Discussion.

Dr. Hogan.

Dr. HOGAN observed that the largest flood measured during the course of the work was 18,200 cusecs (p. 101) which was a surprisingly low figure, but in the Report of the Floods Committee [1] a figure was given of 40,000 cusecs, which had been measured in the year 1886 on a slightly larger catchment-area than Bewdley. The run-off for the 1886 flood had been 19·6 cusecs per square mile, which was 76 per cent. greater than the maximum of the present series of records.

Dr. Hogan then showed a number of lantern-slides illustrating the work described in the Paper.

Mr. Binnie.

Mr. W. J. E. BINNIE said that the published data with regard to river-flow in Great Britain were so scanty that the Paper would prove of very great value. Great Britain was almost unique amongst civilized countries in the apathy which had been shown by the Government in the past with regard to the collection of suitable statistics. The Land Drainage Act of 1930 had caused certain Catchment Boards to be set up and had made provision whereby further Boards could be set up. Those Boards were endowed with ample borrowing powers and they could undertake the systematic collection of statistics, and it was obvious that, arrangements having been made for obtaining all those statistics, some central authority should be set up whose duty it would be to analyse and publish them. The Government had recently appointed the Inland Water Survey Committee with that object in view. Water engineers had attempted in the past to collect information on the subject, and, whilst a good many authorities were quite willing to supply it, there were others who were very reluctant to disclose the figures in case they might be used against them at some future inquiry. He thought that it would be preferable that, although there was no doubt that a large number of statistics could be voluntarily collected, it should be made obligatory to furnish them. He understood that the Inland Water Survey Committee had no financial powers and that any expenditure incurred was met by the Ministry of Health. In paragraphs 29 and 30 of their Report last year, that Committee set out their intention with regard to the publishing of statistics. They themselves apparently proposed only to publish an annual report in which levels and occasional gaugings would be given, and that the Ministry of

[1] "Interim Report of the Committee on Floods in Relation to Reservoir Practice." Inst. C.E. 1933.

Mr. Binnie.

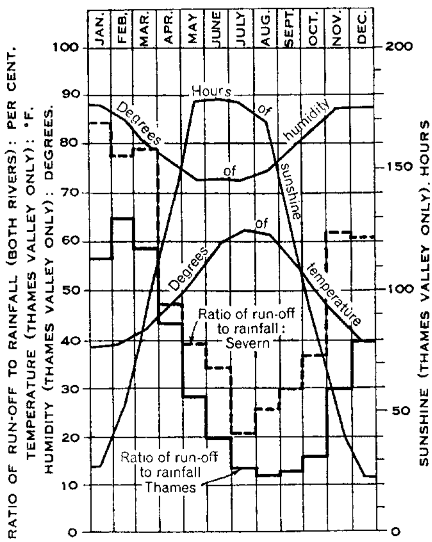
Health should be entrusted with the task of issuing about once a year Tables of actual volumetric measurements, which was the information engineers required.

Dr. Hogan had referred to the fact that during the period of gauging there had been no large flood on the river. It appeared that a flood of 17,400 cusecs had occurred in 1929, but that only represented about 17 cusecs per thousand acres of catchment-area. The highest discharge was given (p. 101) as 18,200 cusecs, and floods reaching 15,250 cusecs in 1922, 14,600 cusecs in 1924 and 16,100 cusecs in 1928 were also recorded. Those figures gave the impression that they referred to a flood which occurred every few years, and not, say, once in 100 years, for which provision should be made in reservoir-construction. The lowest dry-weather flow—200 cusecs—was very low for a catchment-area of the geological character and extent of that dealt with in the Paper, but he thought that the explanation was given on p. 84, where the Authors pointed out that it was probable that a considerable quantity of water might be lost to the river by percolation along the direction of its old channel, particularly at low stages of flow. The monthly run-off and rainfall given in Table I (p. 102), and in Table II (p. 104), were extremely useful; the average annual rainfall for the period from 1921 to 1936 was 38·14 inches while the run-off was 18·9 inches, giving a difference of 19·24 inches, the proportion of annual rainfall to run-off being approximately 50 per cent. The difference between rainfall and run-off depended not only on the amount of the rainfall, but also on temperature, prevalence of sunshine, humidity, the geological character of the drainage-area, the character of the vegetation, the steepness of the valley-slopes, and other factors. It was therefore an extremely complicated problem to deduce what the actual run-off would be from figures of rainfall, because those statistics were not available. They were, however, available in the case of the Thames as several observatories were situated in the area, records of temperature, hours of sunshine, and humidity being available for a period of many years. The effect of those factors was shown in *Fig. 21* (p. 116), which gave the monthly variation in the ratio of the run-off to the rainfall for both the Thames and the Severn, and also the changes of temperature and humidity, as well as the hours of sunshine. The figures of temperature and humidity, and the hours of sunshine, were for the Thames only, as there were no observations available for the Severn. The effect of sunshine, temperature and humidity on the ratio of the run-off to the rainfall during any month was clearly shown.

In the past, in the absence of actual gaugings, waterworks engineers had had to arrive at the run-off in the best way they could, and the practice before Parliamentary Committees had been to deduct from

Mr. Binnie. 14 to 16 inches from the average flow of the 3 driest consecutive years when questions of compensation water to the river were being considered. A curve had recently been put forward which had shown a direct relationship between rainfall and run-off, the difference between the two increasing with increasing rainfall. That might

Fig. 21.



River Thames at Teddington weir :
Catchment-area 3,789 square miles.
Average annual rainfall (1883–1900) 26·38 inches.
,, ,, run-off ,, 8·15 ,, (30·9 per cent.)
Loss 18·23 ,,

River Severn at Bewdley :
Catchment-area 1,632 square miles.
Average annual rainfall (1921–1936) 38·14 inches.
,, ,, run-off ,, 18·90 ,, (49.6 per cent.)
Loss 19·24 ,,

be true if the facts were similar in regard to temperature, humidity, and other questions affecting run-off at all places, but it was not true unless those conditions were exactly similar. In fact, such records as there were of the relationship between rainfall and run-off in regions of low rainfall which were situated to the south and east of England showed a much larger loss than places, say, in the Highlands of Scotland, where there was a very high rainfall but the conditions as to temperature and humidity were quite different. It was not until records of gaugings of rivers and streams were available that it would be possible all over the country to deduce the run-off with any degree of certainty when the rainfall was known. Fortunately, rainfall figures were given in *British Rainfall*, which had been started 77 years ago by the enterprise of a private individual, the late Mr. G. J. Symons; in 1919 the British Rainfall organization had been taken over by the Air Ministry, at first under the late Mr. M. de Carle Salter and then under Dr. John Glasspoole. As a result of that enterprise, excellent records of rainfall in Great Britain were available. Mr. Binnie.

Sir CLEMENT HINDLEY remarked that, as a member of the Inland Water Survey Committee, he might be able to give some information on the history of water-survey in recent years. Further, as a member of the Advisory Council of the Department of Scientific and Industrial Research, he had seen something of the work of the Water Pollution Research Board, which had for a long time been interested in the question of water-survey. Before doing so, however, he would point out that a special debt of gratitude was due to Professor Dixon for the work under discussion, extending over a period of 15 years, and he wished that Professor Dixon could have been present that evening. Sir Clement Hindley.

The importance of water-survey had been urged on the Government for a great many years. Commission after Commission had pointed out the lack of information in regard to water-resources throughout the country. One or two important steps might be mentioned in that connexion, and also one of the reasons why the Water Pollution Research Board was so interested in the matter. The Royal Commission on Sewage Disposal, which had sat from 1908 to 1915, had called attention to the need for more accurate information in regard to river-flow. They had pointed out that the degree to which it was necessary to purify sewage would depend on the dilution afforded by the river or stream into which the effluent was discharged, and that therefore it was of great importance that engineers and others connected with sewage-disposal should have information of that kind available. The particular side of water-survey connected with river-gauging had been taken up actively by the Department of Scientific and Industrial Research. The Authors, on p. 82, called attention to the fact that the Departmental Committee on the Gauging of Rivers and Tidal Currents had really supervised the work at Bewdley for 2 or 3 years, and that later the Department had supported it financially. Two very distinguished Past-Presidents of The Institution, the late Sir Maurice Fitzmaurice, C.M.G., and the late Professor W. C. Unwin, had served on that Committee, so that The Institution had been connected with the matter for a long time. The Govern-

Sir Clement Hindley.

ment had turned a deaf ear to most of the recommendations made. They had had the question of water-survey put before them as long ago as 1902 by the Royal Commission on Salmon Fisheries, and again by the Royal Commission on Sewage Disposal in 1908, as well as by the Canal and Waterways Committee of 1910, the Selected Committee on Water Supplies Protection Bill, 1910, and the Water Power Resources Committee of 1921. More recently the British Association at their meeting at York had appointed a special research committee to inquire into the position generally, and in 1933–34 The Institution and the British Association jointly had made a strong representation to the Prime Minister, which had resulted in a deputation headed by Sir Henry Maybury, then President Inst. C.E., and by Sir James Jeans, then President of the British Association, being received by the Minister of Health. The Inland Water Survey Committee had been appointed 2 years after that, and had, therefore, just started on its third year of work; he was glad to see that Mr. William Allard was present that evening, so that he would be able to answer some of the questions which Mr. Binnie had raised. The Inland Water Survey Committee was assisted by a very strong branch of the Ministry of Health, who were working whole-time on the subject. The work had really been divided up, broadly speaking, into three aspects: rainfall, survey of surface-water, and survey of underground water. For the section on rainfall the Committee relied on the British Rainfall Association which, as Mr. Binnie had said, had for many years made very complete records of rainfall. For the underground-water survey the Committee had the advantage of the services of the Geological Survey, and that work was being pushed forward in a very thorough manner. The surface-water survey depended on work that could be done by the Catchment Boards, and it was in that direction that more work was required. He thought that when the Committee's next Report was published, and when the first Annual Year Book was produced, it would be seen how the problem was being tackled. It was bound to be very incomplete at the start, because detailed and accurate records were wanting in many places, but the Committee hoped that those gaps would be gradually filled in.

He thought that the Paper was particularly interesting as giving a specific instance of practical work of river-gauging—one of the very few in Great Britain which might be said to be based on accurate and careful lay-out and scientific supervision. Another well-known example was the work of Mr. W. N. McClean. Those were outstanding instances of what could be done if the Catchment Boards could be persuaded to carry out the work systematically. Many of the Catchment Boards had records, and they were being made available to some extent, but a lot more work had to be done to institute the systematic taking of records. He hoped that Mr. Allard would be able to supplement what he had said and to give more details of the work which was actually being carried out. Sir Clement Hindley.

Mr. WILLIAM ALLARD, referring to Mr. Binnie's remarks, said that the intention was that the Statistical Year Book would be published by the Inland Water Survey Committee, and would not be published by the Ministry of Health as something independent from the Committee's reports. Mr. Allard.

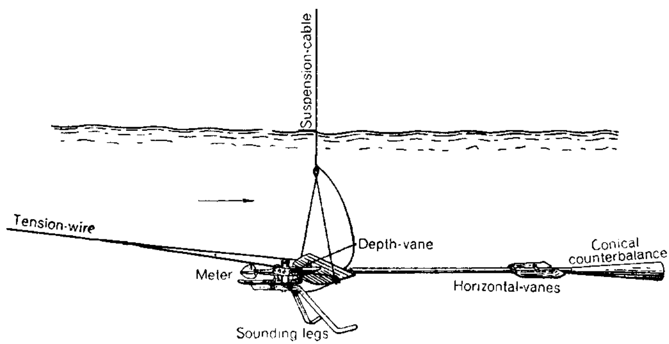
The Paper would be most useful to all who were likely to be concerned in the near future with establishing gauging-stations in Great Britain, although, as it pointed out, the methods to be adopted for any station were bound to depend upon the features of the river at that point. The reasons given for selecting the Severn for study served to illustrate the frequency with which English rivers were obstructed by weirs; they thereby offered to students of flow-measurement in Great Britain several interesting problems to investigate.

He had found, when taking current-meter measurements in the river Tigris, that it was necessary to use a 120-lb. weight suspended from the meter. American river-surveyors considered that their development of stream-gauging equipment could be divided into three periods: from 1888, with the inauguration of a definite gauging-programme, to 1903, dealing with the improvement of an existing current-meter; from 1903 to 1920, dealing with the invention of several water-level recording devices; and from 1920 to the present date, dealing with the development of equipment suitable for obtaining accurate soundings and velocity-measurements in deep swift water. The Paper related to the third period. American practice appeared to be to use as a sinker a heavy weight of as much as 150 lbs., but a well-known Bavarian instrument-maker had designed his meters so that the sinker could be added to the meter itself in such a way as to maintain the latter's streamlined form, the added weight being as large as 220 lbs. The use of such heavy weights had created a corresponding need for a strong suspensory cable and for the combination of that cable with that which conveyed the electrical current, so as to reduce the disturbance of the stream and the drag of the latter upon the cables. A suitable type of cable was made in Great Britain and had been used successfully for some years past in Egypt and Iraq. He thought that it was of the same type as that that the Authors had shown in their lantern-slides of the Severn. With designs of cableway such as that used by Mr. McClean in recent years in Great Britain, or those that the Bavarian maker constructed, the whole of the operation of the cableway could be effected from one

Mr. Allard. bank of the river without any trouble due to tangling such as the Authors mentioned. Such cableways were much heavier in all respects than the one used at Bewdley, whose portability might, perhaps, sometimes be very convenient.

A noteworthy device for utilizing the pressure of flowing water for causing the current-meter to sink was that of Herr Albrecht of the Bavarian Water Survey [1] (*Fig. 22*). The lengthy tail of the meter carried an inclined plate set at right-angles to the tail. The current pressed upon the upper face of the plate and accordingly tended to depress the meter. Underneath the meter was a device for indicating when bottom was touched by an electrical signal through the cable. Unless retaining lines, which were often far from easy to arrange, were used in conjunction with the cable-suspended meter,

Fig. 22.



ALBRECHT METER.

some drag of the suspension cable was bound to occur if the river were running strongly. The Authors had indicated the method used by them for correcting observed depths. The Egyptian method, a reference to which they quoted, related the correction to be used for any observed depth to the mid-depth velocity (Table V). An American method made the correction depend instead upon the angle of declination of the cable from the vertical at its point of suspension (Table VI, pp. 122 and 123).

The general constancy of the stage–discharge curve at Bewdley had been demonstrated by the Authors, but similar conditions could not safely be assumed for all other British rivers, or even for other stations on the Severn. Instances of variability of the relationship were known in the case of French and German rivers (*Figs. 23* and *24*, p. 124).

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[1] "Der Tiefensteuer-Schwimmflügel." *Die Wasserkraft*, 1925 (Part II).

Mr. Allard.

TABLE V.—CORRECTIONS TO OBSERVED SOUNDINGS.[1]

(Conical weight 48 kilograms, suspension 1·6 millimetre diameter.)

Mid-depth velocity: metres per second.	Observed sounding: metres.														
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
	Correction to be subtracted from observed sounding: centimetres.														
0·8	0	—	—	—	—	—	—	—	—	—	—	—	—	—	0
0·9	0	—	—	—	—	—	—	—	—	—	—	—	—	—	1
1·0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1
1·1	0	0	0	0	0	0	0	0	0	0	1	1	1	1	2
1·2	0	0	0	0	0	0	0	0	0	0	1	1	2	2	2
1·3	0	0	0	0	0	0	0	0	0	1	1	2	2	3	3
1·4	0	0	0	0	0	0	0	0	0	1	2	2	3	4	4
1·5	0	0	0	0	0	0	0	1	1	2	2	3	4	5	6
1·6	0	0	0	0	0	0	1	1	2	2	3	4	5	7	8
1·7	0	0	0	0	0	1	1	2	2	3	4	5	7	8	9
1·8	9	0	0	0	0	1	2	2	3	4	5	7	8	10	12
1·9	0	0	0	1	1	2	2	3	4	5	6	8	10	12	14
2·0	0	0	0	1	1	2	3	4	5	6	8	10	12	15	17
2·1	0	0	0	1	2	2	4	5	6	7	10	12	14	18	20
2·2	0	0	0	1	2	3	4	6	7	9	12	14	17	21	24
2·3	0	0	1	2	2	4	5	7	8	10	13	17	20	24	28
2·4	0	0	1	2	3	4	6	8	10	12	16	20	24	28	33
2·5	0	0	1	2	3	5	6	9	11	14	18	22	27	32	38
2·6	0	0	1	2	4	6	7	10	13	16	21	26	31	37	43
2·7	0	0	1	3	4	6	8	12	15	19	24	29	35	42	49
2·8	0	1	2	3	5	7	10	13	17	21	27	33	39	47	56
2·9	0	1	2	4	6	8	11	15	20	24	31	37	44	53	63
3·0	0	1	2	4	6	9	13	17	22	27	34	41	49	59	70

[1] *Reproduced from* "Handbook of Instructions for Discharge Observers in Egypt and the Sudan," p. 5. Cairo, 1929.

The Authors had shown (p. 94) how little was the comparative difference in results that occurred if the discharges of three-month periods were calculated in three very different ways. The same agreement of results would naturally not be obtained for shorter periods, as Table VII (p. 125) showed. He had prepared that Table in order to see how far, even if harmony could be attained in long-period results, there would be variation in the daily results. He had taken the records of three stations with drainage-areas of (X) 747 square miles, (Y) 187 square miles, and (Z) 17 square miles. The discharges had been worked out in the ways stated at the head of the Table.

Mr. Allard.

TABLE VI.—CORRECTIONS IN FEET TO REDUCE WET-LINE DEPTHS TO

Wet-line depth: feet.	Vertical angle in sounding line at							
	4	6	8	10	12	14	16	18
10	0·01	0·02	0·03	0·05	0·07	0·10	0·13	0·16
12	0·01	0·02	0·04	0·06	0·09	0·12	0·15	0·20
14	0·01	0·02	0·04	0·07	0·10	0·14	0·18	0·23
16	0·01	0·03	0·05	0·08	0·12	0·16	0·20	0·26
18	0·01	0·03	0·06	0·09	0·13	0·18	0·23	0·30
20	0·01	0·03	0·06	0·10	0·14	0·20	0·26	0·33
22	0·01	0·04	0·07	0·11	0·16	0·22	0·28	0·36
24	0·01	0·04	0·08	0·12	0·17	0·24	0·31	0·39
26	0·02	0·04	0·08	0·13	0·19	0·25	0·[illegible]3	0·43
28	0·02	0·04	0·09	0·14	0·20	0·27	0·36	0·46
30	0·02	0·05	0·10	0·15	0·22	0·29	0·38	0·49
32	0·02	0·05	0·10	0·16	0·23	0·31	0·41	0·52
34	0·02	0·05	0·11	0·17	0·24	0·33	0·44	0·56
36	0·02	0·06	0·12	0·18	0·26	0·35	0·46	0·59
38	0·02	0·06	0·12	0·19	0·27	0·37	0·49	0·62
40	0·02	0·06	0·13	0·20	0·29	0·39	0·51	0·66
42	0·03	0·07	0·13	0·21	0·30	0·41	0·54	0·69
44	0·03	0·07	0·14	0·22	0·32	0·43	0·56	0·72
46	0·03	0·07	0·15	0·23	0·33	0·45	0·59	0·75
48	0·03	0·08	0·15	0·24	0·35	0·47	0·61	0·79
50	0·03	0·08	0·16	0·25	0·36	0·49	0·64	0·82
52	0·03	0·08	0·17	0·26	0·37	0·51	0·67	0·85
54	0·03	0·09	0·17	0·27	0·39	0·53	0·69	0·89
56	0·03	0·09	0·18	0·28	0·40	0·55	0·72	0·92
58	0·03	0·09	0·19	0·29	0·42	0·57	0·74	0·95
60	0·04	0·10	0·19	0·30	0·43	0·59	0·77	0·98
62	0·04	0·10	0·20	0·31	0·45	0·61	0·79	1·02
64	0·04	0·10	0·20	0·32	0·46	0·63	0·82	1·05
66	0·04	0·11	0·21	0·33	0·48	0·65	0·84	1·08
68	0·04	0·11	0·22	0·34	0·49	0·67	0·87	1·12
70	0·04	0·11	0·22	0·35	0·50	0·69	0·90	1·15
72	0·04	0·12	0·23	0·36	0·52	0·71	0·92	1·18
74	0·04	0·12	0·24	0·37	0·53	0·73	0·95	1·21
76	0·05	0·12	0·24	0·38	0·55	0·74	0·97	1·25
78	0·05	0·12	0·25	0·39	0·56	0·76	1·00	1·28
80	0·05	0·13	0·25	0·40	0·58	0·78	1·02	1·31
82	0·05	0·13	0·26	0·41	0·59	0·80	1·05	1·34
84	0·05	0·13	0·27	0·42	0·60	0·82	1·08	1·38
86	0·05	0·14	0·28	0·43	0·62	0 84	1·10	1·41
88	0·05	0·14	0·28	0·44	0·63	0·86	1·13	1·44
90	0·05	0·14	0·29	0·45	0·65	0·88	1·15	1·48
92	0·06	0·15	0·29	0·46	0·66	0·90	1·18	1·51
94	0·06	0·15	0·30	0·47	0·68	0·92	1·20	1·54
96	0·06	0·15	0·31	0·48	0·69	0·94	1·23	1·57
98	0·06	0·16	0·31	0·49	0·71	0·96	1·25	1·61
100	0·06	0·16	0·32	0·50	0·72	0·98	1·28	1·64

The observed depth, or the depth indicated by a reel at some distance above shown in the above Table are applied.

The corrections should be used to the nearest tenth of a foot; hundredths

Corrections for a wet-line depth of 100 feet are numerically equal to a per-

[1] From report of Mr. F. C. Shenehon in Annual Report of

ACTUAL DEPTHS FOR VERTICAL ANGLES BETWEEN 4 AND 36 DEGREES[1]. Mr. Allard.

or above water-surface: degrees.									Wet-line depth: feet.
20	22	24	26	28	30	32	34	36	
0·20	0·25	0·30	0·35	0·41	0·47	0·54	0·62	0·70	10
0·24	0·30	0·36	0·42	0·49	0·57	0·65	0·74	0·84	12
0·29	0·35	0·41	0·49	0·57	0·66	0·76	0·87	0·98	14
0·33	0·40	0·47	0·56	0·65	0·76	0·87	0·99	1·12	16
0·37	0·45	0·53	0·63	0·73	0·85	1·98	1·12	1·26	18
0·41	0·50	0·59	0·70	0·82	0·94	1·09	1·24	1·40	20
0·45	0·55	0·65	0·77	0·90	1·04	1·20	1·36	1·54	22
0·49	0·60	0·71	0·84	0·98	1·13	1·31	1·49	1·68	24
0·53	0·64	0·77	0·91	1·06	1·23	1·41	1·61	1·81	26
0·57	0·69	0·83	0·98	1·14	1·32	1·52	1·74	1·95	28
0·61	0·74	0·89	1·05	1·22	1·42	1·63	1·86	2·09	30
0·65	0·79	0·95	1·12	1·31	1·51	1·74	1·98	2·23	32
0·69	0·84	1·01	1·19	1·39	1·60	1·85	2·11	2·37	34
0·73	0·89	1·07	1·26	1·47	1·70	1·96	2·23	2·51	36
0·78	0·94	1·12	1·33	1·55	1·79	2·07	2·36	2·65	38
0·82	0·99	1·18	1·40	1·63	1·89	2·18	2·48	2·79	40
0·86	1·04	1·24	1·47	1·71	1·98	2·28	2·60	2·93	42
0·90	1·09	1·30	1·54	1·80	2·08	2·39	2·73	3·07	44
0·94	1·14	1·36	1·61	1·88	2·17	2·50	2·85	3·21	46
0·98	1·19	1·42	1·68	1·96	2·27	2·61	2·98	3·35	48
1·02	1·24	1·48	1·75	2·04	2·36	2·72	3·10	3·49	50
1·06	1·29	1·54	1·82	2·12	2·45	2·83	3·22	3·63	52
1·10	1·34	1·60	1·89	2·20	2·55	2·94	3·35	3·77	54
1·14	1·39	1·66	1·96	2·28	2·64	3·05	3·47	3·91	56
1·18	1·44	1·72	2·03	2·37	2·74	3·16	3·60	4·05	58
1·22	1·49	1·78	2·10	2·45	2·83	3·26	3·72	4·19	60
1·26	1·54	1·84	2·17	2·53	2·93	3·37	3·84	4·33	62
1·31	1·59	1·89	2·24	2·61	3·02	3·48	3·97	4·47	64
1·35	1·64	1·95	2·31	2·69	3·12	3·59	4·09	4·61	66
1·39	1·69	2·01	2·38	2·77	3·21	3·70	4·22	4·75	68
1·43	1·74	2·07	2·45	2·86	3·30	3·81	4·34	4·89	70
1·47	1·79	2·13	2·52	2·94	3·40	3·92	4·46	5·03	72
1·51	1·84	2·19	2·59	3·02	3·49	4·03	4·59	5·17	74
1·55	1·88	2·25	2·66	3·10	3·59	4·13	4·71	5·30	76
1·59	1·93	2·31	2·73	3·18	3·68	4·24	4·84	5·44	78
1·63	1·98	2·37	2·80	3·26	3·78	4·35	4·96	5·58	80
1·67	2·03	2·43	2.87	3·35	3·87	4·46	5·08	5·72	82
1·71	2·08	2·49	2·94	3·43	3·96	4·57	5·21	5·86	84
1·75	2·13	2·55	3·01	3·51	4·06	4·68	5·33	6·00	86
1·80	2·18	2·60	3·08	3·59	4·15	4·79	5·46	6·14	88
1·84	2·23	2·66	3·15	3·67	4·25	4·90	5·58	6·28	90
1·88	2·28	2·72	3·22	3·75	4·34	5·00	5·70	6·42	92
1·92	2·33	2·78	3·29	3·84	4·44	5·11	5·83	6·56	94
1·96	2 38	2·84	3·36	3·92	4·53	5·22	5·95	6·70	96
2·00	2·43	2·90	3·43	4·00	4·63	5·33	6·08	6·84	98
2·04	2·48	2·96	3·50	4·08	4·72	5·44	6·20	6·98	100

the water-surface, must be reduced to the wet-line depth before the corrections

are given to aid in interpolation for odd degrees and depths.
centage correction for any depth.

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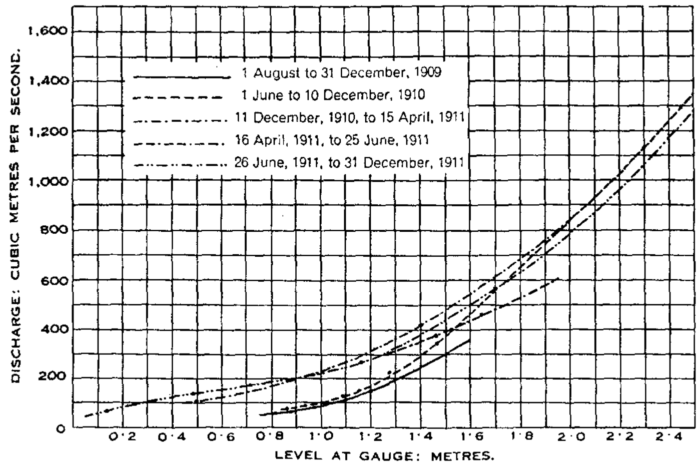
the Chief of Engineers, U.S. Army, 1900 (Part VIII), p. 5330.

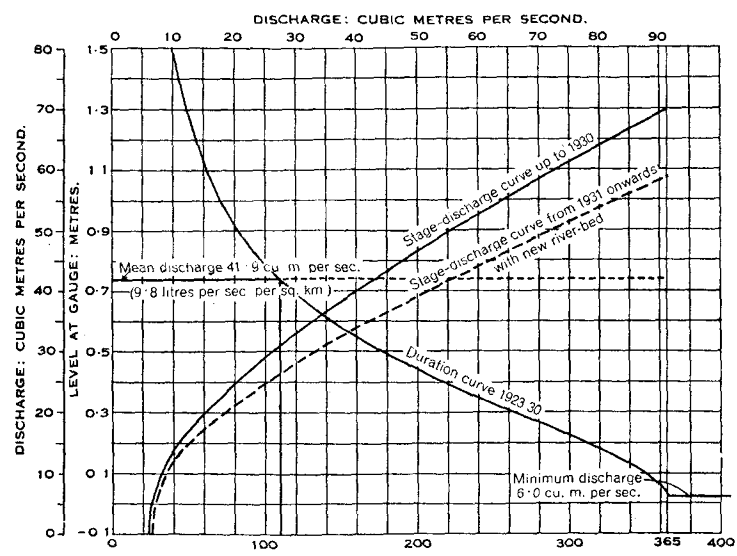
Mr. Allard

Fig. 23.



STAGE–DISCHARGE CURVES FOR RIVER DURANCE AT MIRABEAU.

Fig. 24.



STAGE–DISCHARGE CURVES FOR RIVER NECKAR AT MÜNSTER.

The reason that the hours chosen in the case of B were as shown, and not at regular intervals throughout the 24 hours, was that they were times at which people could be expected to read the gauge without very much trouble. The differences between daily discharges as obtained by methods A and C, and, alternatively, by methods B and C, had been worked out in terms of percentage, plus or minus, and the monthly means of those percentages had been calculated. Mr. Allard.

TABLE VII.—COMPARISON OF RESULTS OBTAINED FROM CONTINUOUS DISCHARGE-RECORDS.

A denotes the result calculated from the discharge at 9 a.m.
B ,, ,, ,, ,, ,, mean of discharges at 8 a.m. and 4 p.m., or, with high stages, at 8 a.m., noon, 4 p.m. and 8 p.m.
C ,, ,, ,, ,, ,, mean of continuous record for 24 hours, midnight to midnight.

	Percentage difference between A and C.		Percentage difference between B and C.	
	Maximum for single day.	Monthly mean of percentages.	Maximum for single day.	Monthly mean of percentages.
Station X				
May, 1936	− 55	− 1	− 22	+ 10
June	− 71	− 2	− 47	− 2
July	− 59	+ 1	− 35	− 1
Station Y				
Nov., 1935	− 63	− 8	− 33	+ 2
Dec.	− 51	− 1	− 30	+ 1
Jan., 1936	− 61	− 8	− 32	− 2
Station Z				
May, 1935	− 64	− 24	+ 29	+ 2
June	+ 171	− 6	+ 39	+ 7
July	− 48	− 10	− 69	+ 3
Nov., 1935	− 84	+ 2	+ 24	+ 5
Dec.	+ 92	− 8	− 41	+ 3
Jan., 1936	+ 89	− 3	+ 43	− 3

Such monthly means would be seen to be at times quite small, like the differences in results obtained by the Authors. Nevertheless, however closely the monthly means of results obtained by two different methods might agree, the daily differences between them, as shown by Table VII, ranged from 22 per cent. to 171 per cent. in those particular cases. Those remarks were not intended to contradict anything the Authors had said, but to remind those who set up gauging-stations that they had to consider (having in mind the results they were trying to obtain) whether they could be satisfied

Mr. Allard. with one reading a day, or whether they would be well advised to make a continuous record, if they could manage to provide the instrument.

The second of the Authors' three methods was to calculate the daily discharge from the mean of four or eight water-levels observed during that day. Although that method was considered suitable for a stream which rose and fell very slowly [1], Table VIII showed the

TABLE VIII.—COMPARISON OF RESULTS OBTAINED BY ESTIMATING OCCASIONAL 24-HOUR DISCHARGES OF A STREAM OVER A CLEAR-OVERFALL WEIR FROM :—

A. Mean level for 24-hour period.
B. Continuous record of rates of discharge.

Item.	Daily discharge as estimated from		Quantity by which A falls short of B : per cent.	Remarks as to water-levels during period.
	A.	B.		
1	38·0	38·1	—	Small rise and fall.
2	12·0	12·1	1	Nearly horizontal.
3	7·0	7·1	2	Small rise and fall.
4	6·0	6·2	3	Small rise and fall.
5	6·2	6·4	3	Moderate fall and rise.
6	28·0	29·9	6	Moderate fall.
7	9·0	9·8	8	Small rise, moderate fall.
8	9·6	10·5	9	Moderate fall.
9	15·0	17·0	12	Steep fall.
10	17·5	20·1	13	Steep rise, fall and rise.
11	53·0	61·6	14	Steep rise.
12	23·5	28·2	17	Steep fall and rise.
13	60·0	72·9	18	Steep rise and fall.

errors introduced by using it in the case selected, which related to the run-off of an area of 5,000 acres. Thirteen tests had been made. The discharge had been worked out by two methods : first by taking twelve observations of level during the 24 hours, taking the mean of those levels, and then calculating the discharge from that level according to the rating curve for that station. The other method had been to take the mean of twelve measurements of discharge made at 2-hour intervals during the 24 hours. It would be seen that the quantity by which A fell short of B ranged from 0 to 18 per cent., the percentage depending upon the total range of level during the day. Again, that was not intended to contradict anything the Authors had said. It was, perhaps, a continuation of an earlier discussion on the subject.[1]

[1] *Discussion on* " Practical River Flow Measurement and its Place in Inland Water Survey, as exemplified on the Ness (Scotland) Basin," by W. N. McClean. Trans. Inst. W.E., vol. xxxviii (1933), p. 269.

It showed that, whilst with a quiet river, or one that was not rising Mr. Allard. and falling substantially on the day that was being considered, it was fairly safe to take the mean level as an index of the mean discharge, once the river got "lively" considerable errors might arise if the same were being done. The foregoing remarks applied to a catchment of 5,000 acres, whereas the Authors' catchment was 1,600 square miles, and he was not suggesting that the same figure of 20 per cent. error would apply to any size of area or any other river.

Referring to the question of relating rainfall and run-off to the calendar year and the water year, apparently it made very little difference which method was used as far as the Authors were concerned; much the same result was obtained. It might be interesting to engineers to know that the Inland Water Survey Committee had considered what 12 months formed the most suitable water year, and in doing so they had also taken into account underground water and the Meteorological Office's studies of seasonal rainfall; they remained of the opinion that 1st October to 30th September was the most suitable 12 months. He did not think the Authors were suggesting an alternative to that in what they said.

Mr. FRANK HIBBERT said that it was interesting to note that, whilst Mr. Hibbert. the work had been commenced for scientific rather than for economic reasons, the latter aspect was already recognized by its value to the Severn Catchment Board. The Inland Water Survey Committee also appreciated its worth.

On p. 84 reference was made to the effect of the Vyrnwy impounding works of the Liverpool Corporation on the discharge at the Bewdley gauging-station, and, whilst it was agreed that the total annual flow was affected to the extent of less than 1 per cent., the effect of the reservoir in times of heavy rain must have been to smooth out to some extent the peak flows. The catchment-area above the Vyrnwy dam was approximately $2\frac{1}{4}$ per cent. of the total area above Bewdley, and the long-period average rainfall at Vyrnwy was approximately 220 per cent. of the long-period average of the Bewdley catchment. In dry periods there would be an increased and more regular flow as a result of the discharge of compensation water at Vyrnwy, and it would appear that, in an exceptionally dry period (for example, July, 1934), the total compensation water paid out had averaged about 10 per cent. of the flow at Bewdley during the driest 14 days.

Figs. 12 and *13* (pp. 98 and 99) were two flood-hydrographs which showed entirely different characteristics, and he thought it would have added interest to the Paper if the Authors had suggested some reason for that difference. An examination of the conditions prevailing on high ground at the time of the floods—taking the Vyrnwy records as representative—might throw some light on their special features.

Mr. Hibbert. *Fig. 12* showed a rapid rise on the 1st June, a sustained peak to the 3rd June, and then a gradual fall. At Vyrnwy, the rainfall for the 4 days, 30th May—2nd June, 1924, had been 2·36 inches, a low rainfall compared to the 3 to 4 inches for the whole of the Severn Valley, 31st May—1st June. The bulk of the rain at Vyrnwy had fallen in the 24 hours from 8 a.m. on the 31st May to 8 a.m. on the 1st June, and the maximum run-off had been recorded in the same 24 hours.

Before the heavy rainfall, the reservoir had been at overflow-level, but had backed up and retained the peak run-off. The maximum discharge to the river had been on the 1st June. Of the 2·36 inches of rainfall, the run-off in the period, the 31st May to the 7th June, had been about 84 per cent., and, by the 7th June, about 68 per cent. had been discharged to the river. The run-off for the two days, 31st May and 1st June, had been about 50 per cent. of the rainfall.

A possible explanation of the rapid rise of the river at Bewdley was:—

(1) The rainfall had been heaviest on the lowland areas.

(2) The flood had occurred at a time when the river-discharge had been low following a period of low rainfall.

The sustained peak and gradual fall could be accounted for by the prolonged period of heavy rain on the high ground. At Vyrnwy, the rain had continued for more than a week after the flood, when over 2 inches of rain were recorded, whilst, according to the Authors, the days following the 1st June had been fine.

Comparing the run-off and rainfall for the year 1923–24, it would be seen from Table II (p. 104), that February and March, 1924, had been months of low rainfall, whilst the run-off for the 3 months, February, March, and April (Table I, p. 102), was only 43·2 per cent. of the rainfall, against a normal 67·2 per cent. The rainfall figures for May (Table II) included the 3 to 4 inches on the 31st May, and, deducting say 3 inches for that day, the remainder of the May rainfall had been about normal.

Continuing the comparison of rainfall and run-off, the period of May and June had had a rainfall of 8·58 inches (Table II) and a run-off of 4·64 inches (Table I), or a run-off of 54·1 per cent. against a normal 37 per cent., whilst June alone had 90·4 per cent. run-off against a normal 34·2 per cent. The rainfall for June had been about 15 per cent. above normal. The high percentage of run-off in June would appear to indicate that a greater percentage of the rain of the 31st May to the 1st June had been ultimately discharged into the river. The suggestion that 52 per cent. had been probably lost did not appear to be substantiated by reference to the figures for loss (Table III, p. 106). The total loss for the year 1923–24 was about normal.

Fig. 13 showed a gradual rise and sudden fall. At Vyrnwy, the rainfall for the 3 days from 14th to the 16th February, 1928, had been 4·8 inches, the bulk of the rain having fallen on the 15th February, the maximum run-off having been recorded the same day. Of the 4·8 inches of rain, the run-off in the period from 16th to the 22nd February had been about 89 per cent., and, in the same period 82 per cent. had been discharged to the river, 69 per cent. having been discharged in the 3 days from 15th to the 17th February. After the heavy rain of the 14th to the 16th February, it had continued fine until the end of the month, frost setting in on the 20th February and continuing into the middle of March. The temperature at the time of the heavy rain had been 45° F. Mr. Hibbert.

Widespread frost throughout the Severn Valley, and especially on the high ground, would account for the sudden drop in the discharge at Bewdley. The Tables of rainfall and run-off showed that for the period from January and February, 1928, the rainfall at Bewdley had been 52 per cent. above normal, and the run-off 73 per cent. above normal, the run-off for January and February being 93 per cent. of the rainfall, which was a very high proportion.

In March, the rainfall had been 17 per cent. above normal, and the run-off 16 per cent. below normal, the run-off being 56·5 per cent. of the rainfall. In April, the rainfall had been 31·6 per cent. below normal, whereas the run-off had been 13 per cent. above normal, the run-off being 78·5 per cent. of the rainfall against the normal 47·4 per cent. for April.

The high percentage run-off during January and February (that was, 93 per cent.), and the small percentage run-off in March, namely 56 per cent., followed by a high percentage run-off in April of 78 per cent., would suggest that some part of the heavy rainfall of February had been held up by the frost which had persisted from the 20th February to the middle of March.

He would like to know whether any difficulty had been experienced in maintaining the gauge-readings during periods of heavy frost, as there was evidence to show that in connexion with gaugings taken on the Severn at Worcester in 1811, the river had been icebound.

Mr. HARRY CHAPMAN said that his remarks would be in the nature of a comparison between the methods of gauging employed by the Authors of the Paper and those by Mr. McClean and himself in the extensive gauging carried out by Mr. McClean during the last 8 years, and also in 1912–13, of certain Scottish rivers, including a very complete survey of the Ness area, the Dee and the upper Spey. He might add that some 300 gaugings had been made, the measured flows ranging from 50 cusecs to 13,000 cusecs. Mr. Chapman.

Mr. Chapman. As none of the sites had been readily accessible from London, their policy had been to aim at gauging the whole range of levels at one visit of 2 or 3 months in the autumn and spring, as floods might be expected then and also frost on the hills would probably occur and low flows would result. In some cases where the work had not been completed, the very little left to be done had been carried out by local engineers when conditions had been suitable. The gauging apparatus had accordingly been designed for use by night as well as by day and observations could be, and had been, carried on continuously throughout the whole period of a flood from the beginning of a rise until the river had fallen again.

The first gaugings, on the river Garry in 1913, had been carried out by means of a ropeway and travelling seat from which the observer took readings by means of a current-meter on a rod. The ropeway had been fixed to convenient trees and the traveller had been worked by a second observer on the bank who had also booked the signals given by the current-meter. That method had been fairly satisfactory up to a certain point, but it had been found impossible to manipulate the rod when the velocity of flow was high.

It had been considered, however, that it was desirable, if possible, to fix the direction of the meter at right angles to the section, and so the next step had been to use a punt or boat, anchored to a traveller on a ropeway and steadied by a cross-rope, with the meter on a frame over the bows. A substantial wire ropeway had been slung from trestles, one on either bank, and the traversing of the boat had been by means of a winch attached to one of the trestles. The most recent boat had been the double punt, fitted with a cabin for the observer from which the current meter could be set at any desired depth below the surface and the position of the boat could be adjusted transversely and longitudinally as required. The meter-rod had been streamlined in section and made strong enough to work in high velocities at considerable depths. The boat had proved very stable, and very regular and uniform results had been obtained, but, as it had been a punt and not boat-shaped, there had been limits to the velocity of flow in which it had been possible to operate it.

Attention had therefore been directed to the use of a similar apparatus to that which had been used on the Severn, and Professor Dixon had very kindly allowed him to examine his gear and, in fact, there had been incorporated in the apparatus some of Professor Dixon's ideas, particularly that of measuring the depth of the meter below the water-surface by means of a spring tape.

The apparatus was worked entirely from one bank by means of a double winch on the standard and an endless traversing rope. The winch was capable of traversing the meter in a horizontal direction, and, having reached the desired distance from the initial point, the meter might be raised or lowered as required. Mr. Chapman.

The matter of the reduction of drift had been dealt with as far as possible by using a streamlined sinker and the finest possible supporting wire, which was also the transmitting wire for the contact signals. It was a stranded steel wire, $\frac{1}{4}$ inch in circumference nominally, but it had bedded into its core until it was even less than $\frac{1}{4}$ inch. Experiments in the National Physical Laboratory tank showed that the supporting wire was very largely responsible for the drift, and by reducing that as far as possible the displacement of the meter had apparently been reduced to such an extent that the difference between the actual and theoretical soundings was negligible, except, possibly, during high floods.

The method of sounding, perhaps, deserved a word or two. For some time a level had been used, a light staff being fixed to the wire supporting the meter above the sinker, and that was traversed across from point to point, lowered until the weight rested on the bottom, and the level read off as in surveying on land. That method had proved to be very successful and quick, and its advantages were that the staff was held perfectly vertical and in the exact spot where the weight would rest during gauging, both of which were difficult to attain when a boat was used for placing the staff or sounding line. It was found that soundings were repeated exactly during gauging, a period of low water being chosen for doing the work.

Although gauging by means of the suspended meter had been the method employed for some time, results had been persistently checked as far as possible by using a rod meter on fixed supports, such as cantilevers, so that obliquity of flow might be allowed for. Arising out of it, some success had been achieved with the rod meter supported on the cableway, and there was a reasonable hope that with certain alterations to the existing apparatus that method of gauging might supersede the free-meter method.

Most of the rivers which had been gauged in Scotland differed considerably from the Severn in the time in which noticeable changes in water-level took place. Except at very low levels, it was impossible to arrive at an average for the day which was satisfactory from the gauging point of view. That being so, it had been the rule to observe water-levels at frequent intervals—in some cases every quarter of an hour—and to plot those on a time base. The time of the day at which each section was being worked was also noted on the gauging-sheets so that the water-level at that time might be identified, and it was therefore possible to plot a stage-discharge curve for each vertical, or the flow per foot of width. From the curve, the

Mr. Chapman. flow at any desired water-level might be read off, and the stage-discharge curve for the whole river was arrived at by reading off from the several curves the individual discharges at intervals of, say, 0·1 or 0·2 foot, as required.

Water-levels were carefully observed by means of wells and a hook-stick. The well might be only a temporary wooden box, fed by a pipe leading out from the bank. Slope-gauges had also been used and they were very satisfactory, especially for permanent sites. A stilling box should be used for such gauges to eliminate surface movement.

Water-slopes in the gauging-reach and beyond were included in the records and temporary gauges were suitable for the purpose. That was looked upon as a very important part of the work and it was unfortunate that water-slope records were not, as a rule, available when choosing a site for current-meter measurement, as such records gave a very clear indication as to how the river was likely to behave at varying levels.

All the meters had been adapted for use either on a rod or suspended on a wire. The 1913 gaugings had been made with two Amsler meters, which had two-bladed propellers and were still in use. In 1930 two more Amsler meters of a later pattern had been purchased, and a Watt bucket-wheel-type meter had been bought about the same time. An English meter made by Messrs. Cooke, Troughton and Simms had been loaned for testing and was subsequently purchased. That was a very good meter having a four-bladed propeller, producing an instrument in which the driving force was high compared with mechanical friction. That was a good point, and it was unfortunate that the firm had discontinued its manufacture, as with certain small modifications it would have been a really excellent meter.

All the meters were tested at frequent intervals—after every survey, if they were much used—in the National Physical Laboratory tank and, without exception, they had adhered very closely to their original ratings. It was correct to say that the variations had been of no practical importance, as far as could be judged from the tests. It was rather unfortunate that the tests were not entirely satisfactory for slow speeds; only one or two points could be obtained on the curve below about 1 foot per second. That was the most difficult part of the curve to define as it was at about 1 foot a second that the curve began to depart from a straight line.

A small number of surface measurements had been made with floats, but generally speaking they were not very suitable for use in Scottish rivers, on which it was difficult to find suitable reaches for the work. Furthermore, the results, even if they were reliable, gave average velocities over a distance rather than the velocity at a point. Mr. Chapman.

When working out the gauging-results, the ratio of the surface velocity, as measured, to the mean velocity in each vertical, was always noted, and it had been found that the coefficients so obtained had been very irregular in almost every case. It was, therefore, very difficult to work out the discharge from surface measurements and little confidence could be placed in the results. As a rough indication, however, surface-floats no doubt had their uses and advantages.

Dr. JOHN GLASSPOOLE said that a study of the distribution of rainfall, both in time and space, seemed of fundamental importance to an understanding of records of stream-flow. In the past it was clear that the impetus for greater precision in the evaluation of rainfall had come more especially from engineers. It was when rainfall was considered in terms of run-off that precision was especially necessary. With an increase in the number of records of stream-flow it seemed likely, therefore, that an even greater precision in the various determinations of the volume of rainfall would be required, and in order to emphasize that point, reference was made to various computations by Mr. E. G. Bilham, which he had been asked to mention. Dr. Glasspoole.

Mr. Bilham had found that the correlation-coefficient of the annual values of rainfall and run-off given in Tables II (p. 104) and I (p. 102) of the Paper was $r = 0{\cdot}92$. That signified that about $\frac{5}{6}$ths of the variations of annual run-off were accounted for by variations of the annual rainfall as a single factor, leaving only $\frac{1}{6}$th of the variations from the means to cover casual errors of observation, the differences in the storage in the area at the end of each year, the seasonal incidence of the rainfall and the other meteorological factors mentioned by Mr. Binnie. In view of the dominating relationship between annual values of rainfall and run-off, it was clear that, in order to study the other factors, precise estimates both of rainfall and run-off were required.

Mr. Bilham had also given an equation connecting the annual values of rainfall and run-off in inches, which was :—

$$\text{run-off} = \tfrac{2}{3}\,(\text{rainfall}) - 6{\cdot}6$$

Using that equation and the annual rainfall amounts only, the computed values for the run-off were usually within 2 inches of the observed values, as shown in Table VIII (p. 134).

Dr. Glasspoole. For the Thames valley above Teddington, the corresponding equation was :—

$$\text{run-off} = \tfrac{2}{3}\,(\text{rainfall}) - 9{\cdot}1$$

In that connexion it was important to note that similar equations had been shown to fit the observed facts reasonably well for those two different catchment-areas.

The relationships given above were between annual values of rainfall and run-off. Mr. Bilham had also considered the relationship between the variations in the rainfall and run-off during the winter and summer half-years separately. The corresponding correlation-coefficients were 0·95 and 0·89 respectively. While that showed a somewhat closer relationship in the summer than in the winter, the differences in the correlation-coefficients were statistically hardly significant.

TABLE VIII.

Year.	Observed run-off: inches.	Run-off calculated from annual rainfall: inches.	Error: inches.
1921–22	16·1	18·1	+ 2·0
1922–23	18·6	17·4	— 1·2
1923–24	22·1	22·7	+ 0·6
1924–25	20·4	20·1	— 0·3
1925–26	15·7	17·7	+ 2·0
1926–27	20·7	23·6	+ 2·9
1927–28	23·2	18·9	— 4·3
1928–29	13·7	13·3	— 0·4
1929–30	26·6	27·4	+ 0·8
1930–31	26·3	24·7	— 1·6
1931–32	19·7	19·0	— 0·7
1932–33	15·3	12·8	— 2·5
1933–34	8·5	10·9	+ 2·4
1934–35	14·3	16·3	+ 2·0
1935–36	22·6	21·6	— 1·0
Average (regardless of sign)			1·65

The correlation-coefficient between the rainfall in the winter half-year and the run-off in the following summer half-year was only 0·18. That signified that the variations in the run-off from the mean during the summer were mainly dependent on the rainfall of that summer and only to a very slight extent upon the rainfall in the preceding winter half-year.

In spite of the close relationship between rainfall and run-off, it

Dr. Glasspoole.

was obvious that neither measurement could be dispensed with, and in fact they could usefully supplement each other. Run-off data were of particular service during periods of snow, when the rain-gauge might not always function properly, whilst the rainfall records were of especial use during floods when precise measurement of the flow presented difficulties. In view of the close relationship between annual run-off and rainfall data over that area it was clear that the annual rainfall amounts, which could be obtained back to, say, 1880, might be used to give estimates of the run-off over a much longer period. Before that was done it seemed desirable, however, to examine the seasonal incidence of the rainfall and other factors, especially in those years where there were differences between the calculated and observed values for the run-off.

Dr. Glasspoole hoped that the most useful piece of work which the Authors had undertaken would be repeated in other areas, and that it would stimulate further study, so that generalizations might be formulated as to the rainfall and the resultant flow in the streams. It seemed that real progress and a substantial contribution to knowledge would be made along such lines.

Mr. Roberts.

Mr. C. H. Roberts remarked that the Paper formed a model of how the flows of rivers might be investigated. During the years 1911 to 1915 he had investigated the flow of several rivers in Scotland —in particular that of the river Dee—for the purpose of a Bill in Parliament. He had afterwards read a Paper on the river Dee before the Institution of Water Engineers.[1] A comparison of some of the results that he had obtained with those described in the present Paper might be of interest, especially seeing that the average rainfall on the Dee catchment was very nearly the same as that on the Severn.

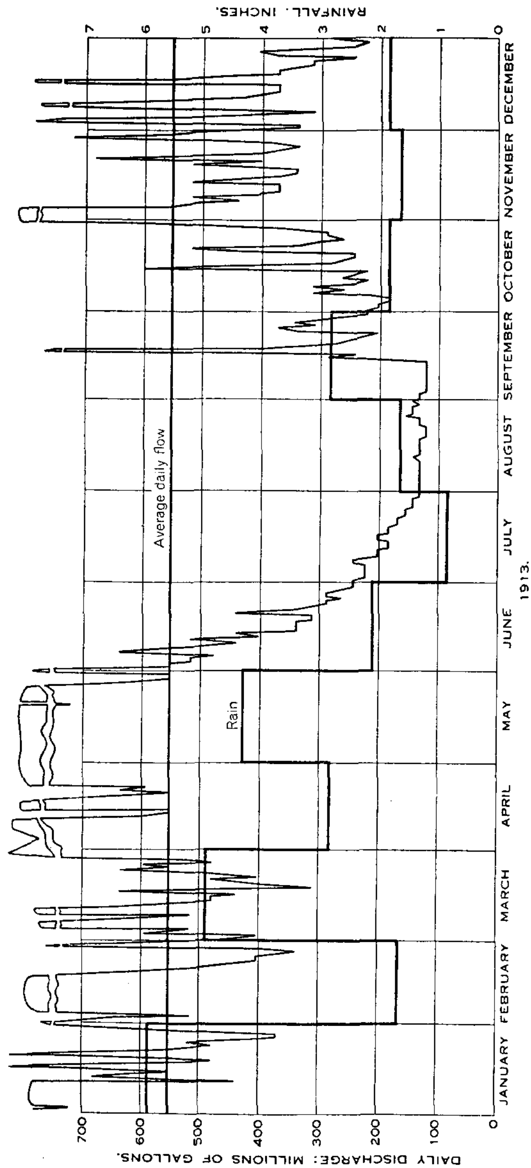
The river Dee rose in the Cairngorm mountains, was a fast-running river, and had a catchment-area of 530 square miles above the gauging station. About one-third of the area consisted of granite masses, and there were large glacial deposits and much decomposed absorbent rock in the valleys and overlying the solid granite. There were several lochs of considerable size in the area, but no weirs. A hydrograph similar to those given in *Figs. 7* to *11* was shown in *Fig. 25* (p. 136), and gave some indication of the character of the flow of the Dee.

The rainfall and average flow during each month were plotted, and the hydrograph showed that the flow of the river responded more quickly to rainfall than it did in the case of the Severn, as well as

[1] "Investigation of the Flows of the River Dee, Scotland." Trans. Inst. W.E. vol. xxiv. (1919), p. 60.

Mr. Roberts.

Fig. 25.



FLOW OF RIVER DEE AT CAIRNTON GAUGING-STATION.
(CATCHMENT-AREA 530 SQUARE MILES).

differing in many other respects from that of the Severn. Some of those differences were, no doubt, due partly to the lesser drainage-area of the Dee above the point of measurement (that was to say, 530 square miles as compared with 1,632 square miles), partly to the steeper profile of the river-bed, and partly to the different physical nature of the catchment-area. The discharge-curve of the Dee was concave instead of convex as it was in the case of the Severn (*Fig. 5*, p. 91). Mr. Roberts.

With reference to the recording of the results of observations, he agreed with the Authors' view (p. 101), that for a Paper such as that under discussion it was desirable for quantities to be stated in inches on the catchment-area so that a direct comparison might be made

TABLE IX.—RIVER DEE BASIN (CATCHMENT-AREA 530 SQUARE MILES): YEARLY PRECIPITATION, DISCHARGE, EVAPORATION, ETC.

Col. (1).	Col. (2).	Col. (3).	Col. (4).	Col. (5).	Col. (6).
Year.	Precipitation: inches.	Total observed discharge: inches.	Evaporation, absorption, etc. (difference of Cols. (3) and (2): inches.	Assumed flood-discharge (from diagrams): inches.	Assumed percolated or underground water (from diagrams): inches.
1911	34·3	23·3	11·0	11·0	12·3
1912	41·1	29·2	11·9	13·0	16·2
1913	33·3	25·7	7·6	11·2	14·5
1914	38·9	25·1	13·8	13·0	12·1
1915	44·1	28·7	15·4	13·9	14·8
Averages	38·3	26·4	11·9	12·4	14·0

with results obtained from other rivers. If, in addition, the results were plotted on a diagram showing the rainfall and the flow, a good deal of very useful information would be obtainable, such as the different effects of rainfall on the flow at different times of the year and in all kinds of weather, the time-lag of increase of flow in connexion with the rainfall, the loss at all times, etc. He joined with the Authors in suggesting that the starting of the water year should not be the 1st January, but should be some time in the late summer or early autumn.

Table IX gave a summary of the results obtained by him from the Dee basin for comparison with the results described in the Paper.

The average rainfall of 38·3 inches in the Dee catchment-area for the period of the measurements had been lower than the mean

Mr. Roberts. rainfall over 35 years (which had been 40 inches), as estimated by Dr. Hugh R. Mill, but it happened to be very nearly the same as that in the Severn catchment-area, namely 38·14 inches, and that facilitated comparison. Other results, however, differed considerably. For instance, in the Dee area the average annual discharge was 26·4 inches, or 68·9 per cent. of the precipitation. In the Severn area it was 19·9 inches, or a little less than 50 per cent. of the precipitation, which meant that nearly 20 inches were lost in evaporation, absorption, etc.; that was a high figure in comparison with the Dee, in which it was less than 12 inches.

With regard to flood-discharges, a hydrograph of the greatest flood in the Dee, which occurred in 1913 (*Fig. 25*, p. 136), approximated in form to that given for the Severn (*Fig. 12*, p. 98). The flood-discharge of the Dee in 1913 had arisen to a rate of 33 cusecs per 1,000 acres. The rise had been remarkably rapid, due to the path of the rainstorm following the direction of the flow of the river. That discharge compared with the highest flood-discharge of the Severn given in the Paper of 18,200 cusecs, or 17·5 cusecs per 1,000 acres. The lower figure in the case of the Severn was doubtless due in part to the greater catchment-area of that river.

With regard to minimum flows, the Severn was given as 200 cusecs, which was equivalent to 0·20 cusec per 1,000 acres. The lowest flow of the Dee had never fallen below 0·65 cusec per 1,000 acres. In order that the gauging of any river might accurately represent the flow, it was important that the position of the gauging-station should be selected where there was likely to be little or no flow in porous material under the bed of the river or in the banks, as any such flow would not be included in the gaugings. If it were not practicable to select such a position then some attempt should be made to estimate the underground flow in the manner recommended by Slichter of the American Geological Survey.[1] He had had the responsibility many years ago of investigating the flow of the river Salado in South America. That river had its origin on the eastern slopes of the Andes, and the character of the flow differed very much from that of both the Dee and the Severn. In particular, it might be mentioned that the flow of one of its tributaries ceased altogether for several weeks in the hot season owing to the heavy evaporation from a lake through which it flowed.

The Authors referred (p. 81) to the lack of information regarding

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[1] C. S. Slichter, "The Motion of Underground Waters." U.S. Geol. Survey, Water-Supply and Irrigation Paper No. 67 (1902).

—— "Theoretical Investigation of the Motion of Ground Waters." U.S. Geol. Survey, Nineteenth Annual Report (1897–98, Part II), p. 295.

the flows of rivers in Great Britain, and to the Commission proposed by the Water Power Resources Committee in their final Report of 1921. He had been nominated by the Ministry of Health on that Committee in 1919, together with Sir Frederick Willis and Mr. Sandford Fawcett, C.B. Although he had not been appointed he had done a considerable amount of work for the Committee and also, after it had reported, in the Ministry of Health in connexion with the survey of domestic-water resources, which the Ministry afterwards made departmentally. It did not seem to him that in Great Britain the benefits to be obtained would justify the formation of such a Commission as that proposed, or that a great expenditure of public money was called for in investigating the flows of a large number of rivers, except for particular purposes, since, as Mr. Binnie had pointed out, Great Britain possessed excellent records of rainfall. Owing to the complexity of the whole matter it would seem to be necessary, whatever records existed of any general investigation, to make further investigations of the flow of a river if any important works concerned with water were contemplated in its basin. **Mr. Roberts.**

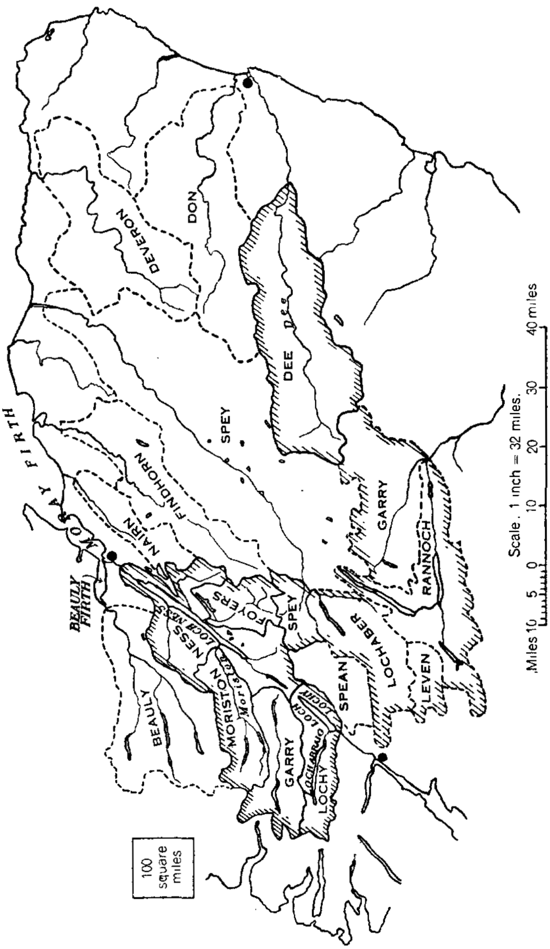
Mr. W. N. McClean observed that the late Mr. F. W. Macaulay, and Mr. Wilkinson and the Birmingham Corporation, had assured the maintenance of water-level records on the recorder up to the present time, and that it was up to the Catchment Board to maintain those records and to extend the survey by some additional gauging-stations, such as, for instance, at Ironbridge and at about 10 miles west of Shrewsbury. **Mr. McClean.**

His own organization of " River Flow Records " had in 8 years accomplished over 300 similar gaugings on nine rivers from catchments of from 85 square miles to 700 square miles, and twelve water-level recorders were in use. Most of the differences in technique between the Severn gaugings and his own were due to the organization of the work. His organization was for the purpose of survey and in from 3 to 4 months the gaugings were complete and no stage of the river had been missed. The perfection of the apparatus had allowed continuous gauging throughout floods. It was that continuity which allowed the correct water-level to be used for each gauging vertical instead of an average level of about 6 hours over the whole river.

His first gaugings had been on the river Garry in 1912–13. The choice of river had been fully justified. In 1929, at the request of Sir Alexander Gibb, he had given evidence as to those flows before the Committee which was considering the West Highland Water Power Scheme. From that date onwards, he had concentrated on the flow-gaugings, water-level records and rainfall of the Ness basin and other areas in those parts of Scotland. For the recent Cale-

Mr. McClean donian Power Scheme the records of the Ness rivers had been available to all parties. It appeared likely that Inverness and the other water interests in the area would take over the maintenance of the

Fig. 26.



water-level stations. That was already done on the Dee, Spey and Foyers. The areas covered by his gaugings and records during the last 8 years, and by the large water-power schemes in the neighbourhood, were shown in *Fig. 26*. His apparatus, in several ways developed from that of Prof. Dixon's, was now to be installed on the Chester Dee, where the gaugings would be carried out by the staff of the Catchment Board after some preliminary instructions.

In every case the principal difficulty to overcome was access to the proper gauging and water-level sites. It was clear that river survey required to be accomplished through the establishment of comparatively few survey stations, but they would have to be suitable sites; further, inland water survey required the proper facilities. The maintenance of the records was bound to be dependent on the obligation of water interests to make observations and to keep records. Mr. McClean.

When a straight reach of 300 yards was available and the bed of the river had been surveyed, there should certainly be full data as to water-slopes, water-sections and mean velocities up- and downstream of the gauging-section. They might not be necessary for figures of water resources but they were of great importance in channel-design. The two gauging-sites on the Severn were 2½ miles apart and that was due to the straight reach being unsuitable for high floods. It would appear that the reach was not too good for low flows, as the maximum velocity was only 0·75 foot per second and the mean velocity was very low indeed. A single gauging-site would frequently be unsuitable for all stages. The important consideration was that the site for the permanent water-level recorder should be suitable for all stages and should not be affected by changes of bed. On his surveys, an extra gauge-post was frequently installed to check the changes in river water-levels.

The coefficients used for floats (Appendix I, p. 110) were derived from the depth–velocity diagrams. On the current-meter gaugings, mean velocity in a vertical was expressed as a coefficient of surface-velocity. Surely, the coefficient applicable for each separate vertical had to be applied to the float-surface velocity of that vertical? The shape of depth–velocity diagrams appeared to be governed not only by depth but by the acceleration or retardation at the section and on the reach. The analysis of that depended on slopes and water-sections above and below the gauging section.

There was a great deal in the Paper about accuracy of measurements. The degree of agreement between gaugings was hardly a complete measure of accuracy; nevertheless, on good reaches, it appeared to be safe to say that gaugings might agree to better than 3 per cent. The biggest change of level (0·3 foot) during gauging would give from 100 to 300 cusecs difference in discharge. That appeared to be 3 per cent. in itself. The averaging of water-levels during gauging was a necessity of casual gauging but was indefensible in accurate survey. It did not arise under his system, where the stage–flow curve was made for each vertical; that course presented no difficulty. The necessity for the proper method was obvious

Mr. McClean. from the hydrograph of June 1, 1924 (*Fig. 12*, p. 98) when, for 4 days, the rate of change was 0·6 foot per 6 hours' gauging time, from 18-foot stage down to 10-foot stage. It so happened that on the actual Severn gauging it had produced very little error. The error would, however, be a very different matter on the upper reaches of the Severn. His method of taking readings was the same as the Authors', but his interval of 2 minutes for observation was certainly preferable to the 1 minute used by the Authors.

The formulas which had been hitherto put forward had been based on the relationship of mean velocity to water-section and wetted perimeter. It was very doubtful whether such a general relationship was going to be usefully applicable to most cases. Depths and the effects of bed-alignment on acceleration and retardation of flow would, in his opinion, outweigh any variation in coefficient of bed-friction due to variation in wetted perimeter.

The Paper showed on p. 94 that the monthly quantities of run-off were not seriously affected, on the Severn at Bewdley, by the use of one daily reading. The reason for that was obvious from an analysis of the hydrograph of the flood of June, 1924. A midnight reading for each 24 hours would give 2,000 cusecs for June 1, instead of 12,000, but on the 4 days' fall that loss of 10,000 cusecs would be made up by an excess of 2,000 cusecs on each of the 4 days and on the continued drop.

On other rivers, when the peak was of short duration, there would be considerable error, as was shown on his hydrograph of the Dee flood in January, 1937 (*Fig. 27*). It might not matter much for statistics of water-resources, but the whole story of the passage of floods and of the storage and loss of several lengths of river was lost, and knowledge of those was of supreme importance in the control and uses of a river and for the prediction of floods. His records were diagrammatic, with an aggregate diagram of rainfall and run-off, showing also the storages of the area from day to day. It was his opinion that the Inland Water Survey Committee, in adopting tabular statistics relating to water-resources, had lost a great opportunity of placing the survey of British rivers on the right plane of British achievement.

The characteristic derived from the duration-curve was considered to have considerable stability over, say, a period of 10 years. He doubted if it had much stability on large rivers, and it would be of interest to know the annual variation between 1929–30 and 1930–31 on the Severn; the characteristic appeared to be 0·33 and 0·48 respectively. That hardly indicated a very stable value. It was generally considered to serve the purpose of Compensation

Water Assessment. Nevertheless, the true characteristic of a river lay in the effect of storages and losses, which were latent in the rate of rise and fall of a river; that was especially true in the case Mr. McClean.

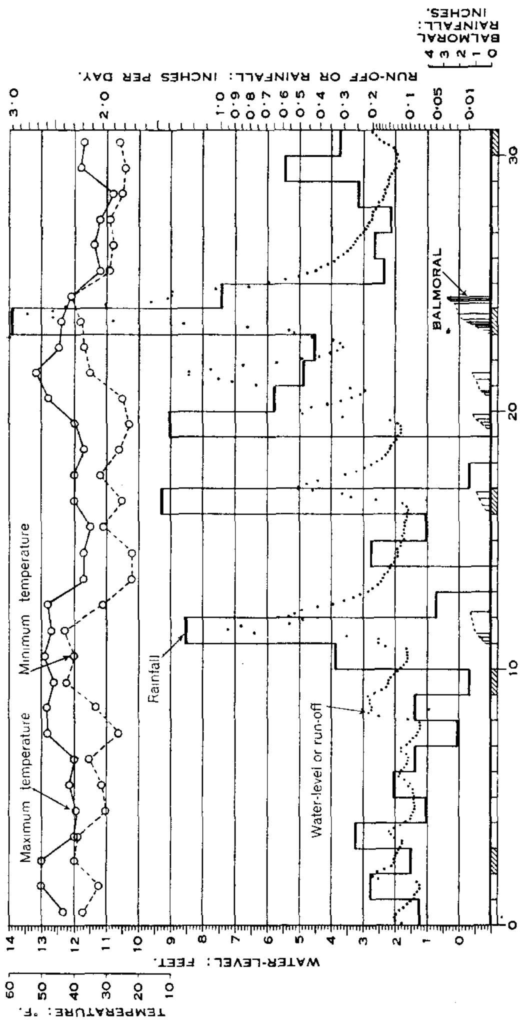


Fig. 27.

FLOW OF RIVER DEE AT CAIRNTON GAUGING-STATION.

of the fall, when the incidence of rainfall was eliminated from the hydrograph.

The assessment of rainfall on a monthly basis from the area isohyetals of the month or year and the monthly isopercentals of the

Mr. McClean. several gauges could not remove the error which was unavoidable in reckoning the distribution direct from the daily reading of rainfall. The daily assessment of rainfall should, he thought, be made, if possible, on standard lines, and he adopted a method which, on large areas, gave results very similar to the monthly method. The comparison of rainfall and run-off could only be made at low-water dates following a period of rain, when the balancing figure of residual run-off was known from the analysis of dry periods.

The losses due to the dry summer were very far from complete on the 1st October, and very large absorption-losses occurred in October and later. That was self-evident in the Severn table of losses, the 15 years' records for October amounting to 39 inches, which was as great as for July. It was clear that annual losses reckoned on January 1 or a later date, when saturation was complete, would always be more uniform in value. The accurate balance-sheet of rainfall and run-off, for his records, was made during a dry period nearest to October 1, when the residual run-off could be calculated with considerable accuracy.

The rating diagram for a current-meter (*Fig. 20*, p. 112) showed how the curve below a velocity of 1·0 foot per second replaced the straight line of the higher velocities. It had been proved at the National Physical Laboratory and at the City and Guilds College that at ⅓ foot per second his meters gave quite regular results; at present, however, the National Physical Laboratory tank was not equipped to rate intermediate low velocities. That difficulty ought certainly to be overcome at the earliest opportunity. For gauging with a suspended current-meter it seemed clear that the Ott loaded current-meter ought to replace the sinker-weight beneath the meter.

There ought to be no doubt that engineers in Great Britain required records of water-level, flow and run-off, and storage.

The drought in 1933 had demonstrated the importance of water resources, and possibly the intense floods of the 1936–37 winter in Scotland, in the west and in the Fens, would encourage surveys. The problem of the Fens and of many estuarial areas was that of storage. The problem of any river-flood was largely concerned with the concentration-time and its dependence on storage. The December, 1936, flood on the Lochy, Garry and Moriston, all with a catchment of 150 square miles, was 6,000, 10,000, and 16,000 cusecs respectively with very similar rainfalls. Those peak values were, respectively, equivalent to 1½ inch, 2½ inches and 4 inches per day intensity, and the variations were entirely the result of Loch storage. He estimated the concentration-time at from 2½ to 3 days for the three hydrographs in the Paper. If, on June 1, 1924, the rainfall of 3 inches were spread over 3 days, in winter time, there would have been a steady rise over those 3 days giving a peak-intensity rate of 1 inch per day, or 44,000 cusecs. On the Dee, that same rainfall in January, with a concentration time of 24 hours, gave a peak at the rate of 3 inches per day from an area of 528 square miles. Mr. McClean.

Mr. C. F. LAPWORTH desired to deal quite shortly with the relation between storage and yield of the particular catchment. The present records included the dry period from November, 1932, onwards, and it had been during that period that the resources of the various catchments over the greater part of the country had been taxed more severely than at any time since 1887. A comparison with the experience in other catchments was, therefore, interesting. Mr. Lapworth.

For a number of catchments where the data was available he had plotted the monthly run-off figures in the form of a cumulative diagram and had evaluated the storages required to give various yields. Those results had been plotted as a curve, one for each catchment. From those curves he had derived a formula which gave the relationship between storage and yield. The formula was an adaptation of one put forward jointly by his father and Mr. Binnie in 1913. That formula had originally been "put forward tentatively and as a temporary expedient of an empirical nature." The formula had been largely based on run-off records then available, covering the dry period 1887–88. A study of the run-off records already referred to indicated that the formula needed revision in the light of the recent drought. The present formula, which was again suggested tentatively and as a basis subject to revision, was intended to give sufficient storage to cover requirements of catchments where the 1933–34 drought had been most severe—conditions which might be expected perhaps once a century. The revised formula was $S = \dfrac{8(y-d)^2}{(Y_{max})^{1 \cdot 6}}$

where S denoted the effective storage-capacity of the reservoir expressed in inches over the drainage-area,
y ,, yield required in inches per annum,
d ,, minimum dry-weather flow over 1 month in inches per annum,
Y_{max} ,, maximum yield in inches per annum, or the long average rainfall minus the average loss.

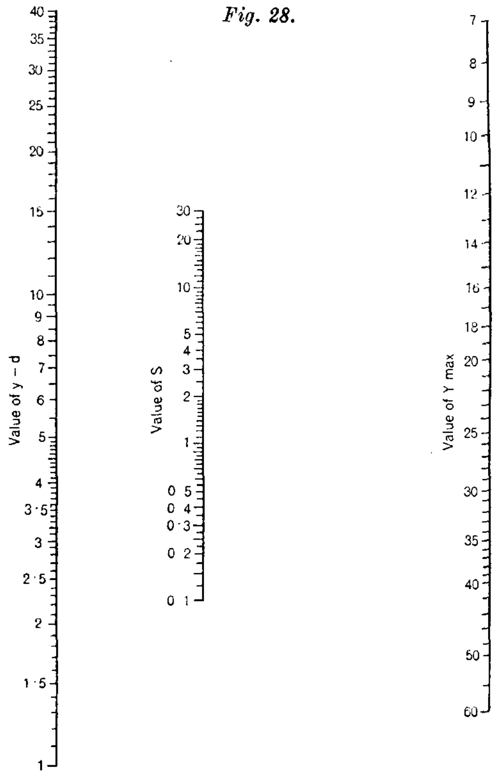
Constants :—

$$\text{Inches per annum} = \frac{\text{Gallons per day}}{(\text{Area of Gathering Ground in acres}) \times 62}$$

$$\text{Storage in gallons} = S \times (\text{Area of Gathering Ground in acres}) \times 22{,}610.$$

Mr. Lapworth. The formula appeared to give reasonably good results for yields up to 80 per cent. of the maximum yield, and for catchments with rainfalls varying between 26 and 75 inches. Advantage had been taken of the logarithmic nature of the formula to prepare an alignment chart (shown in *Fig. 28*), which might be useful in the preliminary design of storage reservoirs by making assumptions in

Fig. 28.



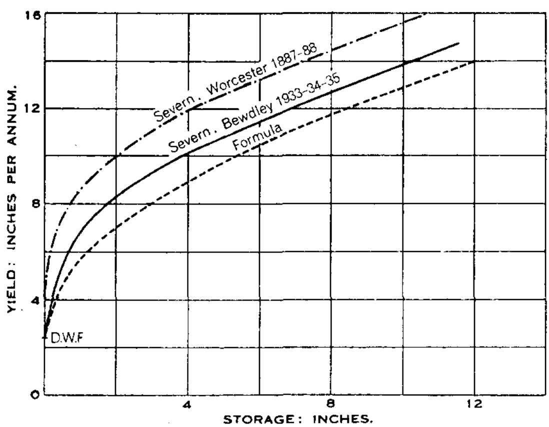
Range of data. Y max. = 8 to 60 inches per annum
Range of formula. Y up to 80 per cent. maximum yield

respect of average run-off and dry-weather flow, and later in conjunction with actual gaugings, which might not include a very dry period, in determining the final design.

In the case of the Severn, the average run-off for the period of gauging had been 18·9 inches. During that period, however, the rainfall had been 110 per cent. of the long-period average; making an adjustment for that, the long-period average run-off would appear to be approximately 16·6 inches per annum. The dry-weather flow was taken as 2·2 inches per annum, which was the monthly flow in September, 1933. **Mr. Lapworth.**

Fig. 29 was a yield–storage diagram for the Severn. The full line indicated the storage required for the period 1933–35, taken from the figures given in the Paper. A comparison was shown with the storage required in the 1887–88 period taken from gaugings at Worcester and referred to in the Paper. It would be seen that the recent drought had required larger storage throughout the range. The lower dotted line indicated the results given by the formula. In comparing that curve with the curve of actual storage required during the 1933–35 period it would be seen that, although the general form was similar, the storage given by the formula was somewhat greater than that actually required. For a yield equal to three-quarters of the average run-off, the difference was about 12 per cent. The discrepancy was accounted for by the intensity of the drought in the Severn valley.

Fig. 29.



The period of twenty-five months from November, 1932, to November, 1934, had given the largest deficiency over England and Wales as a whole. The Severn catchment down to Bewdley covered an area over which the rainfall had been approximately 159 per cent. of the average annual rainfall. There had been, however, an area in the South Midlands, and another in South Wales, where the rainfall had been less than 150 per cent. of the average. The figure for the Thames valley had been 144 per cent. of the average, and in that case the agreement with the formula was very close.

Mr. Lapworth. The difference in storage between that given by the formula and that actually required represented a margin against the possible recurrence of a drought of similar intensity to that experienced in other areas.

Mr. Wileman. Mr. R. F. WILEMAN said that it would be of interest to know if the velocity-depth curves had been analysed with a view to confirming the reliability of the " mid-depth " method for determining the mean velocity. He believed that that method was in use in many parts of the world, as were other methods involving the determination of mean velocity by the observation of velocity at one or two points only in the vertical. It would be of interest to see if the factor for reduction of mid-depth velocity to mean velocity, used for large open water-channels in other parts of the world, was confirmed by the Severn measurements. That factor, which had been adopted in Egypt, was 0·96, and had been checked in Egypt by a very large number of observations of velocity-depth curves. He had been told by Dr. Percy Phillips of the Physical Department of the Public Works Ministry of Egypt that it had been found that the ratio of the velocity at mid-depth to the mean velocity in the vertical was less changed by special conditions, such as strong winds with or against the stream, than the ratio of the velocity at any other single point to the mean velocity.

The saving of time and the obvious simplicity of operation resulting from velocity-observation at mid-depth only, was considerable not only in the field but in computation, and if, as seemed likely, many discharge-measurements were required in Great Britain, that aspect of the question would be of importance.

Mr. Gold. ⁂ Mr. E. GOLD considered that the hydrographs shown in *Figs. 7 to 11* (pp. 96 and 97) provided not only an interesting picture of the years' events in the Severn, but also a basis for a study of the relations between flow of the river and the meteorological factors of rainfall, wind, humidity and sunshine. Were the daily discharges plotted to form the hydrographs derived from single daily readings ? It was clear from the results given earlier in the Paper that single daily readings formed a good basis for means or averages, but they were not likely to be accurate representations of the flow on individual days. The fact that other factors besides rainfall were bound to play a part was evident from an examination of Tables I and II (pp. 102 and 104). If, from those two Tables, the ratio of the run-off to the rainfall were computed for each year, the

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⁂ This and the succeeding contributions were submitted in writing.—SEC. INST. C.E.

following were the results if the ratio were expressed as a percentage :— Mr. Gold.

Year.	Run-off/Rainfall per cent.
1921–22	44
1922–23	52
1923–24	51
1924–25	51
1925–26	43
1926–27	46
1927–28	61
1928–29	46
1929–30	52
1930–31	56
1931–32	51
1932–33	53
1933–34	33
1934–35	42
1935–36	54
Average	49·5

The smallest ratio occurred in the driest year ; but the greatest ratio did not occur in the wettest year: in fact it occurred in a year, 1927–28, with rainfall just below the average.

It was clear that the ratio of run-off to rainfall increased, broadly speaking, as the rainfall increased. In fact, if those percentages were plotted against the rainfall, they grouped themselves broadly about a straight line, from which the following figures were derived :—

Rainfall: inches.	Ratio of run-off to Rainfall: per cent.
20	30
30	40
40	50
50	60

The most exceptional years of the series were :—

Year	Ratio: per cent.	Rainfall: inches.	Computed ratio: per cent.
1927–28	61	38	48
1926–27	46	45	55
1932–33	53	29	39

The observed ratios therefore differed by + 13 per cent., — 9 per cent., and + 14 per cent. from what might have been expected from the rainfall totals on the basis of the results from other years. What was the character of those 3 years which determined the large departure from the average in that ratio of run-off to rainfall ?

Mr. Gold. He thought that it was only by a careful examination of the individual days or individual months in the exceptional years that the causes of the variations of that ratio would be found. The departures were much too great to be due to accidental errors, and he considered that they were bound to have been associated with exceptional conditions of wind or sunshine in the catchment-area. Figures of mean velocity of wind or mean sunshine for the year were not likely to be of much help; it was the effect of wind and sunshine at the time when the ground was wet or immediately following rain which would have the predominating influence.

Mr. Gourley. Mr. H. J. F. GOURLEY observed that the Authors drew attention on p. 90 to the form of the curve for the mean hydraulic radius, as shown in *Fig. 4*. That radius, according to that curve, reached a maximum value of 12·55 feet at gauge-height at 17·0 feet; that was to say, at a discharge of 12,000 cusecs. The Authors observed that the subsequent reduction in the hydraulic radius was a consequence of the river then overflowing its banks. He would point out that the shallow marginal flow was relatively small and often negligible, for observation in such cases indicated that the velocity of flow in the margins was quite small as compared with that of the main channel; he suggested that it was not correct to treat the section as one channel, but rather that it should be treated in two portions, the one being regarded as having an area and a wetted perimeter obtained by extending verticals from the sides of the channel to the water-surface, and the other being taken as the balance of the section.

The form of the discharge-curve (*Fig. 5*, p. 91) rather suggested that no credit had been taken for the flow over the marginal lands, and in any case a reference to the average duration-curve (*Fig. 15*, p. 100) showed that flows exceeding 12,000 cusecs had only occurred during about $1\frac{1}{2}$ per cent. of the time, or on about 70 or 80 days in 15 years, so that no matter how the marginal flows had been dealt with the error in the record could not be material. So far as could be ascertained from the average duration-curves the Severn discharged at or below its average during about 66 per cent. of the time. The Thames at Teddington had a drainage-area of 3,812 square miles, and the percentage in that case was 65 per cent. It was found that over a period of years the flow of British rivers was equal to, or less than, the average during from 65 to 70 per cent. of the time.

The annual rainfall and run-off figures from Tables I and II, which were plotted in *Fig. 17* (p. 107), were approximately represented by the equation $F = \frac{2}{3}(R - 10)$ in which F denoted the annual run-off in inches and R denoted the corresponding rainfall in inches. In individual years the difference between the calculated and the actual run-off ranged from about $\frac{1}{2}$ inch to $2\frac{1}{2}$ inches; the average calculated run-off of the 15 years was, however, 18·90 inches, and that happened also to be the actual average run-off. Mr. Gourley.

During the 3 years 1932–35 the total rainfall was 89·13 inches, and those were the lowest three consecutive years, not only in the Table but probably for 60 or 70 years. The corresponding run-off was 38·07 inches and the average annual loss during those years was 17·02 inches, as compared with the average over the 15-year period of 19·24 inches. It might seem obvious that if the rainfall were less the opportunities for loss were less, but that fact was sometimes overlooked, and the figures just mentioned proved the fact.

Converting the formula just given to give the loss L, the result was $L = \frac{1}{3}R + 6\frac{2}{3}$, and that again showed that the loss had two components, one a constant and the other which varied approximately with the rainfall.

Mr. BEN HOWORTH observed that the choice of Bewdley for a gauging-station for the river Severn appeared to have been made owing to the fact that it was on a length of river stated to be free from artificial controls and river-traffic. Such ideal conditions were always very difficult to find, and on rivers like the Lee and Thames were almost impossible to obtain. The river Lee and its tributaries had either locks or mills, or both, situated at short intervals from one end to the other. The problem in that case was not easily solved by the establishment of a gauging-station of the type described in the Paper. A further difficulty occurred in the change in condition of the channel, the shape of which might alter very considerably during times of flood. In the case of Bewdley it was stated that a prominent ledge of rock ran obliquely across the river near the station, and that undoubtedly helped to maintain a uniform section. A similar condition would be hard to find in most rivers. Mr. Howorth.

The Catchment Boards were in most cases establishing gauging-stations on their rivers and it was clear that the information in regard to the height of floods and their duration was the factor of most importance to such Boards. For that reason the records had to be continuous, and that meant the installation of automatic recording instruments. Further, those instruments ought to be calibrated to read directly the quantity of water passing the station, which meant that the stations had to be correctly designed. Weirs, venturi flumes, or channels of uniform sections would be necessary for that reason, and such works entailed heavy expenditure in the first instance. Automatic diagrams to show quantities saved a large amount of labour in calculation, and as very few Catchment Boards could find the staff necessary to make extensive calculations

Mr. Howorth. that was a very big consideration in the choice of the method to be adopted in the gauging of a river.

The calculation of the run-off and its relation to rainfall which the Authors made was of great interest at the present time, and if the various catchment-areas were in any way similar to the Severn and to each other the average discharge for the various rivers could be easily found owing to the widespread activities over long periods of the British Rainfall Organization. As it was, every catchment-area had characteristics differing from all other areas, and the only satisfactory way to obtain the run-off was to measure it by means of as many gauging-stations as the particular area required. When such stations were established the particular relationship of run-off to rainfall would, however, lose its interest, as the run-off would then be a known quantity instead of, as at present, a matter of estimation based on rainfall.

Mr. Lacey. Mr. J. M. LACEY pointed out that the land of the catchment-area supplying the water might have no intrinsic value, but when assessed in terms of the water it produced, and of the human welfare dependent on its supply, its value was bound to be considerable. It might be expected that the source of such wealth would be given some attention, but in actual practice little had been done to preserve its value as a useful water-producer. In late years, particularly in America, attention had been directed in the study of flood-control to soil-preservation and to the control of "little waters," so that in addition to actually measuring the quantity of water available from a catchment-basin, it seemed equally important to consider how best its value as a water-producer could be conserved.

Where there were durable and resistant beds and banks capable of maintaining the channel-section with little change from year to year, and where the bed-slope was such that slight variation in surface-slope did not materially affect the discharge, the stage–discharge relation was reliable. Where the river-channel was not so nearly permanent, however, and particularly where the channel was notably unstable, the records of stages were less reliable if converted into corresponding discharges. The tendency of rivers to erode, and to deposit bed-loads in the vicinity of the gauges, materially affected the relation. The stage–discharge relation was also affected by phase of flood, and by the manner of successive flood-rises. In some cases two curves were given, one for discharge at any stage "rising river," and one for discharge at any stage "falling river." Even with that provision discrepancies arose, as with a falling flood alluvial rivers generally scoured their beds; further, although, for the same stage, the mean velocity of a rising river might be greater than that of the falling river, the increased area of water-section at the latter stage might give an equal and perhaps a greater discharge. As an example, Table X, which was extracted from the Report of the Indus River Commission, gave the hydraulic details of the river Indus at Sukkur, one of the gauging stations, for the flood season of 1914. Observations for discharge were made at the Outfall gauge. The mean depth was the area of the water-section divided by the width at the water- Mr. Lacey.

TABLE X.

Date 1914.	Goa Ghat gauge.	Outfall gauge.	Fall in 3,642 feet.	Mean depth.	Mean below datum.	Mean velocity.	Discharge: cusecs.
June 27	10·5	$10{\cdot}1_r$	0·41	14·52	18·92	7·34	363,666
July 1	12·0	$11{\cdot}2_r$	0·81	17·30	20·42	7·14	417,153
,, 4	12·6	$11{\cdot}7_r$	0·91	18·12	20·92	7·44	459,823
,, 8	13·7	$12{\cdot}6_r$	1·11	20·80	22·70	9·46	671,876
,, 11	13·8	$12{\cdot}8_r$	1·01	21·83	23·58	9·58	715,346
,, 22	13·0	$12{\cdot}3_f$	0·71	22·65	24·85	9·51	734,439
,, 25	12·9	$12{\cdot}3_{oo}$	0·61	22·58	24·78	9·24	710,931
,, 29	14	$13{\cdot}0_r$	1·01	24·29	25·79	9·68	802·758
Aug. 1	14·7	$13{\cdot}7_r$	1·01	27·19	27·99	10·18	948,928
,, 4	Maximum Flood.—No hydraulic details. Estimated 14·4 on outfall gauge.						
,, 5	15	$14{\cdot}1_f$	0·91	28·76	29·16	8·96	885,165
,, 8	13	$12{\cdot}6_f$	0·41	30·90	32·8	6·94	710,656
,, 12	10·5	$10{\cdot}2_f$	0·31	26·85	31·15	4·43	405,352
,, 15	12·9	$12{\cdot}3_r$	0·61	27·34	29·54	6·35	593,156
,, 19	11·2	$10{\cdot}7_f$	0·51	24·90	28·70	6·31	534,660
,, 22	10·0	$9{\cdot}5_f$	0·51	21·72	26·72	6·19	457,266
,, 26	—	$9{\cdot}9_r$	—	20·29	24·89	7·29	502,799
,, 29	9·6	$9{\cdot}1_f$	0·51	19·00	24·40	6·68	429,866

surface, and the mean below datum was the mean bed of the river below a fixed datum-line, and served to show the changes which occurred in the bed of the river. The datum to which all areas were referred to was fixed at 14·5 feet on the Outfall gauge. The subscript *r* on the outfall-gauge readings denoted a rising river during the past 24 hours, the subscript *f* denoted a falling river, and the subscript *oo* denoted a stationary river. The reduced levels of the zeros of the Goa Ghat gauge and of the Outfall gauge were 184·14 and 184·13.

The procedure adopted by the Authors could hardly economically be applied to gauging a large river, apart from the possibility of the river-level and slope altering during the time occupied in gauging its discharge. On the Indus river observations had been taken at every 100 feet of the cross-section from a launch kept under steam against the current, its position having been fixed by cross-bearings.

Mr. Lacey. The mean velocity at each vertical section, from numerous vertical-velocity observations, was assumed to be at six-tenths of the depth. That single observation had given a satisfactory mean velocity of the vertical section. The true mean, for that river, of several thousand vertical-velocity observations taken from 1901 to 1923 showed the true mean in a vertical to be at about 0·57 of the depth The maximum velocity had been found at the surface in most cases.

The Indus River Commission observations from 1901 to 1923 gave the ratio of the mean velocity to the velocities at various depths as follows :—

Surface.	$\frac{1}{10}$	$\frac{2}{10}$	$\frac{3}{10}$	$\frac{4}{10}$	$\frac{1}{2}$	$\frac{6}{10}$	$\frac{7}{10}$	$\frac{8}{10}$	$\frac{9}{10}$
0·843	0·874	0·896	0·921	0·944	0·973	1·010	1·062	1·128	1·225

The bottom velocity could not be measured with the meter. Those figures were the mean, as stated above, of several thousand observations in that river. A detail examination of the records of the vertical velocities given in the Commission's Report showed the curve of vertical velocities to vary for certain conditions of the river. In a rising flood there seemed to be little difference between the velocities at the various depths, and in that connexion attention might be drawn to Professor Unwin's remarks on a Paper presented to The Institution.[1] The relation between the mean velocity in a vertical and the maximum velocity in that vertical depended also to a certain extent on the resistance of the bed and sides of the channel. The amount of silt transported also seemed to have some effect on the ratio of the mean velocity in a vertical to the maximum velocity in that vertical. The relation of surface-slope to bed-slope in a channel also influenced the curve of vertical velocities, the curve becoming more vertical as the surface slope became greater than the bed-slope. In regard to the latter statement, had the Authors any records of vertical-velocity observations taken when the surface-slope of the stream was greater than the bed-slope ?

The Authors' method of gauging the river was a council of perfection, but a fairly practical estimate of the discharge of a stream could be made by adopting Harlacher's method of gauging by means of surface-floats.[2] The method was simple, no current-meters with their associated equipment being required, but although it was so

[1] W. R. Browne, "The Relative Value of Tidal and Upland Waters in Maintaining Rivers, Estuaries, and Harbours." Minutes of Proceedings Inst. C.E., vol. lxvi (1880–81, Part IV), pp. 38 and 39.

[2] Irrigation Pocket Book, 1911 edition, p. 160. London.

simple, it was never used. It was essential, however, that the surface-slope of the stream should be obtained by means of a level, or from two gauges set some distance apart in the reach being gauged, and that it should be recorded at the time of gauging. Mr. Lacey.

The relation between rainfall and run-off or the surface-yield of a hydrographic basin had been dealt with elsewhere.[1]

Mr. F. O. STANFORD drew attention to an earlier Paper [2] on the subject of river discharge, published by The Institution nearly fifty years ago. The description on p. 85 and *Fig. 2* (p. 86) of the Paper under discussion bore such a striking resemblance to what was known as the Harlacher method that a reference to the original Paper would seem appropriate. It was of interest to note, also, that the float-coefficient of 0·85 mentioned on p. 92 was identical with the figure for the proportion of mean velocity to surface-velocity arrived at by Harlacher. Mr. Stanford.

Mr. R. C. S. WALTERS observed that the period 1921–1936 covered two remarkable droughts and probably some periods of very high floods, and for engineers concerned with waterworks data such as those given in the Paper were most valuable. Mr. Walters.

There were three points of outstanding importance to be studied in river-flow records :—

(i) The dry-weather flow during a period such as 1 month, which was probably more instructive than the smallest flow in any one day. That figure was used directly when it was desired to abstract a portion of the river-flow without resorting to storage.

(ii) The maximum flood occurring during such a period as 1 day. That was directly used for the purpose of economically designing the overflow-weir of an impounding reservoir. In most cases the reservoir could take care of a peak flood during 1 hour, but not of a peak flood lasting 1 day or more.

(iii) The way in which the flow occurred. That was of direct fundamental importance in determining the relationship between storage and yield.

Reliable data were very scanty in Great Britain for such a large river as the Severn. He noticed that at Bewdley the lowest flow during the month amounted to 0·202 cusec per thousand acres, based on the flow of July, 1921, or 0·192 cusec per thousand acres, based on the single day's flow in July, 1921, referred to on p. 101.

[1] J. M. Lacey, "Hydrology and Ground Water." London, 1926.

[2] A. R. Harlacher and H. Richter, "A Simple Method of Ascertaining the Discharge of Rivers." Minutes of Proceedings Inst. C.E., vol. xci (1887-88, Part I), p. 397.

Mr. Walters. It was satisfactory to have the very common allowance of $\frac{1}{5}$ cusec per thousand acres confirmed in that way. Incidentally, the corresponding figure for the Thames at Teddington during July, 1934, appeared to be 0·187 cusec per thousand acres, falling to 0·11 cusec per thousand acres on the 9th July, 1934. A gauge had recently been established on the Mississippi at Vicksburg which commanded an area of no less than 732,480,000 acres, and it was interesting to observe that the lowest dry-weather flow during the period of July, 1931, to September, 1934, worked out at 0·225 cusec per thousand acres in November, 1931, or 0·173 cusec per thousand acres on the 19th November, 1932. It appeared, therefore, that the commonly accepted allowance of $\frac{1}{5}$ cusec per thousand acres was substantially correct for large gathering grounds.

With regard to floods, he observed that the greatest flood recorded in a day in January, 1925, was 18,200 cusecs, or 17·2 cusecs per thousand acres. That was very much lower than a flood from any upland area such as might be estimated from a prolongation of the curve given by the Floods Committee. Similarly, the figure for the Thames flood of 1894 was 15 cusecs per thousand acres and that for the Mississippi flood of the 26th February, 1932, was 19·3 cusecs per thousand acres. On p. 101 the Authors had given the ratio between the lowest daily discharge and the highest daily discharge of the Severn as 91. That ratio was 137 for the Thames and 113 for the Mississippi.

The Authors. The AUTHORS, in reply, observed that the Discussion had amplified many of the topics touched on in the Paper and that they were indebted to the contributors for having given such full details of river-gauging operations elsewhere. The remarks of Mr. Binnie on the need for hydrometric work, and of Sir Clement Hindley on the action which was now being taken to meet that need, were of especial interest, and it was satisfactory to learn that the Inland Water Survey Committee were about to commence publication of a Year Book.

During the 15 years covered by the records the discharge exceeded 10,000 cusecs on 62 days. In the four years 1921–22, 1932–33, 1933–34, and 1934–35 the discharge did not exceed 10,000 cusecs. The frequency of the different flood-discharges during the 15 years was:

Discharge in excess of	Days.
18,000 cusecs	1
17,000 ,,	2
16,000 ,,	6
15,000 ,,	12
14,000 ,,	20
12,000 ,,	33

The Authors.

In studying the ratios of rainfall and run-off for the Severn and Thames, it should be remembered that the period covered by the Severn records was too short to yield a reliable average for the individual months. Records of the flow of the Thames were available for a much longer period, and when the Severn records were extended, a closer agreement might be found to exist.

The Authors were unable to follow Mr. Allard when he suggested that the Paper dealt with work in deep swift water. The equipment for river-gauging had to be proportioned to suit the natural conditions, and at Bewdley those were favourable, the maximum depth and velocity being about 16 feet and 7 feet per second respectively. The weight of the sinker was obviously bound to depend on the depth and velocity of the stream, and on the drag of the suspension-cable and meter; a 30-lb. sinker was adequate at Bewdley. At an early stage in the investigation it had been found that the heavy cab-tire cable supplied with the Price meter gave rise to excessive drag. A galvanized stranded-steel cable $\frac{1}{8}$ inch in diameter gave much better results. The steel cable was connected to the meter through an insulated joint and about 2 feet of hemp cord. Unlike the arrangement advocated by Mr. Allard, there was no insulated lead on the core, and the steel cable was used as the positive lead of the electrical circuit through the meter, a short length of insulated flexible wire joining the end of the cable to the meter contact-box. The return circuit was from the meter-body through the water to an earth-plate at the bank.

It was not suggested that there was any novelty in the cable-suspension method of gauging—a somewhat similar apparatus had been used by the late Dr. G. F. Deacon [1] in 1881—but the Authors felt that the advantages of that method had been rather overlooked. The Ott suspension gear might have certain advantages where the width of the river was sufficient to render communication between the two banks difficult, but the concentration of the controls at one point would be likely to increase the difficulties of erection. The gear used at Bewdley was designed to be light, portable and easily erected, because under normal circumstances the engineers of a Catchment Board or similar Authority would wish to maintain a number of gauging-stations and to carry the apparatus around from station to station.

The "paravane" device (*Fig. 22*, p. 120) for causing a meter to sink was interesting, but in the absence of experience with that type

[1] H. T. Turner, "The Gauging of Flowing Water." Minutes of Proceedings Inst. C.E., vol. lxxx (1884–85, Part II), p. 327.

The Authors. of meter the Authors feared that errors might arise due to the flutter of the paravane.

Mr. Hibbert's close analysis of the floods of May–June, 1924, and February, 1928, in the light of the Vyrnwy records showed how valuable information could be obtained from a comparison of discharge-records at different parts of a catchment. The estimate of 52 per cent. loss was arrived at from a study of the hydrograph for the flood, but in the Authors' view the monthly totals also confirmed that estimate. The rain in May and June, 1924, was 3·31 inches above the average, and the discharge for those 2 months was 1·69 inch above the average, the excess loss being 1·62 inch or 49 per cent. of the excess rainfall. No trouble had been experienced with ice during the period of the records.

The detailed account of the gear devised by Messrs. McClean and Chapman for use on Scottish rivers again emphasized the importance of adapting the equipment and methods to the character of the river under observation. Where expense was of importance, less elaborate arrangements might have to be used, but the Authors' views were intermediate between those of Mr. McClean, who advocated 2-minute observations, and 6 hours' gauging time, and those of Mr. Wileman, who favoured a single observation at mid-depth on each vertical. Under conditions of steady discharge the velocity of flow through the gauging-section varied with both time and position. At any one point there were velocity pulses, but if observations were continued for 1 minute the velocity obtained did not differ (at Bewdley) more than about 4 per cent. from the average of a long period. The velocity varied along each vertical and across the section, so that the problem of discharge-measurement was similar to that of finding the volume of an irregular solid with a rough or indefinite surface resting on a plane base. Practical considerations set a limit to the time which could be spent on a discharge-measurement, and a decision had to be reached as to whether there should be a small number of very accurate velocity-observations, or a large number of more rapid and less precise measurements. Returning to the analogy of the irregular solid, it was obvious that a better result would be obtained by taking a large number of moderately accurate spot-levels properly distributed over the surface than by taking a relatively small number of precise levels. Similarly, in river-gauging the Authors considered that in view of the pulsations in velocity and the variations in velocity-distribution, it was desirable to measure the velocity at a large number of points distributed over the cross-section in such a way that observations were most plentiful in the regions of maximum discharge. The number of observations naturally varied with the stage of the river, and at high stages the observations were not taken at every foot of depth. As a rule a measurement involved meter-observations at from one hundred to one hundred and twenty points and occupied up to 2½ hours. If the rate of change of surface-level were 0·1 foot per hour and the mean gauge-reading were taken, the first and last observations would be 0·12 foot away from the mean. At a medium flow of, say, 5,000 cusecs, a change in level of 0·1 foot at the gauging section corresponded to a change of 100 cusecs discharge, but that did not imply that the measurement would be in error by 120 cusecs. Actually, the stage–discharge relation was practically linear in so far as small changes of level were concerned, and the error involved in taking the measured discharge as corresponding to average gauge-reading would be insignificant when it was remembered that the unit discharges for each vertical were corrected to their mean water-level value before the discharges were calculated. The Authors.

The minimum discharge-measurement (210 cusecs) was taken at a point about 100 yds. above the gauging-section, where the low-water channel was shallower. The velocities measured on that occasion ranged from 0·48 to 1·40 foot per second, and the average velocity for the whole cross-section was 0·60 foot per second.

Mr. Bilham's statistical investigation of the rainfall–run-off relation brought out the close correlation between them, and his suggestion that that might be used for the study of earlier run-offs should be further studied. Mr. Gold attacked the problem in a different way and inquired why certain years showed large deviations from the average straight-line reaction. Both 1927–28 and 1932–33 were characterized by comparatively dry summers; most of the rain fell in winter when the loss was small. In 1926–27, on the other hand, the rain was more uniformly distributed throughout the year, and there were several falls in June, August, and September with high losses.

The formula for storage-capacity quoted by Mr. Lapworth might give satisfactory results within the range of the data from which it had been derived, but since the formula was not dimensionally homogeneous, exterpolation should be avoided. In calculating the flood-discharge due allowance had been made for the marginal flow, but Mr. Gourley's suggestion with regard to splitting up the cross-section when calculating the hydraulic radius deserved fuller investigation. The reduction in hydraulic radius when the gauge-reading exceeded about 17 feet seemed to be connected with the reduction in slope between Elan aqueduct and Bewdley at high flows shown in *Fig. 6* (p. 95). The slope might fall because the channel at the lower end became less efficient due to the drop in hydraulic radius, but the obstruction caused by Bewdley bridge probably had a similar effect.

The Authors. The surface-float observations were subsidiary to the main investigation and the results obtained were more consistent than the Authors had expected from a study of previous work on the subject. Owing to the comparative irregularity of the river-bed no form of sub-surface or rod-floats could be used, and favourable conditions for those devices were of rare occurrence in Britain.

*** The Correspondence on the foregoing Paper will be published in the Institution Journal for October, 1937.—Sec. Inst. C.E.