1949	366

144. From this table it would be observed that in the pre-1907 period the average flows in dry years were greater than those in the post-1907 period. In the first group there were no figures less than 300 m.g.d. while in the second there were three. This was all the more remarkable if these figures were studied in conjunction with Fig. 4 in

FIG. 17: THAMES FLOWS FOR TWO CONSECUTIVE DRY SUMMERS (1943 AND 1944) WITH AN INTERVENING DRY WINTER

the paper. This figure showed that up to 1907 the deficiency in the rainfall was increasing whereas after that year, rainfalls higher than the average were being experienced. He would in consequence have expected lower flows before 1907 than after that year. Why did this occur? He would suggest an explanation: urbanization and land drainage (and all that that implied). The first resulted in appreciable areas of pervious ground being waterproofed while the operations of land drainage engineers, by clearing rivers and watercourses conduced to send off to the sea as quickly as possible rainfall, which should have percolated into the ground and replenished the springs. The

Author himself supplied evidence of the effect of this process, where, in § 134, he stated:

“Investigations in the droughts of 1944 and 1959 gave the interesting results that, in 1944, some 200 miles of watercourses that were normally flowing were found to have dried out. In 1959 the corresponding figure was 298 miles”.

This increase of nearly 50% was due, Mr Cronin suggested, to the Author's activities with his draglines and his dredgers.

145. Had they to look forward in the future to lower minimum flows in dry summers? If so, it was a disturbing prospect, because greater volumes of storage than had been anticipated would have to be constructed to make good the deficiencies. Since sites for reservoirs were becoming scarce, and the limit of the volume of storage which could be refilled in a very dry winter similar to that of 1943–44, was already in sight, the quantity of water available from the Thames for supply would be less than was at present estimated.

146. In § 131 the Author stated:

“During prolonged periods of dry weather, the Thames and its tributaries derive their discharge substantially from ground water”.

This explained why in dry summers, like 1959, following reasonably wet winters the Metropolitan Water Board experienced no difficulty in maintaining their supply, whereas undertakings in the North, which were dependent on run-off from day-to-day or month-to-month rainfall, had run into difficulties. The great problem, however, was to keep up the flow of the Thames during dry summers. A short while ago a suggestion had been advanced that borings should be put down into the chalk in the Kennet Valley and large quantities—up to 50 or 60 m.g.d.—pumped into the Kennet to augment its flow, and so increase the flow of the Thames. Mr Cronin, however, felt by no means sure that the water pumped out of the ground would not in any event have found its way into the river system, or worse still it might have been drawn from the river or its tributaries. In such an event the water would simply be pumped round and round and it would be a case of “Robbing Peter to pay Paul”. He wondered if the Author, whom he believed had something to do with this proposal, would be prepared to express an opinion as to whether it could be put into effect with the results anticipated by its promoters.

147. He looked forward to another paper from the Author which he suggested should be entitled “The potential yield of the Thames Valley for water supply”, because he felt certain that that would be a critical matter before the end of this century.

Mr H. C. Bowen (Chief Engineer, Thames Conservancy) said that there were two questions raised by Mr Cronin which he felt able to answer. The first was whether they would, when another Paper was presented, employ the “Waterworks year” starting on 1 April, instead of the “Water” year starting on 1st October. The answer was that they would not, and for a very good reason. When dealing with hydrology problems it was essential to relate the effect of the winter flow on the subsequent summer flow, but if Mr Cronin's suggestion was adopted they would have last year's rainfalls related to this year's flow.

149. The second point raised by Mr Cronin was an excellent one and most interesting. It was the question of pumping from underground sources to supplement river flows in dry summers. He thought it would work, but there remained the important question whether water pumped from underground would necessarily affect the flow of the river, and if so, to what extent.

150. Taking the particular case of the Kennet, it would be possible to install about 38 boreholes and pump 76 m.g.d. The mean flow of the Kennet in a dry summer was only 40 m.g.d., so that if every drop of water was stopped there would still be a net benefit of 36 m.g.d. To the extent that the springs were not interrupted the gain would be greater. It was not unreasonable to expect that a net gain of 50–60 m.g.d. could be

attained. This could be proved only by test-pumping, but Mr Bowen hoped that it would eventually be possible to convince Mr Cronin.

151. There was no need to emphasize the importance at the present time of the Author's work. It would be most valuable when dealing with the difficult problems arising in periods of low summer flows. At the present time the discharge of effluent into the Thames was running at about 112 m.g.d. and the total flow could easily go down in the summer months to 400 m.g.d., which meant 1 part of sewage effluent to 3 of water. Was it really going to be possible to maintain adequate standards of river purity and quality of water with those very low dilution figures? Was the solution to be sought in the improved standard of effluent, or by some means of supplementing the flow when under natural conditions it would be abnormally low?

152. The only chance of solving this problem seemed to lie in the development of available underground sources. The average flow of the Thames was half storm-water run-off and half groundwater flow, so that if it could be satisfactorily developed, there would be a potential source of water for consumption and for dilution of effluent.

153. What other means were available? The classic form of flow regulation was by regulating reservoirs, but that was extremely difficult in undulating country such as the Thames Valley. There had been a scheme about 30 years ago for four regulating reservoirs, but they were to be 26 sq. miles in extent and would have had a total capacity of 25 000 m.g. in all. That would probably not be sufficient to meet the requirements within the next 40 years, and to put so much of the country permanently under water for that purpose could not be justified. Pumped storage, such as the Metropolitan Water Board went in for, was quite good, but the difficulty was that it was possible to tap only a limited amount of the excess flow of the river, due to limitations in the pumping capacity that could be installed.

154. It was also necessary to consider the question of irrigation. From the hydrological point of view spray irrigation caused great difficulties, because the water was entirely absorbed and there was no return to the river in the form of effluent. Mr Bowen thought that development of underground resources offered the only practicable method of providing for foreseeable future demands in the Thames Basin.

155. The other aspect of the Paper, dealing with the interrelation between rainfall and storm run-off, was also very valuable. The Author dealt first with the question of disentangling the groundwater flow. Until there was a reliable method of doing that, the rainfall/storm run-off relationships were bound to be rather vague. Quite a number of investigations into hydrographs had been made in recent years, but they all depended on assumptions as to the movement of the groundwater during the period of the hydrograph. Mr Bowen knew of an occasion where a hydrograph of 10 days' duration had been considered, and it had been assumed that the groundwater flow would double itself in that time. This seemed most unlikely, and the effect of such an erroneous assumption would be that too low a figure would be obtained for the storm run-off, because too much would have been deducted for groundwater flow. Mr Bowen thought that similar errors in estimated run-off had occurred in a number of cases. With the Author's method there was first the removal of the groundwater flow on a consistent basis and then the analysis of the storm run-off on a consistent basis, each consistent in itself and also, fortunately, consistent with one another. That would be very useful in future studies of total run-off.

156. The prospects of studying peak flow once the total run-off had been determined had proved much more difficult than some of them had thought it would be. It was probably inevitable that on a catchment area of the scale of Teddington the unit hydrograph technique would be unreliable, largely because the influence of the distribution of the rainfall on the catchment area was so great. There had been an example in the floods of the winter of 1960-61. In November there had been a peak flow at Teddington of the order of 8000 m.g.d., and in December of 7000 m.g.d. The difference was about 15%, and had been reflected for three or four reaches above Teddington; but once one went further upstream the reverse had been true, and the flows more than

20 miles above Teddington had been higher in December than in November. The November rainfall had been concentrated largely in the south and south-east of the catchment area and the Surrey rivers had contributed a far greater proportion of the flow than in December.

157. That seemed to lead inevitably to the conclusion that the problem would not be solved solely by means of a unit hydrograph at Teddington. For the purpose of forecasting peak flows it would be necessary to find a method of summing the individual hydrographs of the various tributaries, provided the individual hydrographs could be established with certainty. The summation of the unit hydrographs would be a formidable task in itself, even though complicated computations were now possible on computers. Some hesitation might be felt, however, in setting up all that machinery together with the extra rainfall data that would be necessary because Mr Bowen felt it was not yet known with sufficient certainty that the basic assumption of the unit hydrograph technique was valid, namely that the time-base of the unit hydrograph for any one catchment was independent of other factors.

158. The position was most clearly shown in Fig. 5, which gave the storm recession curves at Teddington. The length of the recession could be anything from 13 to 20 days according to whether the groundwater level was low or high. That point should be cleared up before pursuing the unit hydrograph technique any further on a larger scale with any confidence. Mr Bowen suggested that perhaps some body interested in hydrology would investigate the problem, and find out whether the technique was applicable and whether there was a limit to the size of the catchment area to which it was applicable.

Professor J. C. I. Dooge (University College, Cork) said that the most interesting part of the Paper to him was that concerned with groundwater discharge; here the Author had demonstrated a coaxial method of graphical correlation and had shown how that method could be applied to an individual catchment and gave his results in Fig. 6. This work required patience, a great deal of diligence and not a little artistry in arriving at the final result. If one were to discuss his results adequately, one would most unfortunately have to follow in his footsteps and display the same diligence, the same patience and the same artistry. This made his work in this regard both useful, because it was a thorough job, and more difficult to discuss also, because it was a thorough and painstaking job.

160. There was only one suggestion that Professor Dooge had to make with regard to the further development of this method. He thought that it could probably be improved if the Author were to replace his expression for percolation by an expression for evapotranspiration over the basin. Whether this was to be taken as observed or as computed from data of different types was again a matter for investigation, and it was certainly not Professor Dooge's intention to enter into that disputatious field on the present occasion.

161. He was interested in the groundwater flow. Mr Cronin had said that those who were interested in flows from the point of view of application became interested in minimum flows, and Professor Dooge wanted to talk about the minimum flows and those shown in Table 8, Plate 2. He did not intend to discuss the figures in detail but to mention something with regard to these flows and something with regard to the expressions for groundwater recession which were given in §§ 68 and 69. What he had done was to analyse the data in Table 8 by Gumbel's method for the analysis of droughts. It was interesting to compare the results of these two operations. When one applied the complete Gumbel analysis, one parameter was the ultimate minimum flow. This was a flow below which the minimum flow in any year would not fall. The figure obtained by analysing the data in Table 8 gave a value of 124 m.g.d.

162. Looking at the expression in § 68 for the flow at Teddington, the Author implied the assumption that the groundwater flow at Teddington would never fall below 102 m.g.d. When the figures of 124 and 102 m.g.d. were compared, all those who had

indulged in hydrological analysis would agree that this was virtually complete coincidence. There was a difference of 20%. It was a remarkable confirmation of both the Author's and Gumbel's methods that in this instance both arrived at virtually the same result.

163. The other interesting point was that if the distribution of these minimum flows in the Thames were plotted they followed closely the theoretical distribution of Gumbel, except for the seven lowest years on record, where the results fell about 10% below the theoretical curve. Professor Dooge wondered what had affected the results and whether there was a certain point below which there was a drying out of certain beds in the catchment or whether there might be some effect due to rationing by the upstream authorities and consequent reduction in the return of waste waters. It was interesting to find that there was this 10% reduction. If allowance was made for it it closed still further the gap between 124 and 102 m.g.d.

164. The other point about the Gumbel analysis was that it gave a parameter for variability which showed how variable were the minimum monthly groundwater flows on the River Thames. It was of interest to compare this parameter of variability of minimum monthly flows with four cases which had been analysed in Ireland: one for the Shannon, which had a slightly larger catchment area than the Thames; one for the Erne, which was a little less than half the size of the Thames; and then two small catchments, the Ballymakellet, with an area of 2 sq. miles, and the Annaverna, 1 sq. mile. It was interesting to see how this parameter varied. This $1/\alpha'$ term in Gumbel's analysis was 0.1935 for the Thames, 0.3064 for the Shannon, 0.2906 for the Erne, but for the catchment of 2 sq. miles, which drained a mountain area, of igneous rock as a bedrock, the variability factor was 0.1906, virtually identical to that of the Thames. With two catchments of about the same size there was a difference of 19 to 30, but with two catchments utterly dissimilar in every way the variation of minimum flows seemed to be the same. For the other small catchment, of 1 sq. mile, immediately adjacent to the one just mentioned, and also a mountain catchment of igneous rock, the figure was 0.2884. There seemed to be some mysterious factor here which accounted for this very important parameter of variability of low flows. This had to have an effect. It would affect Mr Cronin very greatly when he got higher water demands. It did not seem to be related to bedrock or size or contiguity. It might be very valuable to have the results of the analysis of records of other rivers in the British Isles, so that comparisons could be made to see whether this elusive factor could be isolated.

165. Turning to the actual recession formulae given in §§ 68 and 69, Professor Dooge recast the equations given there into a precisely equivalent form,

$$(Q_T - 102) = (Q_0 - 102) \exp(-t/K).$$

That was exactly equivalent, and was interesting because the constant K became storage delay constant, the average delay time of the water being considered, in this case the groundwater. The value of K at Teddington based on the numerical constants given in § 68 turned out to be 10.6 weeks, while for the catchment above Day's weir K was equal to 6.2 weeks. The latter value was interesting, because most of the catchment above Day's weir was Oolites. For the River Shannon, which had a limestone catchment geologically similar, a precise value had not been determined, but he had reached the conclusion that the value of K was about six weeks, so that here there was agreement. If the upper catchment of the Thames was eliminated and an attempt made to find a figure for the catchment between Day's weir and Teddington, which was largely chalk, the figure would be about 12 weeks for the delay time. That was again reasonable, but it was desirable to have more data.

166. In the Paper, § 73, the Author suggested that about three-quarters of the June percolation, half the July percolation and a quarter of the August percolation ran off in the water year, i.e. before the end of September. If he was dealing with groundwater and was assuming a form of recession such as he gave in §§ 68 and 69 he was implicitly assuming that the groundwater reservoir was linear in its action, because this was the recession from a linear reservoir. Professor Dooge¹⁰ had put forward the idea

that if a reservoir was linear one could consider both recharge and recession. It was interesting to find that taking a value of K , based on the Author's recession curves, of 10.6 weeks at Teddington, and calculating on that basis how much of the percolation would run off, Professor Dooge obtained a figure of 75% for June, compared with the figure of three-quarters in § 73, but thereafter there was a divergence, for July his figure was 60% as against one-half, and in August 45%, as against one-quarter. Once again he was content to think that the Author was largely justified, but he would like to think that he was, too.

167. The Paper contained a close study of one basin. The job of others at the moment was to take the results set out in the Paper and see whether it was possible to generalize and whether it was possible to apply the Author's methods to other catchments. Could they adopt the Author's methods? He had given them a very good start and a great many data in the Paper. It would help others in developing alternative approaches, however, to have the complete record of monthly rainfall and of the surface run-off as opposed to the groundwater run-off given in the Paper.

Dr T. M. Prus-Chacinski (Partner, C. H. Dobbie and Partners) said the Author had demonstrated that, given a sufficient set of data, by employing modern methods of hydrology it was possible to estimate and predict groundwater discharges and storm run-off with great accuracy. He had only one general observation to make.

169. In Table 11 the Author had computed the mean annual run-off and losses for 60 rivers, and in § 121 he had given a formula for those losses. Although the Author had stated in § 122 that the losses were mostly due to evapo-transpiration, he had also referred to deep percolation losses. His formula implied that the losses were an involved function of annual rainfall.

170. He had been a little puzzled by this because, if the surface catchment area was the same as the groundwater catchment area, the long-term loss should have been equal to evaporation or evapo-transpiration, even for pervious catchments.

171. In order to check the above he had prepared Table 15 in which the mean annual loss was compared with the mean annual evaporation taken from Dr. Penman's¹¹ evaporation map, and the difference between loss and evaporation was computed as a percentage of evaporation. This had been done for all 60 rivers as presented by the Author in Table 11.

172. In Fig. 18a the difference between loss and evaporation was plotted against the mean annual rainfall, and it could be seen that the great majority of catchments were contained within the band of $\pm 10\%$ difference. It seemed that the mean annual loss for the great majority of catchments was equal to the mean annual evaporation $\pm 10\%$.

173. Dr Penman considered that the all-over accuracy of his map was within 1.2 inches of evaporation, which in effect was between say 5–10% accuracy. Inspection of Fig. 18a showed that many points are within the $\pm 5\%$ band. In general, the graph demonstrated that the loss did not depend on rainfall but more probably on evaporation alone, as it was well within the limits of the evaporation figures' accuracy.

174. However, a number of catchments were well outside the $\pm 10\%$ band, and may represent those where the surface area was not equal to the groundwater area. In order to check this, Fig. 18b has been prepared. This was the same graph, but included only those catchments where the period of observations had been equal to or longer than 15 years. This was the minimum period during which one could hope for reasonable balancing-out of the groundwater storage.

175. Inspection of this graph showed that only very few catchments were outside the $\pm 10\%$ band. This graph demonstrated first that mean annual loss was very nearly equal to mean annual evaporation; and second that catchments with a loss or gain due to deep percolation were quite exceptional. In fact only one catchment, No. 35, River Wandle (with a period of observation of 17 years) which was a typical chalk catchment was definitely losing run-off by deep percolation. Otherwise there seemed to be little evidence that there was an appreciable difference between pervious or impervious

TABLE 15: LOSSES AND EVAPORATION

Reference No. (as Table 11)	River	Period of Gauging Years	Mean Annual Rainfall Inches	Mean Annual Run-off Inches	Mean Annual Loss Inches	Mean Annual Evaporation Inches	Difference between Loss and Evaporation Inches	Difference between Loss and Evaporation % evaporation	Type of Catchment
1	Shin	3	60.0	42.27	17.73	15.0	+2.73	+18.2%	Impervious
2	Conon	9	73.0	53.49	19.51	15.0	+4.50	+30.0%	Mixed
3	Ness	26	67.41	51.21	16.20	15.0	+1.20	+8.0%	Pervious
4	Allt	4	61.90	43.40	18.50	15.0	+3.50	+23.0%	Mixed
5	Dee	26	43.42	32.98	10.44	12.0	-1.56	-13.0%	Granite
6	Newton	6	46.40	30.90	15.50	15.50	0	0	Mixed
7	Melgam	4	43.90	27.34	16.56	16.0	+0.56	+3.5%	"
8	Inzion	6	40.60	24.60	16.0	16.0	0	0	"
9	Earn	6	57.40	41.69	15.71	16.0	-0.29	-1.8%	"
10	Fruid Water	8	64.70	45.92	18.78	14.0	+4.78	+34.0%	"
11	Nidd	16	51.10	36.60	14.50	14.0	+0.50	+3.5%	"
12	Blithe	18	30.80	12.76	18.04	18.0	+0.04	+0.2%	"
13	Derwent	17	54.00	37.53	16.47	16.0	+0.47	+2.9%	"
14	Nene	15	24.80	6.39	18.41	17.0	+1.41	+8.3%	"
15	Kislingbury Br.	15	26.20	6.73	19.47	17.0	+2.47	+14.5%	"
16	Kislingbury Br.	15	26.10	7.34	18.76	17.0	+1.76	+10.0%	"
17	Brampton Br.	16	25.90	7.41	18.49	17.0	+1.49	+8.8%	"
18	Ise Brook	10	25.60	8.06	17.54	17.0	+0.54	+3.2%	"
19	Harpers Brook	16	24.80	6.94	17.86	17.0	+0.86	+5.0%	"

(continued overleaf)

Reference No. (as Table 11)	River	Period of Gauging Years	Mean Annual Rainfall Inches	Mean Annual Run-off Inches	Mean Annual Loss Inches	Mean Annual Evaporation Inches	Difference between Loss and Evaporation Inches	Difference between Loss and Evaporation % evaporation	Type of Catchment
20	Great Ouse.	19	25.50	7.60	17.90	17.0	+0.90	+5.3%	Mixed
21	Great Ouse.	19	24.20	5.82	18.38	17.0	+1.38	+8.1%	"
22	Cam.	10	23.90	5.60	18.30	17.0	+1.30	+7.6%	"
23	Lark.	18	24.10	5.40	18.70	17.0	+1.70	+10.0%	"
24	Stour.	10	24.30	4.0	20.30	20.0	+0.30	+1.5%	"
25	Chelmer.	18	23.0	3.15	19.85	20.0	-0.15	+0.75%	"
26	Ter.	18	22.5	3.42	19.08	19.0	+0.08	+0.4%	"
27	Blackwater	12	22.0	3.77	18.23	18.0	+0.23	+1.3%	"
28	Roding.	5	24.9	5.73	19.17	19.0	+0.17	+0.9%	"
29	Lee.	18	24.8	5.50	19.30	20.0	-0.7	-3.5%	Pervious
30	Mimram.	2	24.3	5.50	18.80	20.0	-1.2	-6.0%	"
31	Thames.	17	28.0	9.80	18.20	19.0	-0.8	-4.2%	Mixed
32	Thames.	72	28.8	9.55	19.25	19.0	+0.25	+1.3%	"
33	Windrush.	5	31.2	13.80	17.40	18.0	-0.60	-3.3%	"
34	Colne.	21	26.70	3.47	23.23	21.0	+2.23	+10.6%	"
35	Wandle.	17	33.0	1.70	31.30	21.0	+10.30	+49.0%	Pervious
36	South Teign.	4	67.40	56.89	10.51	21.0	-10.49	-50.0%	Granite
37	Avon.	2	30.20	13.87	16.33	19.0	-2.67	-14.0%	Mixed
38	Severn.	34	35.51	18.32	17.19	19.0	-1.81	-9.5%	"
39	Vymwy.	18	75.9	57.00	18.9	19.0	+0.1	-0.5%	"
40	Avon.	18	26.3	7.29	19.01	19.0	+0.01	+0.05%	"
41	Sowe.	4	26.8	12.6	14.2	19.0	-4.8	-25.0%	"

Reference No. (as Table 11)	River	Period of Gauging Years	Mean Annual Rainfall Inches	Mean Annual Run-off Inches	Mean Annual Loss Inches	Mean Annual Evaporation Inches	Difference between Loss and Evaporation Inches	Difference between Loss and Evaporation % evaporation	Type of Catchment
42	Wye	18	63.1	45.31	17.79	20.0	-2.21	-11.0%	Mixed
43	Wye	18	39.50	22.62	16.88	20.0	-3.12	-15.5%	"
44	Ellan	47	70.01	49.82	20.19	20.0	+0.19	+1.0%	"
45	Irfon	18	69.2	50.60	18.60	20.0	-1.4	-7.0%	"
46	Lugg	15	32.7	13.45	19.25	20.0	-0.75	-3.7%	Pervious
47	Monnow	7	40.0	19.53	20.47	20.0	+0.47	+2.3%	Mixed
48	Dee	18	54.5	36.58	17.92	18.0	-0.08	-0.04%	"
49	Brenig	18	50.8	32.10	18.70	18.0	+0.70	+3.9%	"
50	Weaver	18	30.0	10.50	19.50	18.0	+1.50	+8.35%	"
51	Dane	6	36.0	17.97	18.03	18.0	+0.03	+0.16%	"
52	Gowy	6	29.90	9.11	20.79	18.0	+2.79	+15.5%	"
53	Irwell	6	52.6	41.75	20.85	17.0	+3.85	+22.5%	"
54	Irk	6	43.0	25.61	17.39	17.0	+0.39	+2.3%	"
55	Medlock	5	42.2	26.99	15.21	15.0	+0.21	+1.4%	"
56	Etherow	18	55.5	40.41	15.09	15.0	+0.09	+0.6%	"
57	Douglas	71	46.6	30.64	15.96	16.0	-0.04	-0.02%	"
58	Caaf Water	5	61.4	43.91	17.49	16.0	+1.49	+9.3%	"
59	Kelvin	3	47.1	31.60	15.50	15.0	+0.50	+3.3%	"
60	Leven	5	77.7	65.62	12.08	14.0	-1.92	-13.7%	Granite

FIG. 18a: DIFFERENCE BETWEEN MEAN ANNUAL LOSSES AND EVAPORATION IN % EVAPORATION PLOTTED AGAINST MEAN ANNUAL RAINFALL FOR 60 RIVERS IN GREAT BRITAIN (SEE TABLE 14)

FIG. 18b: DIFFERENCE BETWEEN MEAN ANNUAL LOSSES AND EVAPORATION IN % EVAPORATION PLOTTED AGAINST MEAN ANNUAL RAINFALL FOR 33 RIVERS IN GREAT BRITAIN WHERE THE GAUGING PERIOD WAS 15 YEARS OR MORE

catchments, although it might be that granitic catchments actually gained by deep percolation, as was demonstrated by catchment No. 5, River Dee, where the period of observation was 26 years.

176. Catchments with a really long period of observation, such as No. 32, River Thames (72 years), No. 44, River Elan (47 years), and No. 57, River Douglas (71 years), demonstrated losses exactly equal to evaporation, so it was possible that, taking the long-term view, some catchments now outside the $\pm 10\%$ band might eventually creep inside it, losing their present peculiarity.

177. In his opinion he had demonstrated that for the 60 rivers contained in Table 11 the mean annual loss was probably equal to the mean annual evaporation. Peculiar catchments where there was loss or gain due to deep percolation seemed to be exceptional. He submitted that a sufficient expression for mean annual loss for the great majority of catchments would be the statement that mean annual loss was equal to mean annual evaporation $\pm 10\%$. The difference of $\pm 10\%$ might be due, not to any peculiarity of a given catchment, but purely to errors in gauging and estimating the mean annual evaporation.

F. V. Appleby (Director, W. & C. French, Ltd.) said that after examining 500 hydrographs, Mr Andrews (§§ 41–43) had made some very significant statements which could be summarized in principle as follows:

179. A state of flow (said to be bank full) of 4500 m.g.d. (q_f) was characteristic of the Thames at Teddington and consistent with a virtually constant total volume of recession flow (S_0). Between the level of the flow (q_f) and the ground water flow (q_w) the recession trace varied as to time base between the two extremes from 11 to 19 days, while the recession drop (q_0) varies according to the difference between (q_f) and (q_w). Such statements as these, relating as they did to practical results, must be considered as an essential challenge to methods of hydrograph analysis.

180. On the face of it the statements were not easily reconciled with theory, particularly of the unit hydrograph. On examination, however, Mr Appleby found them to be quite consistent with a theory of runoff which he had put forward in 1954 when he demonstrated that flood waves could arise from a diffusion process such as that met with in heat conduction. In this paper¹² he suggested a function $\phi(\beta)$ as particularly applicable to the recession phase.

181. The parameters for this function were related in the form

$$q_0 K_0 = S_0 \quad \dots \dots \dots (7)$$

where K_0 is the response time (scale) consistent with the hydrological state of the catchment and S_0 , the characteristic volume, and q_0 have a meaning agreeable with Mr Andrews's statements. According to equation (1) the scale of time for the base of recession will vary inversely with the amount of drop. Using this drop as the independent variable (q_0) and considering (S_0) as known, a value of (K_0) may be inferred. A whole group of recession curves may then be drawn using the runoff function $\phi(\beta)$.

182. Applying these principles, the curves shown in Fig. 19 have been drawn and the corresponding values in Fig. 5 are shown for comparison. (Mr Andrews's values in Fig. 5 have been taken from a larger scale diagram kindly supplied by him.) Fig. 19 shows also extended extremes of recession flow relating to the extremes of groundwater flow given in Table 8. The low flow recession (III) is of particular interest. The total natural free recession is B, C, D . Simple natural recession does not occur until point C is reached after 3 days' lag from the commencement of disturbed recession at A . This tangent length seems to be characteristic of many of the Thames hydrographs and clearly represents a delay of simple recession by the arrival of distant storage regulated flows.

183. Mr Appleby asked if Mr Andrews could confirm this peculiarity of the Thames at Teddington and the reliability of the 3-day delay time of remote influence. Disturbances in this tangent length might well be indicators of flows from specific upstream

drainage groups, such as had been found in studies of Loch Ness, which showed very clearly in recession the sequence of flows from separate drainage groups feeding into the lake.

184. This "tangent" characteristic seemed to work out, as the base flow increased, until it was entirely absent at the high flows of Fig. 19, so that the catchment in this fully saturated state is acting in unison as an integrated whole.

185. For the purpose of calculating these curves the standard storage volume (S_0) had been graded from 16 300 m.g. for IV to 28 500 for I, compared with a figure of 10 800 given in the Paper. To get his figure Mr Andrews had taken the area under the recession curve from (q_t) to his stated base flow, which was the rate of flow at his terminal point. These arbitrary terminal points lie on the standard time base indicated in the diagram. Beyond this standard time base recession still continues and falls ultimately to the ϕ base figures shown making the total volume content under the recession graph significantly greater than the figure calculated by Mr Andrews.

FIG. 19: RIVER THAMES AT TEDDINGTON: RECESSION HYDROGRAPHS

186. This process would appear to conflict with Mr Andrews's statement that (S_0) is virtually constant throughout the whole range. He was dealing, of course, with actual hydrograph areas and would have included the increase of area under the curves due to the time delay in the tangent section, and consequently there would be a tendency for the lower flow recession curves to be over-estimated in relation to the recession function graphs. This increase in characteristic volume (S_0) which Mr Appleby had used in his calculations, was to be expected, particularly in the higher states of flood, and was consistent with an increase in the extent of contributing area. He felt that the contributing area was not necessarily a constant. It was always assumed to be so, but as the catchment area became more saturated so it seemed that the area contributing to the flood increased. This would add sense to the increased time and

the higher groundwater of the upper limit of the flood curve, and conversely to the lower limit also.

187. Considering the variation of area to be proportional to (S_0) the zero curve could be consistent with the minimum impervious area of 1200 sq. miles and curve II with 2060 sq. miles and the area for the upper extreme curve somewhat greater still. In the space between I and III a whole range of recession curves can be calculated for various values of (K_0) terminating at the standard time base.

188. Fig. 10 showed an interesting specimen of recession with a marked tangent length. Slight rises at the root of the tangent might well be due to a latecoming flood wave from Day's weir combined with a possible swing of rainfall distribution favouring a remote group.

189. Mr Andrews had shown a steady rise in ground water continuing to the limit of his time base. Was this correct? By definition, recession commences when effective runoff input has ceased and in consequence the ground water rise must also be complete at this point, which for Fig. 10 was about 11 November.

190. In order to compile Fig. 5 Mr Andrews had consistently selected hydrographs rising above the 4500 m.g.d. level. It would be interesting to have his views on the validity of application of Fig. 5 to the smaller rises such as on 29 October, 1916, Fig. 10.

191. The question of demarcation of surface and ground water (so-called) was one for which no theoretically sound rules had been established. Mr Andrews was quite consistent with his method, however, and the validity of his ground water flow studies was quite unaffected by a proportional neglect of recession flow arising from his arbitrary but consistent termination of time. Even so, the gross runoff figures of Table 10 were very sensitive to the method used for demarcation and to this extent the breakdown of the mean discharge between ground water and surface water was arbitrary.

192. In Fig. 10 there was a characteristic flat spot on the recessions of the hydrographs and it seemed unlikely that this was due to chance; it looked as if it could be characteristic of the river. Perhaps the Author would comment on that. It seemed to Mr Appleby to be consistent with the recession function which he had suggested in 1954. He did not propose to go into the calculations, but it was possible to show that the response time could be picked up from that characteristic. Hydrologists looked for singular points on the hydrograph which would give them parameters and constants. The peak was an obvious one but produced very little in the way of results. This flat part might be worth further study.

193. Mr Appleby noted with interest the unit hydrographs given in Fig. 12 and particularly the fact that they all approximated to an equal time base: had Mr Andrews attempted to reconcile the principles governing these unit hydrographs with his findings in §§ 41-43?

Dr J. Ineson (Chief Geologist, Water Department, Geological Survey) observed that the groundwater hydrologists and geologists were naturally interested in the hydrogeological application of this survey. The proportion of the total flow of the River Thames represented by groundwater discharge from chalk and younger deposits at Teddington was about 60%, whereas in some chalk catchments this might exceed 75%. Above Day's weir, the contributory catchment consisted essentially of strata other than chalk, including a high percentage of Jurassic clays, with a groundwater contribution of only 38%. This did not appear to agree with the statement in § 89 that the annual yield from the Jurassic limestones above Day's weir was about the same as the chalk areas draining to Teddington. The Jurassic limestones were essentially more compact than the chalk, relatively impermeable but they had larger fissures with locally very high permeabilities. On the other hand, the bulk of the chalk has a significant permeability, even if small in comparison with the fissured chalk aquifer. The storage facilities in the Jurassic limestones are less than in the chalk. These characteristics of storage and permeability would account for the lower groundwater contribution from the Jurassic

limestones, for the more rapid outflow from these strata in the spring and early summer and for the steeper groundwater recession curve at Day's weir.

195. The reference in § 61, to run-off from pervious catchments was very important. Where soil-moisture deficits had been satisfied, downward drainage of surplus soil-water under gravity to the zone of saturation would occur. Rates of infiltration were governed, however, by a variety of factors, including the permeability of the soil profile. If the soil was fully saturated, the intensity of rainfall would intermittently exceed the potential infiltration rate. In fact, paradoxically, the most impermeable medium encountered in hydrological studies was water itself. For this reason, surface run-off might occur within a so-called pervious catchment, even in chalk areas.

196. The Author had suggested that a single curve of the form of equations (3) and (4) could be fitted to the data for natural recession of groundwater discharge. If the data from Table 8 relative to recession and from Fig. 7 are plotted semi-logarithmically, namely daily mean groundwater discharge against the logarithm of recession, many sequences appear to consist of two distinct straight lines, a break occurring about four months after recession had commenced. Whether or not this might represent either groundwater discharged from different aquifers or an initial rejection of infiltration as interflow would be a matter for further study.

197. The suggested value of 2% which was attributed to the porosity of the chalk refers, not to porosity, but to the specific yield of the strata. The porosity will be of the order of 25–35% in the case of chalk. The value of 2% quoted by the Author agreed with average values of the specific yield under water-table conditions which had been obtained by pumping-test techniques, the range being about 0.5–2.5%.

198. In hydrological studies the surface catchment area should be capable of being adequately defined and all the groundwater should be discharged naturally into the same catchment, as the Author rightly pointed out. In the case of the Thames, the surface catchment area is probably justified, but in other cases, particularly small areas, groundwater contours should be constructed to compare the extent of the surface and groundwater catchments. It might be debatable, therefore, whether or not the surface catchment was the best hydrological unit to study.

199. The numerical difference in mean values of groundwater and surface discharge appeared to be significant in Table 10, but somewhat anomalous. It might be argued that such differences in equivalent run-off could arise if the evaporation over the separate areas was variable, for example the outcrop of the chalk occupying a topographically higher area than the London clay. It was doubtful, however, if a difference as large as that indicated did occur. Since the equivalent run-off was based essentially upon the individual areas of pervious and impervious beds, adjustment in the selected areas might be necessary. The area of pervious beds providing groundwater discharge would have to be increased to about 2000 square miles in order to have an equivalent run-off comparable with the natural discharge over the whole Thames catchment. On geological grounds this would not be unreasonable. Over the Author's impervious areas detailed on Fig. 2, there must not only be pervious drift deposits, but additionally even the so-called impervious London clay is pervious near the surface because of weathering. This weathered zone functions as a thin surface aquifer, which would contribute to the groundwater component of the hydrograph. The interpretation of a geological map in relationship to the hydrogeology and groundwater hydrology of an area required careful consideration. If the figure of 0.9 in. per annum loss from chalk areas as surface run-off during wet seasons was also considered, then the area contributing to groundwater discharge might be considerably greater than that assumed by the Author. Dr Ineson asked if the Author would comment on the variations in the equivalent run-off due to groundwater and surface discharge.

200. Although the Author made reference to so-called "percolation" gauges in the chalk, these could only be regarded, in the opinion of Dr Ineson, as representing limited sampling points for the determination of the infiltration characteristics of an aquifer. Their small cross-sectional area was probably not representative of the surface geology

of the whole catchment. One of the most valuable results of the analysis of the ground-water contribution to river flow was the derivation of a mean figure for infiltration. This contribution might represent surplus groundwater resources, provided that the total volume of discharged effluents derived from groundwater was known. The out-crop of the pervious beds could be regarded as a large-scale infiltration gauge of field dimensions.

201. The greater proportion of pervious strata contributing to the flow of the Thames between Day's weir and Teddington was essentially chalk. Using a flow of 557 m.g.d. for groundwater discharged between Day's weir and Teddington, an equivalent infiltration rate into the chalk would be 8 or 9 in. per year. This compared with data obtained from similarly exposed chalk catchments, as for example in Hampshire, where the figures may be of the order of 11 to 14 in. per year. In the Thames catchment the difference between rainfall and evaporation was less than in Hampshire. It should also be remembered that some of the water infiltrating into chalk was not discharged into the Thames but flowed under cover of post-Cretaceous strata towards the centre of the London basin as underflow. The Wandle catchment had a high groundwater loss due to northerly flow of groundwater in the chalk, and this would account for the apparent anomaly in Fig. 13 relating rainfall and run-off. In the case of the London basin, this might imply that a somewhat higher figure for infiltration ought to have been derived. This suggested that there might be a contribution from interflow included within the groundwater component determined in this study. Dr Ineson asked if the Author would say whether or not the loss of chalk groundwater flowing towards the centre of the London basin could be regarded as significant in his present analysis.

Dr J. V. Sutcliffe (Hydrologist, Hydraulics Research Station), asked the Author if he had been able to check the formula for percolation given in § 52 against the rise in well levels during the winter, or was it based on an average percentage of the winter rainfall which percolated to the water table?

203. In Fig. 7 there was a family of recession curves which followed equation (3) in § 68. Could not this family of curves have been given simply as one curve? It was perhaps easier to use in the form in which it was given, but if it was from one equation the curves should be parallel, which they did not appear to be.

204. In §§ 91 and 92, the tentative conclusion that the Author had been able to reach on the effect of water level on discharge suggested quite strongly the need for further recorded well levels, especially near the river. Dr Sutcliffe hoped that it would be possible to install these in the future.

205. He would like to suggest that equation (6) in § 121, the equation for loss, should be considered in relation to the position of the catchments within the country and that this loss should be related to the potential evaporation. He had replotted the graph as loss related to rainfall. There appeared from this to be a minimum loss at about 40 in., but this simple conclusion would be deceptive, because catchments with an annual rainfall of about 20 in. were mainly in the south and east of the country where the potential evaporation was greater. It was more difficult to explain what seemed to be a greater loss at the upper end of the scale, but these were presumably in mountainous catchments where the records might not be so reliable or wind effects might be greater.

Mr P. O. Wolf (Reader in Hydrology in the University of London, Department of Civil Engineering, Imperial College of Science and Technology), recalled the numerous occasions during the preceding five years when the Author had studied hydrological theory and sought advice on hydrological phenomena observed elsewhere. The effort which had gone into the preparation of the Paper was much greater than the reader would deduce from the impressive figures of hundreds of hydrographs and thousands of "antecedent index" calculations quoted. Mr. Andrews had, to Mr Wolf's knowledge, attempted to apply published methods and simpler theories to his data, but had

been forced to seek refinements which assured better accuracy, even though few such refinements were usable in other areas.

207. The Author's duties included the assessment of the yield of his basin for water supply, navigation, and the flushing of effluent, the prediction of floods, and the design of flood-mitigation works. When writing of the "natural" flow of the Thames he had very properly drawn attention to the highly artificial conditions of the catchment, of the river channel, and of the flow conditions as affected by variable large abstractions and sewer discharges.

208. The Department of Scientific and Industrial Research had set up a Committee on Hydrological Research. Several members of that Committee were present at the meeting and would be particularly interested in the methods which the Author had adopted for the solution of his problems. For him, the first aim had been to obtain accurate answers by means of methods which lent themselves to speedy and economical applications. The Committee, on the other hand, would be interested in the physical laws of hydrology and in generally applicable methods. There was still a wide gap, and from the Committee's point of view the Paper and the subsequent discussion were of especial value in that they showed (a) what questions were asked in practice, (b) how they could be answered in an *ad-hoc* manner, and (c) where further research was needed. Having deeply probed the deficiencies in the current hydrological theory and practice, the Author was in an unusually strong position to make suggestions on (c).

209. Mr Andrews had proved the usefulness over a great part of hydrology of the methods based on linear approximations. There were exceptions: earlier speakers had pointed out that Fig. 5 was so much at variance with the idea of linear storage and of the unit hydrograph as perhaps to suggest some special, unique feature on the Thames. Method 2, on the other hand, relying on the straight lines of Fig. 6 (and—apparently—Figs 9a and b) showed that linearity was a good working approximation. Here Mr Wolf pointed out that Professor Dooge had, modestly, omitted to refer to the Author's linear groundwater recession as yet a further confirmation of Professor Dooge's theory.

210. Everywhere the Author appeared to have been guided by the observations made on the catchment and to have been ready to depart from preconceived ideas of linearity where necessary. Fig. 11 was a good example. It was of the type which Linsley⁷ had developed in his first attempt to correlate rainfall with Thames run-off. Even if the scale of the horizontal axis linking the first two quadrants was distorted so as to yield a greater degree of linearity in these two quadrants, the diagram of Fig. 11 would still have to remain curvilinear in order to give the best practical description of the run-off response of the Thames to rainfall.

211. Again empirical methods had triumphed in Table 4. There the Author had adopted weighting factors which followed a mathematical progression which compelled him to multiply every monthly "standard" rainfall nine times. Mr Wolf suggested that, admittedly without any great improvement in theoretical justification, a geometrical progression of weighting factors should be substituted which would reduce the labour of computation by approximately 90%. To prove the usefulness of such alterations, however, all the data available to the Author were needed: Mr Wolf hoped that the Author would, with his reply, publish the tables of observations against which suggested improvements in technique could be tested.

212. In contrast to the matters just discussed, Fig. 13 and Table 11 took them on to entirely different ground. There they were dealing with overall averages which were not of immediate use to the river engineer. The problem of describing the hydrological pattern over the whole country in a climatological way was of a different kind and in a different category. There was no need to worry about it too much in the present connexion.

213. In conclusion he would again like to draw attention to the many questions which had been raised. In fact more had been raised than had been answered. He was sure that the Paper would be of value to the Institution and to the hydrological world for many years to come.

Mr J. A. Cole (Hydrology Division, Water Research Association) said that it was worth considering ways of studying the groundwater component of a river which had *not* the benefit of 77 years' very full data but maybe only 10 years' records or less. He thought that measurements of hydraulic gradient in the aquifers feeding the river would give the best and quickest forecast of groundwater discharge in such cases. Here he endorsed Dr Sutcliffe's suggestion of many more observation wells near the river. In § 92 the Author said:

"The Thames maintains its dry-weather discharge from pervious areas close to its course and that of its tributaries, where the fluctuations in the level of the water table are small . . ."

215. Here, Mr Cole submitted, it was changes in the *gradient* that should be looked for. There would be small changes in the level, in part due to a high hydraulic conductivity in alluvia. It might be an appalling task to unravel the complexity of certain aquifers (such as lenticular gravel and silt deposits) but he suggested that their groundwater discharges could be empirically correlated with the well observations. There was a very useful paper by W. E. Clarke¹³ which was relevant here. The other reason for mentioning alluvia was the importance they can have as a reservoir. The extraction of water from gravels was possibly something which had been a little neglected in this country. He could not speak with authority here, but it would be interesting to have the comments of the Author on that point.

Mr G. B. Lewis (Consulting Engineer) said his interest in the Paper fell under two headings. First, for 25 years "sweete Thames" had flowed softly past his garden and from time to time quite swiftly over it. Secondly, he found himself being called on more and more to advise on the problems of obtaining and abstracting water from ever-deepening wells. He felt it would be of great benefit if some of that water could be prevented from flowing so swiftly to the sea and kept where it was needed, in the wells.

217. He would like to quote a paragraph from the Final Report of the Sub-Committee on the Growing Demand for Water (Central Advisory Water Committee), published by H.M. Stationery Office.¹⁴ In Section 4, § 57 read:

"There is scope for a good deal of expert study and consideration of this problem"—flood control and water conservation—

"to see whether means cannot in time be developed for combining measures for the conservation of water with those for the mitigation of floods. In this connection improved knowledge of the hydrological characteristics of a river basin will be essential."

The Author should be congratulated on being well ahead of the demand.

218. He wished to ask whether the Author had any data, or could derive any, which might serve to show the way in which the hydrological characteristics of the catchment area, and more particularly the charging of aquifers and the peak rates of storm-water run-off, might have been affected by the intensive schemes of land drainage to which Mr Cronin had referred, and which Mr Lewis had observed increasingly in the years since the war, not only by the Conservancy but by private and public landowners. It would appear from general observation that this activity, although undoubtedly beneficial from the point of view of agriculture and cattle-raising, was producing many problems in regard to the water resources of the country, to short term flooding and to bank erosion.

Mr Colin Allsebrook (A.M.I.Mech.E. Managing Director of Guthrie Allsebrook & Co. Ltd, Water Supply and Irrigation Engineers, Reading) called attention to the fact that nothing had been said about groundwater re-charge in times of flood and there seemed to be a considerable possibility of putting some of that flood-water back into, say, the Kennet Valley. At Arborfield, near Reading, they had put down a borehole with a 12-in. casing pipe going down 220 ft through the clay to the chalk. During

boring operations the river Loddon flooded and water from it ran down through that borehole into the chalk at a great rate. The River Loddon ran mostly over clay, but it also had a feed from the Blackwater, which ran out of Bagshot sands; and the interesting point there, on which the Author might care to comment, was the way in which this maintained a flow of 3 in. over a 50-ft weir all through the dry periods. There was always that basic flow, but the clay hinterland towards Basingstoke brought rapid floods and therefore the possibility of groundwater re-charge, which could also be practised in the Kennet Valley with great effect.

220. There was another question on which it would be of interest to hear further comments. When the ground was wet in the summer, was there greater percolation? Mr Allesbrook suggested that, if one maintained the moisture in the soil by artificial irrigation, it might in fact help the percolation of natural rain and the ultimate store of water in the ground. It seemed from the Paper that summer rain falling on dry soil tended to run-off or evaporate rather than to percolate.

The following contributions were received in writing:

Dr John Glasspoole (formerly Meteorological Office) asked if Mr Andrews was satisfied with the use of mean rainfall values based on twelve representative stations since these twelve rainfall stations had changed during the period and have not always been as shown in Fig. 1.

222. Daily means of twenty-four stations were available, certainly since 1911, and these means represented the rainfall over the area rather better than means of twelve stations. Even more reliable *monthly* values were available since 1906, prepared by plotting all the rainfall values over the area and obtaining the mean by the cartographical method. These were published in the annual reports of the Metropolitan Water Board. The best *daily* values would therefore be obtained by adjusting the daily means of the 24 stations to give the monthly totals obtained by the cartographical method, the adjustments being made mainly to the values for those days where there were wide variations in the daily rainfall over the area.

223. It would be helpful to have some statement from the Author as to whether he had found the means of twelve rainfall stations sufficiently accurate for this purpose. This should give some guidance to workers on other areas, and also would be of help to those carrying out further work on *this* area. The value of the Paper would be increased if Mr Andrews gave some indication of the effects of the use of the cartographical estimates, which were often used, on the various workings in the Paper.

224. A comparison of the *monthly* means obtained from twelve stations, as given in Table 2, and by the cartographical method, had indicated that the difference on the average exceeded 0.10 in. in 3 or 4 months each year.

225. They exceeded 0.20 in. about one month each year; 0.30 in. once in 5 years; and occasionally there were differences of more than 0.40, 0.50 and even 0.60 in. On by far the greater number of occasions the mean of the twelve stations gave the greater value, but that was not always so and sometimes the mean of the twelve stations was smaller by 0.2 or 0.3 in. when local rains missed this open network of twelve stations.

Mr R. C. S. Walters (Senior Partner, Herbert Lapworth Partners) referred to § 26, observing that the true underground catchment was usually not only less than the surface catchment but also variable, so that the *exact* theoretical relationship between rainfall and run-off was not practicable.

227. He was very grateful to learn from §§ 30 and 31 that the second rainfall period gave an average of $1\frac{1}{4}$ in. more than the first period.

228. The most important aspect of the Paper to his mind was the appreciation and significance of underground water (Fig. 5). It had been customary for many Waterworks Authorities to say in evidence, when sinking a borehole in a river valley, that they

were not taking river water and sometimes went so far as to say that they did not want river water because it was polluted. Mr Andrews had shown very clearly that if they were not taking water that flowed in the river they would sooner or later be taking water which would at some time enter the river.

229. The greater part of the Thames catchment, composed of permeable chalk and Oolitic limestones, he considered to be a vast overflowing reservoir.

230. He had questioned the Author on several occasions if Teddington weir was practically watertight. However, he was satisfied from the evidence which the Author had produced that it was watertight, for if it did leak, his conclusions would be wrecked.

Mr T. B. Keavill (Assistant Engineer, Surrey County Council) wrote that in his Paper Mr Andrews referred to the systematic gauging of the river at Teddington Lock, which commenced in 1883.

232. In view of the fact that there were a large number of sluice gates of various sizes and methods of operation at the weir in addition to the lock gates, it must have been a complex operation to establish a basis for measurement. The problem is still further complicated by the fact that the river downstream of the lock was tidal and this presumably affected water levels upstream, particularly at high stages of flow.

233. It would be of great interest to all those who have contemplated similar problems elsewhere if Mr Andrews could say how these difficulties were overcome and whether the methods devised needed revision in later years.

Professor H. D. Ayers (Visiting Professor, School of Civil Engineering, The University of New South Wales, from Ontario Agricultural College, Guelph, Canada) observed that to further the exchange of information he would suggest that there was a need for simplification and standardization of dimensions and definitions in the writings in hydrology. He wanted to draw attention to certain examples in the author's paper in the hope that this complex subject of hydrology may be presented in a more simplified style in future papers.

235. The unit of discharge adopted by the Author was millions of gallons per day with cusecs and equivalent depth in inches being introduced later. A much simpler approach, particularly where relationships between rainfall and run-off were involved, was to use the equivalent depth over the catchment or portion thereof in inches or millimetres. The adoption of this system would have greatly improved the value of the literature and provided a simple basis for the comparison of different catchments.

236. The term "loss" is one which was somewhat abused in the literature on hydrology. Mr Andrews used the term to include evapotranspiration and catchment leakage. In other literature it was being used to include interception and soil moisture and ground-water accretion during storm rainfall.

237. In either case the term conveyed the sense of wastage. It depended upon one's point of view as to whether evapotranspiration by vegetation (an important physiological function in plant growth) was a loss, or whether streamflow was a loss. Engineers might benefit a great deal from the knowledge of other scientific disciplines such as biology, and therefore should not shrink from the adoption of a terminology descriptive of the actual physical processes involved in the hydrological cycle.

238. The use of common statistical terms to indicate the dispersion of estimates of discharge about observed values in multi-variable relationships would have added greatly to the argument that estimated values were in reasonable agreement with observed values. This of course was difficult when graphical correlations were used, but even so the standard error of estimate could be approximated and related to the mean and extremes of the observed values. This would have provided a valuable basis for the comparisons of the various correlation methods.

Groundwater discharge

239. The three methods outlined for determining groundwater discharge were based

on two premises: (a) that all the groundwater discharge was derived from the areas classified as pervious (1644 sq. miles) and (b) that the discharge measured in the few days of any month following "the requisite period without effective rainfall", was the average for that month.

240. Taking the second premise first, this would almost certainly underestimate the groundwater discharge for the month and for interpolated months. Groundwater discharge during periods of effective rainfall and even light showers would certainly be higher if only as a result of the reduction in the evaporative draft by riparian vegetation and from other areas of shallow water table. With the data presented it was not possible to assert positively the possible error involved in the procedure adopted. However, examination of Fig. 10 and the statement in § 112 to the effect that the proportion of storm rainfall which runs off was independent of rainfall intensity, would have led one to assume that the groundwater hydrograph should have indicated a peak on or about November 10 or 11, 1916, and that a large portion of the discharge above the groundwater flow was in the form of interflow with very little actual surface run-off. If the hydrograph of Fig. 10 was typical, estimates of groundwater flow were certainly too low.

241. The first premise would seem difficult to justify also, since certainly there would be regions of intermediate permeability, such as the 416 square miles of formations structurally classed as pervious, but stated by the Author to have contributed little to groundwater discharge, and the 444 square miles of mixed formations. Examination of Fig. 2 would indicate that certain pervious formations contiguous to so called mixed or impervious formations would not likely contribute to stream flow unless the latter areas had some capacity for transmission of water from higher chalk, limestone or Greensand areas. In that case the mixed and impervious areas would certainly contribute some of the rainfall on the surface, to groundwater discharge.

242. It appeared that what the Author had accomplished was to analytically construct a model system which in behaviour closely represented the flow of the Thames River at Teddington. But the model system with a low estimate of groundwater discharge, also had to assume that the groundwater contribution came from an area somewhat less than the actual area. In order to balance the observed and calculated elements of discharge the equivalent depth of direct run-off from the mixed and pervious areas was over-estimated.

243. The use of an analogous model in hydrology was a very useful tool in prediction studies for particular catchments but the model should not be applied to other areas, except with extreme caution.

Antecedent conditions index

244. The author presented an interesting approach to the calculation of the state of saturation of the pervious areas. Since the soil moisture status was a function of evapotranspiration, the use of monthly values of potential or actual values of evapotranspiration would have obviated the necessity for a series of A.C.I. versus rainfall and percolation curves for each month April through August, as illustrated in Fig. 8. He pleaded for the use of an approach involving actual physical processes.

Rock porosity

245. The porosity of chalk and limestone had been calculated as 2% and 5% respectively, apparently based upon the release from storage of 184 000 million gallons between February and September from an aquifer 25 ft deep by 1644 sq. miles in extent. The basis for determining the depth of effective storage in the aquifer would seem to be in error if it assumed that the aquifer was recharged to a depth of 25 ft throughout, or the elevation difference between the water table at river valley level and the watershed. The water table elevation at the stream would be reasonably stable throughout the year. If the well levels at Rockley were representative of those on the watershed one might assume a maximum range of about 50 ft under extreme conditions, or an average

over the chalk portion of the catchment of 25 ft. Could the Author clarify the method used in making the estimates?

Mr G. E. Hartley (Lecturer in Hydrology, Royal College of Science and Technology, Glasgow) requested the Author to supply other rainfall records, and the resultant hydrographs in support of § 114 which had no doubt been read with great interest abroad.

247. Mr Hartley had found that the unit hydrographs of Fig. 12 were reasonably consistent and that the 2-day graph (Fig. 12) operated upon by the storms of November 1916 (Fig. 10) gave peak floods of 5900 million gallons per day and 4400 million gallons per day.

Mr J. R. A. Garland (Chief Engineer, West Sussex River Board) was surprised that some of the contributors to the original discussion should have felt that it could be inferred from the figures given in the Paper that the land drainage work of the Conservancy could have affected the water supply position.

249. The figures quoted referred to the summer flows of the periods before and after 1910 but was there very much land drainage work carried out before 1930 and would this in any case have affected summer flows?

250. Several million acres of land in this country were dependent on efficient land drainage to maintain their effectiveness to produce food and it was partly to this end that the land drainage engineer designed his schemes. There was obviously a need to balance the needs of an area between the disposal of the surplus and the retention of the essential water and this the Engineer of a River Board endeavours to do remembering the country's need to eat as well as to drink.

Mr Herbert Addison (Consultant) wished to suggest that the significance of Table 8 of the Paper would be heightened if the figures of groundwater flow were to be set by the side of other records of Thames flow. This had been done in Table 16, which shows: (1) The daily average natural flow of the river at Teddington for the first nine months of the year 1959, (2) The daily mean discharge of groundwater (from Table 8 of the Paper), and (3) the daily average rate of abstraction of water, above Teddington, by the Metropolitan Water Board and other water companies.

TABLE 16

1959	Jan.	Feb.	Mar.	April	May	June	July	Aug.	Sept.
(1)	4657	2273	2523	2039	1253	792	656	585	368
(2)	1650	1850	1450	1300	950	650	500	450	350
(3)	247	235	247	273	270	280	287	252	187

252. These figures, which were all expressed in millions of gallons per day, revealed the important contribution that groundwater made to the total flow: without it, the water companies could not possibly abstract the supplies they needed. This contribution would have an enhanced value when increasing volumes of Thames water are pumped eastwards to the Lee valley and beyond.

253. With these comparisons in mind, readers might wonder whether the Author's *General observations*, §§ 94–98, did full justice to the storage capacity of the porous strata which yielded up the groundwater flow. Taking that to be 184 000 million gallons, it represented about one-third of the total annual flow of the Thames, and it was several times greater than the combined capacity of all the artificial storage reservoirs

in the Metropolitan area. In an exceptional year such as the year 1959, whose characteristics are indicated in the above Table, doubtless a still larger volume of water was delivered from underground storage. Could the Author say how much it was?

Dr J. C. Rodda (D.S.I.R., Hydraulics Research Station, Wallingford) wrote that perhaps no other river basin in the whole of the British Isles had been the subject of such a detailed long-term hydrological study as was made of the basin of the River Thames in Mr Andrews' admirable paper. It was hoped that other authorities would publish similar papers on the catchments under their control, when they were in a position to do so.

255. Because of the geological complexity of the Thames Basin and the large areas of pervious measures which it contained, it was fitting that a considerable part of the paper should have been concerned with the estimation of groundwater discharge. However the geological divisions were unlikely to be quite so clear-cut as Mr Andrews implied, due to local variations in lithology and the presence of glacial drift. Thus the estimates of area of the basin contributing to groundwater discharge in one case and surface run-off in the other might be a little different from those quoted.

256. Three methods of estimating groundwater discharge were presented in which graphical rather than statistical methods were employed. For comparisons of both the method and the results described by Mr Andrews, the 25 observed values for the groundwater discharge of March (Table 8) and the general rainfall of each month (Table 2), for the nine months preceding March were subjected to a multiple regression analysis by Dr Rodda. Nine linear regression equations were produced, the last four equations (containing terms representing the general rainfall for 6, 7, 8 and 9 months before March) having coefficients of correlation greater than +0.94. Of these four equations the following was the most significant:

$$Q_{\text{March}} = 100R_1 + 103R_2 + 76R_3 + 98R_4 + 81R_5 + 125R_6 + 48R_7 + 28R_8 + 10R_9 - 589$$

where Q_{March} = Daily mean of groundwater discharge in M.G.D. during March
 R_1 to R_9 = general rainfall in inches for the months from February to June preceding March

Coefficient of multiple correlation = +0.97

Standard error of estimate of Q = ± 14

257. The high degree of correlation demonstrates the satisfactory nature of the relationship, while at the same time the relative sizes of the coefficients of R indicated that there was no uniform diminution of the effect of rainfall with time, except during the summer months. Only a repetition of the analysis for the remainder of the year and for antecedent periods longer than 9 months would have allowed a complete comparison with Mr Andrews' results, but the relationship shown for March suggested that the groundwater discharge of any month needed to be related only to antecedent rainfall.

258. The long-term volumes of mean annual rainfall and run-off were given and their difference (19.25 in.) gave the mean annual actual evapotranspiration amount, assuming no changes in storage. These were the volumes of water taking part in the long-term water balance of the catchment, but it would be interesting to see an extension of Penman's¹⁵ short study of the monthly water balance of the Thames Basin to include the whole period for which there were records.

259. An investigation of the water balance type had formed part of the basic research programme of the Hydraulics Research Station¹⁶ for the last two years. A small portion of the Thames Basin in North Buckinghamshire was being employed as an experimental catchment to determine what factors control stream flow. An area of some 7½ sq. miles surrounding the headwaters of the River Ray formed a well-defined watertight catchment where measurements of rainfall, run-off, evapotranspiration and soil moisture changes were being made. It was hoped that an analysis of these water balance components and of the topographic and other characteristics of the catchment

would allow a rational determination of the factors which governed the flow of that part of the River Ray.

Mr Allard (Consulting Engineer, Guildford) remarked that, as the Paper would be for a number of years to come the leading subject of reference for anyone concerned with Thames Basin hydrology, its discussion could very suitably include a mention of Mr E. Gold's study¹⁷ of the relation between run-off and quarterly values of rainfall in the Thames Valley, based on 44 years of records.

261. As to the effect of land drainage on groundwater resources, he suggested that the exposures of the principal aquifers of the United Kingdom, e.g. the Chalk formation, were in general situated above valley level and were accordingly only rarely the subject of land drainage operations. Even as to valley land, did not the drainage of it tend to render it ready to absorb rainfall and so to render more uniform the run-off of that land? Views of this kind had been expressed elsewhere,¹⁸ even by a member of the Metropolitan Water Board staff!

The Author, in reply to Mr Cronin thanked him for opening the discussion, and said how pleased he was that Mr Cronin was still so actively interested in this subject.

263. Mr Bowen had come to the Author's rescue in replying to a number of his questions. In answer to the question as to whether the Author could forecast a dry year; as Mr Bowen had said, this would only be possible if the rainfall could be forecast, but it was possible, as a result of this hydrological study of natural recession of groundwater, to say as early as March in any year, what the *approximate minimum* flow would be in each month for the rest of the year, on the assumption that rainfall was going to be insufficient to give rise to percolation—that would be taking the most cautious view possible.

264. If the estimated groundwater flows for each month as given in Table 8 were plotted on Mr Cronin's Figs 16 and 17, it would be seen how little *surface* run-off occurred during many of the months, particularly the summer months. In view of the dry conditions, this was understandable, and the plottings would seem to confirm the reliability of the groundwater figures in Table 8 at least for this period.

265. The Thames has been gauged in all dry weather periods from 1921 and the summation of gaugings of all the tributaries has agreed so closely with the recorded discharges at Teddington weir under these stable low flow conditions as to suggest that there was no significant leakage through the weir.

266. Mr Cronin had compared the flow in the two 5-month periods before and after 1907, and wondered whether land drainage operations would result in still lower summer flows in the future. The Author however did not see how such a charge could be laid at the door of land drainage engineers, since their operations did not begin seriously until sometime after the passing of the Land Drainage Act in 1930. Dry weather discharge is almost wholly derived from pervious areas in which little or no land drainage works have been carried out. The suggestion that such works may affect the flow of rivers was fully considered in 1951, in the Report of the Land Drainage Legislation Subcommittee (the Heneage Committee) of the Central Advisory Water Committee.

267. The close relation found between rainfall and flow in each of the 76 years, if the antecedent conditions indices and other factors discussed in the Paper are allowed for, does not suggest that there have been any factors other than natural ones that have influenced the flow of the Thames in the period, except perhaps the discharge of effluents, which have tended to maintain higher minimum flows in recent years.

268. With regard to Mr Cronin's comments upon the drying out of watercourses in 1944 and 1959, it would be unwise to make too rigid a comparison, as it might well have been that other watercourses found to be dry in 1959 were not inspected in 1944.

269. The figures were given to enable a general picture to be formed of the effect of drought years. The Author would, however, think that a greater length was dry in 1959,

having regard to the antecedent conditions index on 1 October, 1959, being 59%, compared with 91% on 1 October, 1944, as given in Table 5.

270. The Author was grateful to Mr Bowen for answering some of Mr Cronin's questions. All aspects of the Paper had of course been discussed between them, many times over, and Mr Bowen's guidance and advice had been valuable.

271. The Author readily agreed that the unit hydrograph technique was not generally applicable to Teddington, having regard to the size and to the topographical and geological complexity of the catchment.

272. The object of computing the depth of run-off from such a very large number of storms and of comparing the results with observed figures was to test the validity of combining an antecedent precipitation index with an antecedent conditions index to give a realistic assessment of the state of saturation or soil moisture content of the catchment.

273. Having found such close agreement between computed and observed figures in the majority of cases, the Author was tempted to indulge in the unit hydrograph technique!

274. The analysis of data, carried out in the preparation of the Paper, would not have been possible had the records of flow, rainfall etc. not been assembled and analysed with such care over the past 79 years.

275. Professor Dooge had suggested that the method could be improved by employing expressions for evapo-transpiration in lieu of percolation. The Author having examined the "loss" (mainly evapo-transpiration) in 60 catchments, came to the conclusion that as run-off was so much more closely related to rainfall, it would be preferable to attempt to express the state of saturation or soil moisture deficiency of the catchment in terms of antecedent conditions indices derived from actual rainfall, in comparison with conditions resulting from standard rainfall.

276. By employing these indices in estimating not only direct or storm run-off but also groundwater, good agreement was found between observed and computed discharges.

277. Professor Dooge had made a most interesting comparison between low flow on the Thames, and the theoretical distribution suggested by Gumbel, in which the time element is essentially present—the longer the record the worse is the extreme case.

278. A point worth mentioning is that the activities of man have upset the natural processes of recession where effluents derived from deep well pumping are discharged to a river. They probably diminish with the advance of drought. To what ultimate value who can say? They may, and in fact do on the Thames and many of its tributaries, set a minimum to the flow which is above nature's minimum, and the effluent discharges are increasing year by year.

279. Plotting theoretical droughts on extremal probability paper in order to estimate the probable extreme (lowest) value when there is a proportionately large and disturbing element in the form of effluent, could in such cases be very misleading.

280. The choice of the number of consecutive low flow days, weeks or even months must be made prior to such an estimate, as the period will depend upon the purpose for which the estimate is required. It is doubtful whether the theory of extreme values could be applied where the period required exceeds a limited number of days.

281. With regard to the storage delay constants given by Professor Dooge, it should be possible to obtain more data for the Oolites in future, as the Conservators are proposing to instal a weir to measure the flow of an important Cotswold river deriving its discharge almost wholly from these formations.

282. It was gratifying to learn that Professor Dooge agreed exactly with the Author's estimate of the amount of percolation from rainfall in June which reached Teddington within the water year.

283. With regard to July and August, he would favour using Professor Dooge's figures of 60% and 45% as against his own of 50% and 25% arrived at in a rough-and-ready way from digressions from natural recessions. However, the amount of percola-

tion in these months is small, and the total summer percolation figures given in Table 6 would not be materially affected.

284. Professor Dooge asked that the monthly rainfall and surface run-off figures for Teddington be given to help others adopt the Author's methods. The former are given in Table 2 and the latter can be obtained by deducting the figures for groundwater flow in each month given in Table 8, from those of natural flow now shown in Table 17.

285. Dr Prus-Chacinski had referred to the Author's estimates of long term mean annual losses in 60 basins in Great Britain, and to the losses obtained by deducting run-off from rainfall given in Table 10. Having regard to the difference in the mean annual rainfall on the pervious and impervious areas above Teddington and Day's in Table 10, the losses are not dissimilar, though it would appear that surface run-off from the catchment above Day's exceeds that for the area above Teddington (which of course includes that above Day's) by about one inch. The Author had wondered if the explanation lay in the fact that much of the impervious areas, the *lias*, above Day's, lay in the steep Cotswold Hills. However, having computed the storm-water (surface) run-off at Day's weir from 125 separate hydrographs, it appeared that surface run-off per unit area from the *pervious* areas was greater than it was per unit area from all the *pervious* areas above Teddington. This was evident when employing the coaxial diagram Fig. 11 for Day's weir. Only by taking an area, not of 854 sq. miles of impervious formations, but a total area of 1100 sq. miles as contributing to storm run-off at Day's weir, did the computed depth of run-off agree satisfactorily with that measured from the hydrographs, under the conditions described in § 61 (i.e. a saturated catchment and high rainfall). He was inclined to prefer this explanation, particularly as it would account for the lower yield from the *pervious* areas above Day's weir, as seen in Table 10, as compared with that at Teddington, taking the difference in mean annual rainfall into consideration.

286. As long term losses appear to vary so little over a wide range of long term mean annual rainfalls, it would probably have been better to have given the expression for the rainfall/run-off relation shown in Fig. 13, namely:

$$\text{Run-off in cusecs} = 5\sqrt{86.3 + 0.64\left(R - \frac{R}{20}\right)^2} - 49.6$$

instead of that for loss given in expression (6).

287. Dr Prus-Chacinski's interesting comparison between the 60 rivers graph and Dr Penman's figures for losses suggests that, with a sufficiently long period of observations, there is reasonable agreement.

288. With regard to granite catchments could it be that, with its unusually shallow soil cover, potential evaporation is low, as suggested by Lloyd?

289. Mr Appleby's comments upon the Author's treatment of surface run-off recession at Teddington in the absence of further rainfall, and his supporting argument, have been studied with great interest.

290. It was stated in the Paper that this recession appeared to be unaffected by the groundwater flow until discharge had fallen to about bank full value (4500–5000 m.g.d. at Teddington), and that storm run-off after this was promoted by discharge of water stored mainly in the channels carrying this storm water, between the stages corresponding with this value and the levels obtaining after this discharge had substantially ceased.

291. At this point it would be well to define the meaning assigned to the term "Groundwater flow", as it would appear that conflicting nomenclature in this connexion may have given rise to misunderstanding.

292. The Author has not attempted separation of surface run-off and "interflow" (i.e. sub-surface flow) associated with a particular storm. Consequently the stated values of groundwater flow refer to river discharges quite independent of any form of run-off from the immediately preceding storm, and are in fact the long term residues of (possibly) nine or more months' antecedent rainfall.

293. Mr Appleby on the other hand appears to have visualized a combined recession

TABLE 17: DAILY AVERAGE NATURAL FLOW (IN MILLIONS OF GALLONS) OF THE RIVER THAMES AT TEDDINGTON FOR EACH MONTH AND YEAR DURING THE 77 YEARS 1883-1959

Year	Jan.	Feb.	Mar.	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Annual Daily Average	Year
1883	3,926.7	6,298.1	2,417.3	1,441.6	1,227.8	824.7	780.0	613.1	650.8	1,153.7	2,007.8	1,550.8	1,879.1	1883
1884	1,635.3	2,526.4	2,026.2	1,275.2	807.6	611.1	494.5	377.7	408.9	391.9	409.3	917.8	985.2	1884
1885	913.0	2,660.9	1,900.4	1,050.6	931.1	658.8	397.9	308.0	475.8	690.6	1,916.3	2,318.1	1,174.8	1885
1886	2,939.4	2,598.8	1,417.5	1,783.7	1,952.1	1,216.1	690.7	598.3	484.0	745.2	1,744.8	2,801.4	1,575.6	1886
1887	4,353.7	2,040.2	1,479.2	1,046.0	794.7	841.6	401.6	341.0	413.0	419.5	808.4	953.9	1,154.7	1887
1888	824.3	749.4	2,344.0	1,855.2	960.2	706.3	1,098.6	1,083.4	614.4	560.1	1,783.5	2,464.8	1,251.7	1888
1889	1,944.8	2,560.6	2,269.4	1,894.0	1,525.0	1,081.4	672.3	556.5	477.8	688.2	959.4	1,131.4	1,305.4	1889
1890	1,769.8	1,748.2	1,100.2	903.1	694.8	469.7	842.1	490.2	392.8	374.0	524.1	452.7	808.6	1890
1891	924.3	1,212.8	1,001.5	694.2	581.3	481.1	343.3	517.8	648.9	3,404.9	2,850.4	3,956.0	1,390.0	1891
1892	2,488.9	1,821.6	1,358.2	883.4	648.7	500.5	468.1	450.7	475.4	916.4	2,152.5	1,732.5	1,156.1	1892
1893	1,657.3	3,023.9	2,260.4	922.0	621.5	439.8	395.4	348.7	298.3	493.7	505.7	1,080.8	992.4	1893
1894	1,492.8	1,805.0	1,696.6	901.9	697.3	720.3	471.2	539.1	527.5	896.3	6,451.2	3,163.1	1,606.0	1894
1895	3,673.4	1,954.4	1,767.2	1,313.0	810.1	467.6	462.0	462.8	373.0	494.0	1,478.6	1,844.7	1,256.5	1895
1896	1,408.0	939.9	1,711.6	893.0	535.8	468.1	326.0	334.7	959.3	1,663.6	1,264.1	2,520.8	1,088.2	1896
1897	2,782.8	3,844.9	3,381.6	1,900.1	1,038.0	886.1	597.6	519.1	656.2	586.2	596.4	1,256.9	1,490.0	1897
1898	1,648.5	964.5	784.9	520.8	958.0	550.4	317.4	272.0	213.9	411.2	851.1	1,625.1	760.6	1898
1899	2,874.5	3,258.2	1,207.7	1,045.9	667.0	370.6	300.1	231.5	273.9	384.4	1,039.6	587.8	1,005.4	1899
1900	2,330.1	4,272.3	2,704.8	1,274.9	841.5	569.9	384.5	373.1	325.7	342.6	515.5	996.1	1,225.6	1900
1901	2,017.4	1,226.8	1,535.5	2,000.5	873.9	446.3	398.5	342.3	336.3	374.2	357.7	829.0	893.3	1901
1902	1,199.4	667.7	1,028.3	752.2	573.4	773.9	352.9	383.3	387.4	377.5	486.5	920.3	659.1	1902
1903	1,974.4	1,049.0	2,225.2	1,207.6	2,399.9	3,397.3	1,422.1	1,229.9	1,019.2	3,522.5	3,351.9	3,646.3	2,212.8	1903
1904	2,817.3	6,615.2	2,534.2	1,420.1	1,217.2	918.8	547.0	504.7	449.9	399.9	497.1	903.2	1,549.3	1904
1905	612.7	477.5	1,841.4	1,125.7	568.4	661.1	386.5	322.5	365.1	309.3	855.9	926.9	705.8	1905
1906	3,225.6	2,111.1	1,619.2	914.5	687.4	445.4	386.5	266.8	248.2	507.6	1,608.2	1,241.1	1,100.2	1906
1907	1,743.7	1,356.1	930.2	1,340.3	964.1	694.4	459.7	428.4	348.5	896.9	1,637.8	4,093.5	1,242.8	1907
1908	2,450.1	1,389.8	1,286.3	1,192.1	2,677.9	1,085.4	727.8	522.3	670.1	599.1	567.2	966.0	1,321.8	1908
1909	1,173.4	742.8	1,655.3	1,053.9	669.0	923.6	684.6	506.2	449.8	1,833.7	1,384.8	3,100.1	1,187.4	1909
1910	2,529.0	3,508.9	2,435.4	1,353.2	979.4	1,148.8	795.3	588.8	500.8	665.7	1,595.4	5,064.2	1,756.2	1910
1911	2,657.0	1,443.0	2,033.2	1,346.9	1,021.6	669.7	436.3	322.7	356.8	469.6	864.5	3,175.4	1,236.0	1911
1912	4,177.6	3,351.7	3,879.7	1,886.3	1,178.2	1,033.4	737.4	1,268.9	1,235.1	1,555.1	2,057.9	3,146.9	2,125.2	1912
1913	4,221.8	3,036.6	2,271.6	2,246.7	2,660.8	1,079.1	792.5	459.6	526.6	772.1	1,211.6	1,023.4	1,685.5	1913
1914	867.7	2,173.3	3,255.6	1,791.0	968.2	685.6	583.6	500.0	385.1	487.1	709.9	3,554.3	1,328.0	1914

Year	Jan.	Feb.	Mar.	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Annual Daily Average	Year
1943	3,386.7	4,038.0	1,473.1	923.6	825.1	525.2	382.9	338.5	345.9	466.6	474.8	641.1	1,134.5	1943
1944	834.5	750.2	519.8	571.8	346.5	256.7	268.0	214.3	289.4	554.1	1,991.2	2,284.7	739.6	1944
1945	1,533.0	3,272.2	1,257.7	806.4	664.0	484.6	474.9	340.0	366.8	580.0	496.5	1,222.7	943.8	1945
1946	2,094.4	2,652.6	1,602.8	932.0	933.6	885.2	501.2	596.2	1,612.9	794.5	2,366.9	3,933.4	1,568.0	1946
1947	3,088.6	2,138.5	7,049.0	3,739.0	1,649.8	961.7	742.2	456.9	427.2	423.2	457.7	560.9	1,809.7	1947
1948	1,557.9	1,928.2	837.1	875.6	677.1	791.5	414.4	534.4	470.6	653.4	945.3	1,741.8	948.9	1948
1949	2,383.5	1,437.0	1,389.4	912.1	628.2	436.7	275.4	240.3	250.9	978.1	1,763.6	1,541.1	1,018.2	1949
1950	937.2	4,120.0	1,639.6	1,168.6	1,063.7	584.5	638.4	470.8	675.9	743.9	2,396.5	2,637.6	1,403.3	1950
1951	4,168.1	5,050.5	4,456.3	3,930.4	2,254.9	1,264.5	765.6	751.6	910.0	722.2	4,116.7	2,691.5	2,570.3	1951
1952	2,701.2	2,050.4	2,315.8	1,907.7	1,668.5	850.6	526.6	564.9	458.6	806.3	1,496.2	3,186.5	1,545.7	1952
1953	2,227.0	2,086.3	1,188.2	1,103.4	867.0	541.5	451.1	419.7	486.2	647.6	1,303.8	713.9	995.6	1953
1954	954.4	1,863.5	1,958.4	1,354.5	862.5	1,526.3	726.6	816.0	640.3	773.3	2,921.8	4,734.4	1,591.9	1954
1955	3,327.4	2,495.5	1,777.2	1,305.4	1,560.1	1,645.2	690.5	498.9	456.0	641.7	765.6	1,041.6	1,344.4	1955
1956	2,053.8	2,010.2	1,141.7	920.1	598.6	513.3	549.7	542.7	945.6	907.4	611.5	1,609.0	1,031.4	1956
1957	2,309.1	3,929.6	2,283.2	1,217.0	842.0	510.5	580.0	556.9	604.8	655.2	1,558.9	1,842.7	1,391.5	1957
1958	2,630.4	3,240.5	2,267.9	1,739.3	957.0	1,152.6	831.4	819.3	1,263.9	2,651.9	2,651.4	2,841.7	1,912.1	1958
1959	4,656.8	2,272.9	2,523.5	2,039.2	1,253.5	792.1	655.7	585.4	367.7	428.7	635.7	2,065.6	1,523.1	1959
35years' Average (1916- 1950)	Daily Flow	2,840.3	2,733.9	2,336.0	1,806.5	884.0	662.9	620.1	667.5	899.1	1,661.1	2,158.1	1,537.8	General Daily Average
	Per- centage of Rain- fall	55.2%	66.4%	68.9%	45.0%	26.8%	14.0%	13.9%	14.9%	17.5%	28.9%	42.9%	34.5%	Average Percent- age of Rainfall
77years' Average (1883- 1959)	Daily Flow	2,623.6	2,586.4	2,167.6	1,586.7	862.2	623.8	573.8	599.2	881.7	1,574.0	2,137.1	1,443.4	General Daily Average
	Percent- age of Rainfall	56.5%	64.1%	60.7%	45.3%	23.2%	14.2%	12.4%	14.7%	16.7%	29.3%	41.0%	33.1%	Average Percent- age of Rainfall

of true surface run-off and interflow, both occasioned solely by the storm in question, with the surface run-off factor terminating on the attainment of the Author's stated "groundwater flow", but with continuance of interflow yield down to a " ϕ base flow", which contains no storm contribution.

294. In fact a confusion of terms has arisen, the Author's 'Groundwater flow' being synonymous with Mr Appleby's " ϕ base flow", whereas Mr Appleby assigns the former term to a combination of storm-derived interflow and a base (ϕ) flow associated with long term antecedent rainfall.

295. The Author's contention that the volume of storm run-off below 4500 m.g.d. given by the sub-area of the recession curve above the groundwater ordinate (Mr Appleby's " ϕ base") is sensibly constant for all values of the latter, would now appear to be acceptable, as it refers to the volume of all residual storm-water on the catchment below a specific stage.

296. Since natural recession flow is observed as being sensibly unaffected by the value of this groundwater ordinate until confined within banks, it follows that this residual volume is defined solely by the physical characteristics of the basin, and is independent of any other factor.

297. After clearing the air in this way, Mr Appleby's analysis of surface run-off recession presents aspects of great interest, and appears to go a long way towards solving the very difficult problem, unattempted by the Author, of separating surface run-off from interflow. His flood wave diffusion theory merits detailed study as a tool of potential value to the hydrographer.

298. With regard to the flat spot noticed by Mr Appleby in Fig. 10, the Author found many similar instances in the hydrographs examined. They were particularly evident where rainfall had been much heavier, in the west and north west part of the catchment, and this suggests that the "flat spot" may be occasioned by the arrival at Teddington of unusually heavy contributions to flow from those areas. However, the "flat spot" in Fig. 10 might well be due to variations in flow created by tackle movement, as it occurred at the time when weirs would generally be closing in.

299. Dr Ineson had compared the yield of the chalk areas with that of the Jurassic Clays, expressed as a percentage of the total flow. The Author would prefer to express the yield as equivalent run-off per square mile of pervious area as shown in Table 10. It will be seen that the run-off per thousand acres above Day's Weir is only 0.12 cusecs less than above Teddington, and when expressed in equivalent mean annual run-off in inches, it is 10.94 in. above Day's from a mean annual rainfall of 28.95 in. compared with 11.84 in. from a rainfall of 29.47 in.

300. The lucid explanation by Dr Ineson of the movement of water through permeable soils under different conditions of moisture deficiency is, in the Author's view, a most valuable contribution. It is not always appreciated that the most impermeable medium encountered was water itself.

301. With regard to surface run-off from pervious catchments, estimated as described in paragraphs 61 to 63, this formed, when it occurred, an integral part of the storm hydrograph, and since the coaxial diagram (Fig. 11) was derived empirically, it allowed for run-off from pervious areas, when the conditions described by Dr Ineson in § 183 were present.

302. The Author is grateful to Dr Ineson for drawing attention to the misnomer in referring to the porosity of the chalk instead of to its specific yield. It was gratifying to the Author to find that his figure of 2% agreed with average values under the conditions obtained by pumping-test techniques.

303. Dr Ineson has drawn attention to the numerical difference in mean values of groundwater and surface discharge given in Table 10. For strict comparison, it is necessary to adopt the same period of records, whereas Dr Ineson has compared the 21-year-period 1938/9 to 1958/9 at Day's weir with the 76-year period at Teddington. An exact estimate of areas contributing to groundwater and surface flow is not possible when dealing with a basin the size of the Thames, but the figure of 1644 square miles of

water bearing formations giving an equivalent mean annual run-off of 11.7 in. and "losses" of 17.67 in. over the 76-year period, were not considered unreasonable. The surface run-off from these formations averaging 0.9 in. per annum are not included in the above figure of 11.7 in., but in the figure of 8.15 in. immediately below it in Table 10, for this forms part of the run-off arising from individual storms.

304. In answer to the question whether or not the loss of chalk groundwater flowing towards the centre of the London basin could be regarded as significant in the Author's analysis, he did not think it could. The uplift in the chalk formation at Windsor, the flatness of the upper surface where lying beneath the tertiaries and the flatness of the water contours suggested that there was little contribution to the London basin from the west, while to the north and south of it pumping had intercepted any appreciable flow that might once have taken place.

305. In reply to Dr Sutcliffe, the formula in § 52 gives total percolation derived from total winter rainfall following standard soil moisture conditions (A.C.I. 100%) at the beginning of the winter. The considerable influence upon percolation and thus upon groundwater flow when antecedent conditions are far from standard can be seen from an examination of the A.C.I. influence lines shown in Panel 4 of Fig. 6. The following Table sets out the amount in inches to be deducted from or added to percolation obtained from the above formula when antecedent conditions are below or above standard on 1 October in any year, on the basis that one inch of percolation is equivalent to an annual average of daily mean discharge of groundwater of 65 m.g.d. at Teddington.

TABLE 18

A.C.I.	From or to percolation	Inches
50	Deduct	3.5
60	"	2.8
70	"	2.1
80	"	1.4
90	"	0.7
100	—	—
110	Add	0.6
120	"	1.2
130	"	1.8
140	"	2.4
150	"	2.9

306. The Author, having prepared this Table, wished to check its validity against actual observations of soil moisture. He therefore carried out such observations from October 1959 to 1961, taking samples at every 4 in. depth down to 6 ft, through old pasture, loam and London clay. Rainfall records for the area were observed from a rain gauge on the property, and new trial holes were dug on each of the 37 occasions when samples were taken. Soil moisture deficiency at the end of the 1959 drought was found to be 7.1 in. (with A.C.I. 59%), compared with a normal deficiency of 4½ in. following standard antecedent conditions (A.C.I. 100%). The relation between the A.C.I. and the soil moisture content is shown in Fig. 20 for the winter months. The soil did not reach field capacity until the third week in December, 1959, although run-off commenced on 6 December, following a total rainfall of 1.0 in. on the 5th and 6th.

307. As a further check upon the reliability of the formula for winter percolation, the Author prepared rainfall/percolation graphs for each winter month adding also September, since this was not included in Fig. 8. The A.C.I. was worked out for each month from the actual 9 months' antecedent rainfall. From the graphs shown in Fig. 21 the percolation in each winter month of the 76 years was obtained. The total for each of the 6 winter months differed from that obtained by the above formula (with the appropriate deduction or addition given in Table 18) by less than about ½ in. in all but

six years, when the difference in those years was about $\frac{1}{2}$ –1 in. At the beginning of these water years, the A.C.I. was very low, but it was particularly high in the late winter months, pointing to the possibility that the graphs for individual months are more reliable than the formula giving total percolation for six winter months.

308. With regard to the family of curves in Fig. 7, these were prepared from a large number of natural recessions, with widely differing initial values (between 1000 m.g.d. or more and 300 or 400 m.g.d.). The upper curve would in fact suffice, all others being portions of this curve.

309. The Author agrees that more observation wells, especially near the rivers, are desirable and these are being brought into use. He also agrees with Dr Sutcliffe that at present there are far too few records of rainfall and run-off for areas having mean annual falls of 70 in. and more, to enable the curve in Fig. 13 to be extrapolated beyond a rainfall of about 70 in., or the expression (b) in § 121 to be used with any confidence.

FIG. 20: RELATION BETWEEN A.C.I. AND SOIL MOISTURE CONTENT FOR THE WINTER MONTHS

310. The Author was indeed grateful to Mr Wolf for his kind comments upon the Author's endeavours to gain greater accuracy of prediction by extensive and tedious analysis of available data. He had expressed his agreement with the Author in some of the latter's theories and methods. They may well have been adopted as a result of the help and advice that Mr Wolf had been so willing to give him.

311. Mr Wolf had suggested that a geometrical progression of weighting factors could be substituted to reduce by about 90% the labour of computing the A.C.I. The labour was considerable, as some 30 000 separate calculations had to be made, to cover all months in the 76 years period for the Thames as well as all months from 1860 to 1875 to cover the percolation observations of Evans and Greaves. However, having done the spade work, calculations in future to obtain the antecedent conditions for any month, can be made in about 3 minutes.

312. The Author feels that any progression as suggested by Mr Wolf would require to be applied term by term to each month's rainfall during the period to which the progression applies, and allowance has often to be made in individual months for run-off to be deducted from total rainfall, where such run-off is in excess of the long term standard for the month.

313. Mr Cole had suggested that measurements of hydraulic gradient in the aquifers feeding the river would give the best and quickest forecast of groundwater discharge, and that readings of a sufficient number of well levels might enable such a forecast to be made. The observations of water levels in the well at Rockley near Marlborough since 1933 were plotted against the groundwater flows at Teddington, and the plottings of the average level and flow for the whole period to 1959, and for the years 1943/44

FIG. 21: RAINFALL/PERCOLATION GRAPHS FOR WINTER MONTHS

and 1947/48 are shown in Fig. 22. Within rather wide limits, using observations from only one well, it would seem to be possible to give an estimate of groundwater flow.

314. Mr Lewis had asked whether the Author had found that land drainage operations had affected the charging of aquifers and the peak rates of storm run-off. The Author had already given his views in reply to a similar question by Mr Cronin, but he would add that, as regards storm run-off, it is generally agreed that substantial local channel improvements may tend to increase the rate of discharge downstream, but river engineers are aware of this, and compensatory works are usually carried out downstream if considered necessary. There is no evidence to suggest that the proportion of rainfall that is run-off in any storm is increased as the result of land drainage operations.

FIG. 22: OBSERVED WATER LEVELS AT ROCKLEY PLOTTED AGAINST GROUNDWATER FLOWS AT TEDDINGTON

315. Mr Colin Allsebrook had called attention to the absence in the Paper of any reference to recharge. The methods of recharge by spreading water over permeable beds, or feeding it through pits, wells or boreholes have met with mixed success in this country, but they have been on a small scale. In most areas of the Thames Basin the permeable beds, where exposed, lie upstream of impermeable formations, so that storm water from the latter could only be introduced into the permeable beds where they lie, usually at considerable depths beneath these formations. Recharge for the relief of flooding would have to be on a large scale to be of real value, and might well be undesirable at a time when most needed for flood relief, owing to the water table already being at an inconveniently high level in the permeable beds.

316. With regard to percolation in the summer months, from Table 6 and including September, the total percolation from the 6 summer months in the 76 years amounted to about 73 in. out of a total rainfall of 1015 in., or an average of 0.95 in. per annum from a mean summer rainfall of 13.4 in. The effect upon percolation when the ground is wet can be seen from an examination of Fig. 8.

317. If the ground could be maintained in a saturated state during the summer months by methods such as irrigation or recharge, the conditions would be very similar to those obtaining in October, 1960, but these methods would have to be applied on a very large scale to have a significant effect upon groundwater flow. Only if the winter following turned out to be a dry one would they be beneficial. If it were a very wet one, they might be most harmful and might give rise to a great number of claims for damage!

Applied on a scale sufficient to make up for the additional soil moisture deficiency of about 2½ in. resulting from a severe drought they might usually be beneficial.

318. Dr John Glasspoole, in a written contribution had asked the Author if he was satisfied with the use of 12 rainfall stations. To enable him to answer this question, he had kindly supplied him with monthly rainfall figures in the Thames Basin since 1880, partly from 24 stations and partly obtained by the cartographical method. The Author had compared these figures with those obtained from the 12 stations averages, in all months when calculations of storm run-off at Teddington had been made. He found that there were significant differences only in January 1919 (12 stations 4·50 in.; 0·39 in. too high), January 1937 (12 stations 5·02 in.; 0·50 in. too high), February 1951 (12 stations 5·23 in.; 0·40 in. too high), November 1951 (12 stations 6·98 in.; 0·47 in. too high). Agreement between the computed and observed storm run-off on these occasions was so close as to suggest that the employment of the 12 stations average had no measurable effect upon the results.

319. The Author frequently had recourse to Dr Glasspoole's Paper "The Areas covered by Intense and widespread Falls of Rain".¹⁹ He had prepared from Dr Glasspoole's figures a curve showing the relation between rainfall intensity and areas covered, from which it appeared that the intensity increased rapidly for areas of less than about 100 square miles. Therefore it would seem that 12 rainfall stations were sufficient coverage for a large area like the Thames Basin, which has a smoothing effect upon falls over individual areas, but much smaller catchments require a proportionately higher number of rainfall stations, and in areas of a few square miles, a very intense fall may even then be missed altogether.

320. Mr Walters had stressed the importance of attempting to define the true underground catchment from a study of the underground water contours. He had, however, modestly refrained from drawing attention to his own valuable contributions to this subject, for example in "The hydro-geology of the chalk of England"²⁰ and in "The nation's water supply".²¹ These contributions have greatly helped the Author in his study. He was gratified to learn that Mr Walters accepted the view that Teddington Weir was reasonably watertight. Mr Walters would see that the Author had commented further on this question in his replies to Mr Cronin.

321. Mr Keevill had asked the Author for details of the methods of obtaining the daily discharge at Teddington Weir. Late in the last century, formulae were evolved for each set of sluices of varying types, based upon numerous gaugings. Both head and tail water levels are recorded continuously and the discharge is calculated each day from these records.

322. On each occasion that the weir has been altered, it has been recalibrated from current meter gaugings, and the formulae modified accordingly or new formulae introduced.

323. In high floods, when the weirs are fully drawn, the flow is obtained from a stage-discharge curve, the stage being read at low tide. The curve is checked at intervals by current meter gaugings.

324. During times of low flow, the whole discharge is passed over a 70 ft long sharp edged weir, which can be lowered to increase discharge. From the records of headwater and the appropriate formula, the daily discharge can be accurately obtained.

325. Professor Ayres justifiably criticized the variety of dimensions and definitions used in the Paper. Data for flow of the Thames at Teddington for the past 79 years has been given in millions of gallons per day, and those associated with its study have become so accustomed to this terminology that they are reluctant to change it! The natural flow of the Thames is made up of two elements, (i) the daily recorded discharge over the weir and (ii), the abstractions by the Metropolitan Water Board and Suburban Water Companies. The latter, as is often the practice of Water Undertakings, have always supplied the daily figures in these units.

326. With regard to expressing run-off in terms of equivalent depth, this the Author has done, both as regards groundwater flow and storm run-off. Expressed in this way,

however, it may be misleading where the *true* contributing areas are not accurately known.

327. The Author deliberately used the term "loss" within inverted commas, as he had appreciated that the term had a variety of meanings according to the context in which it was used. In river and water engineering, the accent is upon available run-off, so that "loss" is usually regarded as the difference between rainfall and run-off. The Author agrees that standardization of many hydrological terms is overdue.

328. With regard to groundwater discharge, there may again be a confusion arising as to the definition of the term, for the Author did not include interflow within this term, for interflow, whether it is derived from impervious, mixed or pervious areas with a shallow water table, arises mainly as a result of individual storms, and the comparatively long periods of recession of the storm hydrographs adopted by the Author from actual hydrographs suggested that this type of run-off had substantially ceased within these periods. The Author was only concerned with two forms of run-off namely:

- (i) That which resulted from an individual storm, and
- (ii) That which was derived from pervious water bearing formations as a result of many previous months of antecedent rainfall, and which could be counted upon as a steadier and more reliable form of discharge when run-off of the type given in (i) had ceased.

The Author must therefore admit that he thereby avoided the necessity of attempting to separate interflow by the only arbitrary methods that have been evolved.

329. While it would be impossible to suggest exact yields from each of the many formations within the basin, the Author was guided by a considerable amount of data from catchments consisting almost wholly of one type of formation or another. It was only after examining such data that it became possible to arrive at what was considered to be a reasonable estimate for the general subdivision of the basin into pervious, and mixed and impervious areas. When Table 10 was then prepared, using these subdivisions and the run-off estimated for each, it was encouraging to find how closely the equivalent run-off over a long period agreed with similar data for other rivers with less complicated geological patterns but with similar mean annual rainfalls.

330. The Author would agree that an analogous model in hydrology in one area should only be applied to another area with extreme caution.

331. With regard to the use of the A.C.I., it must be remembered that the Author did not have access to the necessary data (e.g. evapo-transpiration) to cover a period extending as far back as 1883. Only observations on percolation were then available and were used by him. Much work is now being done in this field of investigation in this country, and that carried out by the Author and described in his replies to Dr Sutcliffe's contributions would seem to lend some credence to the admittedly unscientific method of indicating soil moisture by an A.C.I. requiring no field observations.

332. In reply to Professor Ayres' request for clarification of the method used in making the estimates of the specific yield of the permeable strata, the Author felt that the average range of the water table in the well at Rockley gave a reasonable indication of the average between the nearest chalk river and the watershed. The range near the river is about 2 ft, and the well is situated nearly half way between the river and the watershed. The mean range in the well over a period of 27 years has been 23 ft.

333. Mr Hartley had found good agreement between the computed and observed peak discharges for the storms of November, 1916 (Fig. 10) and had asked for other rainfall records and hydrographs in support of § 114. Unfortunately space does not allow of inclusion of additional data here, but the Author, in noting Mr Hartley's request, would advise caution in using the unit hydrograph technique for predicting peak discharges at Teddington. Not only is the area greatly in excess of that to which the technique is applicable, but past records do not indicate whether rainfall, shown (say) as falling on two consecutive days, in fact fell within a period of 24 hours, partly on one day and partly on the next.

334. Mr Garland had expressed surprise that from figures given in the Paper, it could be inferred that land drainage work had affected the water supply position, and the Author would like Mr Garland to know that he shares his surprise, and agrees with him that a proper balance should be kept between the needs of an area for disposal of surplus and retention of essential water.

335. A water table that is too high is often worse than one that is too low. Where the former conditions exist through lack of drainage, plant roots become suffocated and stunted, and the plant is more subject to wilting in the event of rainfall deficiency. In the latter case, the roots penetrate to greater depths in search of water, and are less affected by drought. Furthermore, evaporation from water-logged land is higher than from well-drained land, so that neither the plant nor the river will get the benefit from it.

336. The Author is grateful to Mr Herbert Addison for demonstrating by his Table the importance of groundwater flow to meet the demands of Water Authorities. He had asked what the total volume of water delivered up in 1959 from underground sources amounted to. The Author estimates this to have been 275 800 million gallons by the end of September, and 316 475 million gallons by the end of the year.

337. The fall in the groundwater level in the well at Rockley between its peak in February and its lowest level in September as given in Table 3, was 40 ft, suggesting a specific yield of 1.9% as compared with an average of 2.0% given in § 97.

338. The Author agrees with Dr Rodda that no exact estimates can be made of the true contributing areas within the complex geological formations of the Thames Basin. The greater part of the glacial drifts overlying the chalk, as for instance within the valley of the Colne, has been eroded by the rivers, and water from these formations finds its way in large measure to the chalk, emerging in due course as groundwater flow. Such areas were generally included in the estimates of the pervious formations.

339. The method described by Dr Rodda of subjecting the groundwater discharge and the general rainfall to a multiple regression analysis, the Author found most interesting. In considering the effects of the A.C.I. upon groundwater flow, the Author would draw Dr Rodda's attention to the percolation graphs shown in Fig 20. It will be seen that the index diminishes in importance with the advance of winter. In Method II the total winter rainfall is taken, and the resultant percolation given by formula (1), in § 52, is adjusted only by the A.C.I., i.e. the soil moisture deficiency, at the beginning of the winter. This Index has for its first six months, which are the summer months, the highest weighting factors, the remaining three winter months, March, February and January being assigned the low factors of 0.379, 0.236 and 0.111 respectively. It will also be seen that the percentage correction factors on the bottom line of Table 4 for the winter months are only about 80% of those for the summer months.

340. The relationship between monthly averages of daily mean discharge and accumulated winter rainfall as shown in Figs 9 (a) and (b), which were evolved empirically, would also seem to accord with Dr Rodda's findings that groundwater needed to be related only to antecedent rainfall, provided of course that the soil moisture deficiency at the beginning of the water year is taken into consideration, as the Author has done by employing the A.C.I. at the beginning of October in each year, as represented by the influence lines in panel 4 of Fig. 6.

341. The Author hopes that it will be possible for Dr Rodda in due course to test the reliability of the methods described in the Paper against his findings in the experimental catchment of the River Ray and particularly the relationships between the A.C.I. and soil moisture deficiency given in Fig. 20.

342. Mr Allard had drawn attention to E. Gold's study¹⁷ of the relationship between run-off and quarterly values of rainfall in the Thames valley based on 44 years of records. The method described by Gold enables an estimate of run-off to be made for any 3 months' period assuming average rainfall in the quarter concerned.

343. The run-off estimated in this manner is total run-off, and therefore includes the two principal components of widely differing characteristics, "flashy" surface run-off and "sedate" groundwater flow. The Author sees no reason why Gold's method

should not be applied to each type separately. By introducing rainfall of corresponding quarters of preceding years, Gold is in effect applying weighting factors not unlike those used by the Author.

344. Mr Allard had kindly added the weight of his valued opinion to that expressed by other contributors, and by the Author, as to the effect of land drainage, for which he is most grateful, having himself been a land drainage engineer for many years!

345. In conclusion, the Author would like to try to answer the following question, which he has frequently been asked:

“How could the methods described in the Paper be applied to other rivers?”

FIG. 23: COMPARISON BETWEEN COMPUTED AND OBSERVED DEPTH OF RUN-OFF

346. These methods do not differ materially from those described by Linsley, Kohler, and Paulhus⁷ and used extensively in the United States on many types of rivers. What the Author has endeavoured to do is to introduce into this technique of flood forecasting a simple method for assessing the state of saturation of the catchment based upon actual antecedent rainfall related to standard rainfall.

347. Employing this technique for the Thames at Teddington, the extent of agreement between computed and observed depth of run-off in 470 cases examined is shown in Fig. 23, while in Fig. 24, computed and observed peak discharges are compared.

348. It is known that, on a number of occasions, the whole or part of the catchment was frozen and/or covered by snow. Furthermore in no instance was it known whether rainfall, credited to two days, did not in fact fall within a period of twenty-four hours.

Lack of better agreement may well be ascribed to such insufficient data, as no doubt also to failings on the part of the Author to apply correctly this technique from time to time. For that reason at least the Author is confident that others employing it may well meet with greater success.

349. However, the method of assessing the state of saturation of the catchment was found to give results sufficiently encouraging for it to be applied in estimating percolation and, as a result, ground water flow also.

FIG. 24: COMPARISON BETWEEN COMPUTED AND OBSERVED PEAK DISCHARGES

350. If the technique is employed on other rivers, it should be used with caution. Sufficient data must be available. Rainfall and flow records are necessary over as long a period as possible, but preferably not less than 20 years. Even this period may not have had within it a sufficient number of floods to enable the unit hydrograph for various rainfall durations to be developed with sufficient confidence; it being remembered that a unit hydrograph for one catchment may differ widely from that of another catchment having different characteristics.

351. Where a catchment consists predominantly of chalk, as is the case in much of south-east England, it is hoped that the methods described in the Paper will be applied to those rivers, in order that at least the annual averages and possibly even the monthly averages of the daily mean discharges computed by these methods may be compared with recorded figures.

REFERENCES

10. J. C. I. DOOGE. 'The routing of groundwater recharge through typical elements of linear storage'. Int. Ass. Scientific Hydrology. Helsinki, July 1960. No. 52, pp. 286-300.
11. H. L. PENMAN. Evaporation over the British Isles. *Quart. J. R. met. Soc.*, vol. 76 (1950), pp. 372-383.
12. F. V. APPLEBY. 'Run-off dynamics'. Int. Ass. Scientific Hydrology. Rome, 1954.
13. W. E. CLARKE. Forecasting the dry-weather flow of Pond Creek, Oklahoma. *Trans. Amer. geophys. Un.*, vol. 37, 1956, pp. 442-450.
14. CENTRAL ADVISORY WATER COMMITTEE. 'Land drainage in England and Wales'. Final Report of the Sub-committee on the Growing Demand for Water. Ch. 4, § 57, H.M.S.O., London, 1951. p. 26.
15. H. L. PENMAN. Components of the water balance of a catchment area. *Quart. J. Roy. met. Soc.*, vol. 81 (1955), pp. 280-284.
16. D.S.I.R. HYDRAULICS RESEARCH STATION. 'Hydraulics Research 1961'. H.M.S.O. London, 1962.
17. E. GOLD. 'The relation between run-off and quarterly values of rainfall in the Thames valley'. Int. Ass. Scientific Hydrology. Brussels, 1951. No. 34, pp. 235-236.
18. M. N. MEDRINGTON. Land drainage channel improvements and their possible effect on underground water. *J. Instn wat. Engrs*, vol. 8. 1954, pp. 483-488.
19. J. GLASSPOLE. The areas covered by intense and widespread falls of rain. *Min. Proc. Instn civ. Engrs*, vol. 229, part I, 1929/30, pp. 137-194.
20. R. C. S. WALTERS. The hydro-geology of the chalk of England. *Trans. Instn wat. Engrs*, vol. 34, 1929, p. 79.
21. R. C. S. WALTERS. 'The nation's water supply'. Ivor Nicholson and Watson. London, 1936.

CORRIGENDA

Proceedings, vol. 21, January 1962, Mr Andrews' Paper No. 6568, p. 81, § 108.

$$\text{For } -\frac{(t)^{2.5}}{(14)} \text{ read } -\left(\frac{t}{14}\right)^{2.5}$$

Fig. 9b (folding plate). Against 100% Antecedent Condition under 'March' column For 400 read 600, for 600 read 800 et seq. to 1,800 should read 2,000.

Table 9. Ref. Nos. 84 and 85. 'S' should be omitted against 1954.