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A unit hydrograph study, with particular reference to British catchments †

by

James Edward Nash, M.E., A.M.I.C.E.I.*Discussion*

Mr P. O. Wolf (Reader in Hydrology, Department of Civil Engineering, Imperial College of Science and Technology), who presented the Paper on behalf of the Author, said that it seemed appropriate at the outset to examine the idea of the unit hydrograph in hydrology and to comment on some of its uses and limitations. The origin of the unit hydrograph was attributed to Sherman.¹⁰ In its original form, the unit-hydrograph theory assumed, first, that an "effective" rainfall of 1 in., falling during a period T uniformly in time and space over a given catchment, would result in "the unit hydrograph", i.e. a hydrograph of storm run-off which was fixed for that catchment; secondly, that the ordinates of the hydrograph of storm run-off for any storm of duration T would be the ordinates of the unit hydrograph multiplied by the amount of "effective" rainfall (subsequent investigators accepted a variability in time and space, provided this variability was regular); and, thirdly, that the ordinates of hydrographs arising from successive rain storms could be added linearly, i.e. that hydrographs could be superimposed. The term "effective rainfall" denoted that portion of precipitation which contributed to immediate storm run-off and implied the need for separation from losses and ground-water flow.

71. In terms of modern phraseology, the unit-hydrograph theory simply assumed that, if there were taken out from the total rainfall of a storm that portion which was effective in producing storm run-off, and if it were possible to isolate the run-off due to the storm from antecedent flow and base flow, then the storm run-off derived from the effective rainfall by means of a linear operation. That meant that if the effective rainfall was broken up into periods of duration T sufficiently short for the effect of variations of intensity during a period to be neglected, the storm run-off from each of these periods was an elementary wave of volume equal to the volume of effective rainfall in that period and with ordinates proportional to the volume of effective rainfall in the period. It was further assumed that the total rise in the hydrograph of storm run-off was simply the sum of the several elementary waves appropriately displaced in time.

72. An example would, with the aid of simple sketches, show that the longer the duration T of a storm on a given catchment the lower would be the peak and the longer the base of the unit hydrograph. If the 3-hour unit hydrograph (caused by an effective rainfall of 1 in. in $T_A = 3$ hours) had the shape A , then the hydrograph caused by an effective rainfall of $\frac{1}{2}$ in. in 3 hours would have the same base but half each ordinate (B_1). If the storm continued a further 3 hours, yielding an effective rainfall of a further $\frac{1}{2}$ in., a new hydrograph, B_2 , of equal magnitude and shape to B_1 but displaced by 3 hours, would have to be superimposed on B_1 . Linear addition of the ordinates of B_1 and B_2 yielded the 6-hour unit hydrograph B arising from an effective rainfall of 1 in. in $T_B = 6$ hours. Conversely, if the duration of the storm was shortened, the base of the unit hydrograph became shorter and the peak taller.

† Proc. Instn civ. Engrs, vol. 17, pp. 249–282 (Nov. 1960).

¹⁰ References 10–18 are given on p. 479.

73. As the duration T was reduced indefinitely, the T -hour unit hydrograph became the instantaneous unit hydrograph (IUH). This was a unique kind of unit hydrograph with greater theoretical significance and utility than the others, although the use of the IUH was similar to that of the finite-period UH except that, instead of adding finite elements, an integration was generally necessary to convert an effective rainfall into a hydrograph of storm run-off.

74. The unit-hydrograph idea was limited. It applied only to the relation between effective rainfall and storm run-off and therefore required their prior definition and isolation. Furthermore, it was not justified on the ground of the theory of fluid mechanics. Its merit was that it was justified by the experience of practical hydrologists who had used it with acceptable success in connexion with flood prediction and similar problems. The specific use was that when the unit hydrograph of any duration was known for a catchment it could be used to convert a known effective rainfall into storm run-off.

75. A consequence of this was that the unit hydrograph for a catchment could be used to specify some of the flood-producing characteristics of the catchment. The effects of flood attenuation schemes such as storage reservoirs could be conveniently considered by studying their effects on the unit hydrograph. However, the most frequent application was undoubtedly in flood prediction work, where estimates were made of the losses and hence the effective rainfall in a storm, for example by means of co-axial graphical correlations obtained from past experience, as developed by Linsley and his associates⁴. The estimated effective rainfall was usually transformed into a hydrograph of storm run-off by means of a uniform hydrograph calculated from the records of previous floods.

76. It frequently happened, however, that sufficient stream-flow gauges were not available to enable engineers to derive unit hydrographs for all the points at which it was necessary to predict the discharge. Thus, many investigators had attempted to find empirical correlations between unit hydrographs and the characteristics of the catchment to which they applied in the hope that such correlations might be used to derive unit hydrographs for ungauged areas.

77. Such was the work described in the Paper. The records of a large number of catchments had been analysed and parameters of the unit hydrographs obtained. These latter had been correlated with the area, slope and length of catchment. The prediction equations obtained were all highly significant in the statistical sense, but the standard errors of estimate were also high. This was disappointing, though it must be borne in mind that some of the residual variance must be attributed to errors in the original data due to lack of synchronization in the clocks of the rainfall and streamflow gauges and so on. The actual UH parameters which had been correlated of the catchment characteristics were the lag of the IUH, which was defined as the time from the instant of effective rainfall to the centre of area of the IUH, and the spread of the IUH, defined as the second moment of the IUH about a vertical line through its centre of area.

78. A method had been developed of obtaining these parameters from records of effective rainfall and storm run-off without actually deriving the IUH. This was a considerable convenience. In general, such parameters alone were insufficient to define the IUH completely; however, if a general two-parameter IUH equation was known, the values of the parameters could be determined by equating first and second moments respectively to the lag and spread of the IUH as obtained from the correlation. Such a general equation was suggested. It was shown to be empirically suitable in that the third moment of an IUH as obtained from actual data was fairly well represented by the third moment of the IUH described by the general equation when its parameters for the particular case had been determined.

79. Mr Wolf concluded with the emphatic warning, with which the Author and others working in this field agreed, that when adequate records of streamflow were available, these rather than the correlations described in the Paper should be used to obtain the unit hydrographs. The Author hoped, however, that in the absence of such records the correlations might provide an estimate and a measure of reliability of the

estimate; also that the general IUH equation could be used with reasonable confidence when only records of complex floods were available for analysis. The Author deserved every encouragement for the continuation of his studies which, Mr Wolf felt, might be usefully extended to two major sources of error: the separation of base-flow in terms of the peculiarities of each catchment; and the variation of the T-hour unit hydrograph with antecedent and current rainfall intensities (i.e. the effect of non-linearity in nature).

Mr H. C. Bowen (Chief Engineer, Thames Conservancy) felt anxious about the strictly geometrical approach used in a large part of the investigation. In the Paper the characteristics of catchments were listed under area of catchment, slope of main channel, overland slope, and so on. Those were undoubtedly very important characteristics of a catchment area; but the investigation did not deal with the effect on that catchment of antecedent conditions generally, though more and more it was coming to be realized how important antecedent conditions could be in trying to assess the behaviour of catchments under given conditions of rainfall. Moreover, a fundamental part of the investigation was the separation of the base flow from the storm run-off.

81. In § 8 the Author had stated:—

“The method used in this investigation was to draw a line from the start (A) of the rising portion of the flood hydrograph to a point (B) on the recession such that the time elapsed between the end of effective rainfall and the point B is equal to three times the time lag between the centres of area of the graphs of effective rainfall and storm run-off, Fig. 1.”

It was on that point that doubts arose about whether the matter could be treated by quite that unvarying method.

82. Fig. 20c, for Blackwater at Swallowfield, illustrated the point, because on the occasion of the storm in question the flow at Swallowfield when the flood started had been 47 cusecs. The duration given was 60 hours, or $2\frac{1}{2}$ days, but in fact the flow after $2\frac{1}{2}$ days was about 100 cusecs. That would mean that the base flow had increased in $2\frac{1}{2}$ days from 47 to 100 cusecs, and that was difficult to accept. The catchment area was 112 sq. miles and the length of the river $51\frac{1}{2}$ miles. It was doubtful whether it would respond to such an extent in so short a time. The method of separating base flow from storm run-off must have gone somewhat astray on that occasion, and that was borne out on looking again at the figure of the effective rainfall. The effective rainfall was deduced from the actual rainfall by taking the area of the storm hydrograph. The effective rainfall was just more than 2,000 cusecs for about 1 hour, which for that catchment was 0.03 in. of water on the ground. The rainfall which caused the storm was 0.42 in., or fourteen times the effective rainfall, and the time of the year was January. It was surprising that such a small proportion of the actual rainfall should have appeared as effective rainfall, and Mr Bowen suggested that it was due to the fact that the storm hydrograph should have a longer duration than $2\frac{1}{2}$ days and that the total volume of storm run-off was substantially higher; therefore the effective rainfall was substantially higher. That was borne out by looking at what happened to the river at the end of the $2\frac{1}{2}$ -day period. The river had eventually settled down after 6 days at a flow of approximately 51 cusecs; so that it started at 47 cusecs, rose to a peak, and after 6 days came back to 51 cusecs. That seemed to be a truer measure of what really happened to the base flow, and gave a better insight into what was really the storm run-off on that occasion.

83. In the study of hydrographs much more attention should be paid to disentangling the base flow from the total flow. It was unlikely that empirical relations would really arrive at a true solution of that, and, if they did not, how was it to be reached? He thought that there were two lines of investigation which could be pursued. One was a study of the long-continuing records of flow of rivers, from which, plotted over a period of time and with the corresponding rainfalls similarly plotted, it should be possible to find different periods at which confidence could be felt that base flow alone was operating.

If those studies were pursued there was some prospect of arriving at how the base flow varied, not only with the rainfall but also with the season of the year.

84. The second line of investigation which might be pursued with advantage concerned the recession curves of isolated hydrographs to which more attention should be paid. It seemed that those for any given catchment followed a fairly similar pattern, varying in time but apparently dependent principally on the wetness of the catchment area or on the quantity of base flow operating at the time—which, largely, were two different ways of saying the same thing. If these questions of base flows could be settled, the whole question of storm hydrographs could be put on a better footing. In particular it might solve the problem which was really basic so far as that matter was concerned, namely, was it a fact that the time base of a storm hydrograph was invariable over the catchment area, and that if the rainfall varied the only thing that varied with it was the ordinate of the hydrograph and not the time base?

Professor J. C. I. Dooge (Professor of Civil Engineering, University College, Cork) observed that in his Paper the Author had introduced a number of most significant contributions to surface water hydrology.

86. His first point dealt with the Author's contribution to the general scheme of unit hydrograph analysis and synthesis. In the traditional scheme of unit hydrograph analysis the shape of the unit hydrograph was derived from the records of effective rainfall and surface run-off. The practice had been to seek a basis for synthesis by making some assumptions about the shape of the unit hydrograph (i.e. by choosing a simple linear model), and then finding the appropriate parameters for the unit hydrograph shape found by analysis. Those unit hydrograph parameters could then be correlated with some catchment characteristics so that the parameters could be determined for other catchments where no records were available. Thus, O'Kelly⁵ and his associates had derived a number of unit hydrographs for Irish catchments. They had assumed that the unit hydrograph could be reproduced to sufficient accuracy by routing an isosceles triangle (of unit area and base T) through a linear reservoir of average delay time K and had then expressed the two parameters T and K as functions of the two catchment characteristics, area and overland slope.

87. The present Author had taken the second and higher unit hydrograph parameters as the dimensionless moments about the mean, and had used equation (6) to derive those moments directly from the records of rainfall and run-off. In that way he had side-stepped both the tedious difficulties of deriving an accurate unit hydrograph and the necessity of choosing a specific linear model before the parameters could be determined. That was a theoretical advance of great importance, and also a remarkable improvement in actual computation procedure. The approach was also important because the relation between the parameters and the catchment characteristics was independent of the linear operator involved; thus the analytical phase could be completed without deriving a single unit hydrograph or making any assumptions about the type of linear operator.

88. The Author had followed up this contribution to the general scheme of unit hydrograph analysis by an important contribution to the general method of synthesizing unit hydrographs for ungauged catchments. That was the ingenious device of correlating the moments among themselves, which was described in §§ 36–39.

89. The regression of m_1 on the catchment characteristics, as described in §§ 29–32, gave some interesting and apparently dependable results. Professor Dooge was particularly interested in equation (10):

$$m_1 = 27.6 A^{0.3} \text{ OLS}^{-0.3},$$

which had a coefficient of multiple correlation of 90%, indicating that 80% of the initial variance was accounted for. It was of interest to compare the value of m_1 with the values obtained by using similar correlations found by previous Authors. Table 12 showed the approximate values of m_1 for a standard catchment in morphological equilibrium which was 100 sq. miles in area and had an overland slope of 400 ft/mile.

TABLE 12

Author	Location	Year of publication	Value of m_1 for standard catchment: hours
McCarthy	Connecticut	1938	16.2
Snyder	Appalachians	1938	16.5
Mitchell	Illinois	1948	15.4
O'Kelly	Ireland	1955	14.0
Nash	Britain	1960	15.9

There was a reason why the figure given by O'Kelly in Table 12 might be expected to be lower than the others. His study had been confined to fully drained catchments, which therefore had a quicker run-off than the average. Ignoring his result, the figures were 16.2, 16.5, 15.4, and 15.9, a spread of 7%. In hydrology that meant that there was no error worth speaking of and that the Author's correlation appeared to match the results found in different areas of the United States.

90. A further point of interest was that the exponent of the slope in equation (10) was about what would be expected by analogy with regime theory of alluvial channels. Thus, if the silt factor was eliminated from Lacey's equations the velocity was found to be proportional to the cube root of the slope. The alternative approach used by E. W. Lane¹¹, of the U.S. Bureau of Reclamation, also indicated that the velocity would be proportional to the cube root of the slope. If velocity were proportional to the cube root of the slope then m_1 , which represented the average time of travel to the outlet, should be inversely proportional to the cube root of the slope. The Author had given an exponent of -0.3 , which was again an indication that that correlation was most useful and valuable, and well supported by outside data. The similarity of the two results for catchments and alluvial streams supported the idea that most catchments were in morphological equilibrium.

91. Professor Dooge then referred to the higher moments and the Author's attempt to get a correlation between his second and third moments and his catchment characteristics. That part of the Paper was open to criticism. It was all very well to say that statistically the results were significant. Statistically they might be significant, but hydrologically they were not good enough to be used.

92. The regression of m_2 with the catchment characteristics and the regression of m_3 with m_2 were less satisfactory than the regression of m_1 . The first point to be considered was the fact that in the regression of m_2 the "best grouping taking account of the residual errors and the significance of the indices" accounted for only 26% of the initial variance of $\log m_2$. That was far too frail a basis for determining m_2 for synthetic unit hydrographs. The most likely explanation for the relatively poor results was that m_2 was largely controlled by catchment characteristics other than the eight chosen. If m_1 was related to $(A/S)^{0.3}$ might not m_2 be significantly correlated with the distribution of $(A/S)^{0.3}$ or even A/S about the centre of area? There was need for further study before a really satisfactory correlation with catchment characteristics was obtained.

93. In § 35 it was stated that:—

"The fact that the coefficients of $\log$ OLS and of $\log L$ are significant means that m_2 is related to the catchment characteristics not solely through m_1 . Therefore a two-parameter correlation is justified."

The second sentence was misleading. The existence of significant coefficients meant that a correlation of *at least* two parameters was justified. With such a low coefficient of multiple correlation no further conclusion was justified. The inconclusive result

might be due to one or more of a number of causes—the need for a third parameter, the failure to include the most significant catchment characteristics, or the effects of errors in either the data or the computed moments.

94. In those circumstances the hypothesis that the data could be well represented by a two-parameter system should be tested in terms of equation (15). By correlating the moments of the data among themselves any effect arising from the choice of catchment characteristics was eliminated. If the first fifty-five events in Table 1 (the most reliable data) were taken, the correlation between m_3 and m_2 was found to be 0.717, so that only 51% of the variance of m_3 was accounted for by the variation in m_2 . Thus, a two-parameter simulation was possible only if half of the variance could be accounted for by errors in the data.

95. The alternative hypothesis, that the data suggested a three-parameter correlation, could be tested in a similar fashion. The approach used in equation (15) could be extended to the three-parameter case by stating that for such a system:

$$m_4 = f(m_3, m_2).$$

The same data used above gave a value of 0.93 for the multiple coefficient of correlation of m_4 with m_3 and m_2 . That value indicated that m_4 was very well determined by m_3 and m_2 and, therefore, that the data could be well represented by a three-parameter system.

96. Generally it seemed reasonable to conclude that the data assembled by the Author supported the idea that any system of synthetic unit hydrographs should be a three-parameter rather than a two-parameter system. To determine the values of these parameters would require three independent relations between the unit hydrograph parameters and the catchment characteristics. So far only one such relation had been established, that between m_1 and area and slope.

97. In §§ 36–56 it was assumed that a two-parameter correlation had been obtained. Professor Dooge was of the opinion that the Author's data pointed to a three-parameter rather than a two-parameter correlation. Accordingly, the discussion had been somewhat hampered by the insistence in the Paper on two-parameter systems.

98. The Author in equation (33) had proposed the formula:

$$u(0, t) = \frac{1}{K\Gamma(n)} e^{-t/K} (t/K)^{n-1}$$

as the general IUH equation, and had justified that on two separate grounds. First, he had suggested that the linear differential equation with constant coefficients was sufficiently general to be used in place of the general linear operator. He had gone on to recommend equation (33) as being general enough and very much more convenient than the equation based on the linear differential equation with constant coefficients. Secondly, he had argued that equation (33) “is the most suitable general equation for the IUH as well as being the most convenient mathematically”, on the ground that equation (33) gave the “best representation of the scatter of points” in Figs 11 and 12, so that Figs 11 and 12 justified equation (33). They did nothing of the sort. The Author was comparing things which were quite different.

99. The restriction of the linear operator to the operator of equation (20), based on the equation with constant coefficients, necessarily involved a concentration on the phenomenon of storage, to the exclusion of translatory effects. That was the opposite extreme to the rational method, which was a special case of the unit hydrograph in which storage was ignored and only translation was allowed for. It would seem preferable to pay some regard to each of these factors and avoid such extreme positions. This was done, for example, in the Zoch-Clark method, where the IUH was obtained by routing the time-area concentration curve through a single element of linear storage. General considerations of that type would predispose one to look unfavourably on equation (33) as a “suitable general equation for the instantaneous unit hydrograph”.

100. The supposed verification of equation (33) shown in Figs 11 and 12 was open to serious criticism, which stemmed from the fact that the plotted points represented unit

hydrographs with finite time bases, whereas equation (33) and the other systems examined all generated unit hydrographs in which the flow fell to zero only after infinite time had elapsed. The attempt to match those two distinct types of unit hydrograph on the basis of their first four moments was a dangerous procedure. The tails of the infinite unit hydrograph did not have much effect on the area but could affect the higher moments considerably. Either the unit hydrographs derived from the catchment data should be on an infinite base or the theoretical unit hydrographs should be truncated in exactly the same way as the actual unit hydrographs. Only the latter course could be followed in the present discussion.

101. If the method of separation described in § 8 and illustrated in Fig. 1 was applied to the curve given by equation (33) the moments would all be altered. Tables 13 and 14 showed the estimated effect for some typical cases. The result of that correction was to alter the curves corresponding to equation (33) in Figs 11 and 12, so that those curves could no longer be considered as a good two-parameter representation of the plotted points.

TABLE 13

Equation (33) unadjusted				
	$n = 1$	$n = 3$	$n = 5$	$n = 10$
m_1	1.0K	3.0K	5.0K	10.0K
m_2	1.00	0.33	0.20	0.10
m_3	2.00	0.22	0.08	0.02
m_4	9.00	0.55	0.17	0.04

TABLE 14

Equation (33) adjusted				
m_1	$n = 1$	$n = 3$	$n = 5$	$n = 10$
m_1	No solution	2.85K	4.95K	10.0K
m_2	„	0.28	0.21	0.10
m_3	„	0.11	0.05	0.02
m_4	„	0.25	0.16	0.04

102. Summarizing, Professor Dooge said: (a) the Author had made several very important contributions to the general scheme of unit hydrograph studies; (b) his correlation with catchment characteristics of the lag (or first moment) of forty-nine British catchments was well established and most valuable; (c) his attempt to seek further correlations was not a success and required further investigation; (d) his data suggested the use of a three-parameter system rather than the two-parameter system as used by him; (e) the comparison in Figs 11 and 12 between moments derived from catchment areas and moments derived from theoretical systems was not valid; and (f) his case for the adoption of equation (33) as a general instantaneous unit hydrograph equation had not been proved.

Mr Terence O'Donnell (Lecturer in Civil Engineering, Imperial College of Science and Technology) said that those familiar with the Author and his previous Papers would have been prepared for the penetrating analysis presented in the present Paper. Anyone unfamiliar with routine unit hydrograph practice might feel, on reading the Paper, that he must stay unfamiliar. That would be a pity, since the basic elements and normal use

of the unit hydrograph idea were extremely simple, a fact which could not be emphasized too highly. The complexity of the Author's latest contribution to unit hydrograph theory must not be allowed to create a contrary view.

104. That was not to accuse the Author of making a simple thing unnecessarily complicated; the complication had necessarily arisen because he had set out to examine the problem of a correlation study. He had made a first-rate attack on the problem of predicting a unit hydrograph for an ungauged catchment. The criticism which must be made was of the concept of synthesizing unit hydrographs from empirical correlation laws. Only on very minor schemes, or possibly as a stop-gap feasibility study on larger schemes, should that approach ever be tolerated.

105. The solution of the problem of ungauged catchments was very simple; it was to gauge them. In the nature of things it was almost inevitable that considerable time would elapse between the conception of any sizeable scheme and the labour pains of a detailed design. Possibly 2 years would be a gestation period sufficient to provide storms suitable for unit hydrograph derivation. As soon as any major project was contemplated a first priority should be the setting up of adequate rainfall and stream-flow recording systems on the catchment concerned. No longer need the large capital cost of a float-type water-level recorder be a deterrent in setting up a rating station. Research directed by Professor C. H. Munro¹², of the University of New South Wales, had removed the stigma from the pressure-type level recorder. There was now available a satisfactory, cheap, and reliable water-level recorder which was admirably suited to the suggestion advocated.

106. A thorny point in unit hydrograph derivation, mentioned in § 8, was the procedure of separating storm run-off from base flow in the total flood hydrograph. The Author had roundly condemned most methods of doing that as lacking in any physical justification and being completely arbitrary. The system which he had used was not claimed to be any less arbitrary, but was said to be a simple and constant method. The word "simple" might be questioned not as a description of the principle used but with regard to the application of that principle. It seemed that each new trial estimate for the base length of the storm run-off hydrograph involved extensive recalculation of areas, centres of area, and times of the end of effective rainfall. So far as the last quantity was concerned, awkward cases might be visualized where the "steppy" nature of the rainfall diagram caused trouble. One might nearly achieve balance with one trial yet the next trial might take one to the other side of a step and result in a worsening of the previous, nearly eliminated, error.

107. The Author had not given a physical justification for his method of base flow separation, though that did not mean that it lacked one. In fact, as Professor Dooge had pointed out, it could be seen that the 3-to-1 rule used meant that the base length of an IUH was fixed at 3 times the first moment of that IUH. Such constancy of the geometry of all IUHs was unlikely, though the factor 3 might be close to an average value for the catchments studied. One result of that arbitrary stipulation was that some of the storm run-off hydrographs would have tails longer or shorter than they ought to be. Though the ordinates in the tail region were small, such ordinates were at the greatest distances from the centre of area of a hydrograph. They would thus have an effect on the moments used in the correlation analyses which would be disproportionate to their size. The effect would, of course, be more marked with the higher moments. Professor Dooge had already shown by the calculations which he had made on that point just what the quantitative effect was.

108. In deriving equation (33), the general exponential-type equation for the IUH, the Author, in § 45, had avoided a dilemma by taking a constant value of K , the constant of proportionality between storage and outflow in a series of linear reservoirs. That step was one of mathematical convenience and it would be interesting to know what effect it had had. Some indication might be afforded by results presented in a recent Paper¹³ describing work done at the Imperial College. In that Paper, the IUH obtained by an application of the Author's equation (33) had been compared with the IUH obtained by a harmonic analysis and synthesis technique using the same storm

run-off and effective rainfall data for both derivations. The two IUHs had shown some differences. Using the criterion of compounding the two IUHs with the original effective rainfall and comparing the resultant run-off hydrographs with the original, the harmonically derived IUH, at least in that isolated case, had been found to give the better result. Further work was needed to establish how significant was the assumption of constant K .

Mr F. V. Appleby (Director, W. & C. French Ltd), whose remarks were concerned mainly with the mathematical aspects of the Paper, said that Professor Dooge had implied that the Author had chosen equation (33). This was not a matter of choice; equation (33) had been brilliantly derived as the system response of a catchment.

110. The research project presented by him was of considerable magnitude, particularly when measured by the personal effort which it must have involved, and was a continuation of his previous work¹ which had been published by the Institution. His notation lacked an engineering flavour, but that had been necessary for his exposition.

111. His work fell into two parts. The first dealt with analysis of statistics, and an important point there was the use of the theorem that the difference between the mass centres of the outflow and inflow (in the form of rainfall) gave the mass centre of the IUH. Unfortunately he had omitted any information about the corresponding peak flood flows. There could be no doubt whatever, in the light of practice, that m_1 and the response time K varied with the height of the flood, and all that he had to say about this statistic was limited in that respect. The second part of the Paper was given up to a mathematical argument leading to formula (33) for the IUH. The Author was to be congratulated on his rigorous approach to that aspect of the problem, and as an engineer-mathematician his work was very welcome in this generally difficult field of analysis.

112. His purpose, through statistical processes, was evidently to demonstrate a possible means of predicting the behaviour of catchments for which information on rainfall and run-off was not easily available. He had eliminated from consideration any possibility of the magnitude of the flood affecting his basic theory. Therein lay the weakness of his Paper and of all linear approaches, for which this assumption was unavoidable; twice the rainfall did not produce twice the flood.

113. The Author had exhausted the possibilities of pressing linear functions any further into the service of the hydrologist. The Paper rested on the validity of equation (33) as the system response function, being the differential quotient of the incomplete gamma function and representing the notional IUH. Mr Appleby felt that "instantaneous hydrograph" would be a better term than "instantaneous unit hydrograph", since the "unit" did not exist at this point.

114. The Author's mathematical approach and development was rigorous and satisfactory as a study in linear response. He had shown that there was a "linear system law" which connected the input (effective rainfall) with the output (flood flow). The IUH as such was only a convenient notional concept, but it was brought into real terms of time by the method of corresponding S curves at a time interval T .

115. His operational equation (20) had demonstrated very clearly some of the limitations of a linear theory. He had used the differential operators $\frac{1}{(1+K_1D)} \cdot \frac{1}{(1+K_2D)}$ to any number desired. That equation had a commutative property, and like ordinary algebra, the order in which these were applied did not matter. As the Author had noted, the physical significance of this equation was that of water flowing through a series of reservoirs, each with a different response time. Since that was represented by the linear operator equation (20) the commutative property made the order of flow through the reservoirs a matter of indifference, so that in effect the form of the catchment area and the nature of the isohyetal distributions were matters equally indifferent to his linear theory; such a theory must be considered to reflect those factors only as related to some uniform condition. In this case the Author made the K s equal. His analysis

had highlighted the two parameters n , a number, and K , a response time. That response time formed a natural basis of time scale for a given catchment. The product of those two parameters equalled the first moment of the actual hydrograph. The significance of that result should not be underestimated.

116. In 1951, Edson¹⁴ had studied the hydrograph from the angle of combining two dominant influences. They were: (a) the concentration of the flood water to the outfall; and (b) the effect of the concentration flood water on itself as a reservoir. That had led to an equation exactly the same in principle as the present Author's equation (33).

117. In 1954, Mr Appleby¹⁵ had demonstrated that the run-off problem in general could lead to a non-linear diffusion system similar to heat flow. As a special case of constant K it had again been found that the hydrograph could be represented by the differential quotient of the incomplete gamma function. There were tables of that in the Institution Library. A similar result had been found, therefore, by three independent and dissimilar modes of approach. Mr Appleby was confident that that function was the best form of the hydrograph equation which could be arrived at from linear considerations alone.

118. The use of statistics coupled with his analysis of actual flows, justified the Author's adoption of equation (33) in principle for an orderly presentation of material available from actual catchment flows and catchment characteristics. Figs 19 and 20 showed the practical results of his work. Fig. 19 demonstrated that he was able to repeat the form of the flood hydrograph very closely, first by calculating the value of m_1 and n for the flood in question, and then by setting up the unit S curve, to which he had applied the sequence of rainfall excess. That result of analysis was very satisfactory, and effectively emphasized the important position of K as a time-scale factor in run-off hydrology; so that when used as a mass value for a particular flood, as for Fig. 19, it became a factor of great potential.

119. Fig. 20, however, showed quite a different picture, when the Author sought to produce the flood hydrograph from mass statistics of the catchment alone, and the result could hardly be considered satisfactory. The fault lay largely in his neglect of the variation of K with the magnitude of the flood in question. The peak value of flow and the time of peak were very sensitive to the value of K . For example, referring to Fig. 20a and using the graphs of Figs 17 and 18, if K was 2.4 instead of 3.4, as might well be the case for the sharply rising high flood shown, the peak was increased from 650 to 1,000 cusecs, and the time of the peak was shortened from 9 to 5 hours. Incidentally, in Figs 17 and 18 the abscissa should be T/K , not t/K , and the reference to the UH, not the IUH.

120. Touching on the question of the variation of K , Mr Appleby in his 1954 Paper had suggested that the product of mass K with the mean outflow velocity v would be constant for a given area and rain distribution:

$$vK = \bar{L}$$

where $\bar{L}$ was the mean effective concentration path for given area and rainfall distribution. So that for peak flow conditions:

$$\begin{aligned} \text{since} \quad q_p &= va \quad (a = \text{concentration of flood}) \\ \text{and} \quad m_1 &= \beta K \\ \text{then} \quad m_1 q_p &= vK\beta a \\ &= \bar{L}\beta a \text{ in units of total storage.} \end{aligned}$$

Alternatively, it might be an advantage to use the time of the peak, as follows. Since t_p was also proportional to K , say $t_p = \alpha K$, then $q_p t_p = \alpha \bar{L} a$, where a was the cross-sectional area of flow or the concentration of the flood at peak of flow. The peak flow conditions were virtually linear and determinate. The estimation of zero time would depend largely on the mass centre of rainfall distribution and offered some difficulty in other than simple cases.

121. This additional relation involving K should enable the Author to extend his studies to the variation of the hydrograph with the height of flood for a given catchment.

Mr G. E. Hartley (Lecturer, Royal College of Science and Technology, Glasgow) recalled that when in 1892 Binnie presented his Paper¹⁶ he had been told that his results were impossible, that his mathematics were out of date, and that more information could have been abstracted from his data; but there had been general agreement that it was a great Paper. It was in this light that Mr Hartley raised the following queries.

123. First, in § 48 the Author said that short-period unit hydrographs were invariably of the general shape of Fig. 16. This was generally the case; if, however, unit hydrographs could be considered as routed time/area curves, more than one peak should be possible.

124. Secondly, in § 52 the Author had given two uses for his equations. The first was the derivation of unit hydrographs from complex storms, and the question was, how complex? The example chosen was not complex, and a better result was obtained by the old method using Figs 1 and 19. Did not the Author's equations enforce a solution even though base flow separation had been inaccurately effected?

125. Finally, in § 52 the UH and IUH were obtained from the area, the overland slope, the length, and a measure of channel slope. It seemed that the same catchment turned end to end would have the same catchment characteristics but that the IUH and the UH would not, surely, be the same.

Dr J. V. Sutcliffe (Hydrologist, Sir Alexander Gibb & Partners) said that in order that the Paper, which virtually produced synthetic unit hydrographs based on catchment characteristics, might be used in flood designs in Britain it was necessary that a hydro-meteorological investigation should be carried out relating storm intensity and duration with catchment characteristics and with frequency. He had been pleased to learn that the planning of such an investigation had been discussed between the Meteorological Office and the Hydraulics Research Station.

127. On the question of the base time of the unit hydrograph, Dr Sutcliffe referred to the lines on which he was attempting to solve a problem in rainfall/run-off correlation, in the hope that someone might wish to follow the matter up. He had tried to treat the recession curve as the constant factor, and to treat the total run-off as the difference between two recession curves laterally displaced by a unit of time and vertically displaced so that the area between the two curves was related to the total storm rainfall, on the lines suggested recently by Nash¹⁷. It might be possible to treat the total rather than the surface run-off as a function of storm rainfall.

The following contributions were received in writing.

Professor C. H. Munro (Professor of Civil Engineering, University of New South Wales, and Visiting Professor, Imperial College) referred to the notable contributions to the theory of the unit hydrograph which the Author had made in his previous Papers^{1,17}. In the present Paper he had developed further some theory, and had attacked the practical problems of synthesizing unit hydrographs for ungauged catchments. In so doing he had rendered a service to the science of hydrology, but there was a grave danger that he might render a disservice to the practice of civil engineering in Britain. The danger arose from two causes, viz:—

- (a) The Author had failed to stress sufficiently that "synthetic" unit hydrographs should only be used for minor works and that for major works (including all dams costing more than, say, £50,000) the project catchment should be used as a calculating machine to produce directly its unit hydrograph from rainfall and streamflow measurements of several storms.
- (b) The Author had not expressed equation (1) in its finite-difference form. As a result most practical civil engineers would retain their existing impression

that unit hydrograph theory was complex, whereas in fact it was simple and practical.

129. Professor Munro found it surprising that rarely, if ever, had there been any attempt to derive directly unit hydrographs in Britain. This was partly because the few publications which had appeared in the Proceedings had been written for the specialist engineering hydrologist, and not for the "man in the street" among the civil engineering profession. Hence, the following notes on (a) and (b) above were an important accompaniment of the present Paper, particularly because the 1933 Flood Report was also being re-considered.

130. With regard to (a), there was no justification for an indirect roundabout procedure of low accuracy such as the Author had described, when direct measurement was scientifically and economically feasible. To collect directly the data to derive a unit hydrograph on a catchment, the only requirements were:—

- (i) A dozen or so daily read manual raingauges, which in Britain always existed on the catchment.
- (ii) One or two automatic rainfall recorders, which sometimes existed, but in any case could be purchased for approximately £80 each.
- (iii) A pressure type automatic streamheight recorder¹² costing about £60, or a float type recorder costing rather more, each used in conjunction with a current meter, which could often be borrowed for occasional use to "rate" the station. Alternatively a measuring weir might exist.

131. The capital cost of this instrumentation was extremely small, and in any case the instruments could, if necessary, be transferred to another catchment after a year or so, so that depreciation only need be charged against the job. Labour costs of installation, chart changing, "rating" the stations, and, analysing the data was a bigger item, but was still trivial in relation to the cost of the project as a whole.

132. In regard to (b) in §128, equation (1) appeared formidable to practical engineers, but its meaning was simple. Suppose, said Professor Munro, the excess rain in three successive 1-hour periods was P_1 , P_2 , and P_3 inches, and this storm produced a surface run-off hydrograph extending over 7 hours, and the rates of surface run-off discharge at a given site on the stream at the end of each successive hour were Q_1 , Q_2 , Q_3 , Q_4 , Q_5 , and Q_6 , while $Q_7 = \text{zero}$. Then:

$$\begin{aligned} Q_1 &= P_1x_1 \\ Q_2 &= P_2x_1 + P_1x_2 \\ Q_3 &= P_3x_1 + P_2x_2 + P_1x_3 \\ Q_4 &= P_3x_2 + P_2x_3 + P_1x_4 \\ Q_5 &= P_3x_3 + P_2x_4 \\ Q_6 &= P_3x_4 \end{aligned}$$

where x_1 , x_2 , x_3 , x_4 were the discharges for the unit hydrograph at the end of each hour ($x_5 = \text{zero}$). If Q and P had been measured, the values of x could be obtained by solving these simultaneous equations, and thus the unit hydrograph was derived. For any future "design storm", P and x were known, and Q_1 , Q_2 , etc. (the shape of the surface run-off design flood hydrograph) could be computed by a reversal of the process.

133. Admittedly, there were certain "tricks of the trade" when it came to applying this simple concept in practice, as discussed by Body¹⁹. Further, it could be seen that in the above simplified example there were three separate sets of four simultaneous equations containing the unknowns. Because of errors of measurement of rainfall and run-off this set of equations would be inconsistent, and a least squares or iterative solution was necessary. With the advent of the digital computer this presented no difficulty to the practising engineer, for he merely had to post a tabulation of his rainfall and run-off data to the computer operator (see introduction to reference 18).

134. In the opinion of Professor Munro it was a professional crime for any engineer to attempt a flood study for a major work without first measuring rainfall and run-off on the project catchment and deriving unit hydrographs.

135. Until some experience had been gained, the practising engineer might need some advice from specialists in engineering hydrology in planning the instrumentation network and preparing his results for the computer, but the detailed procedures were quickly learnt. Occasionally a catchment gave erratic and inconsistent answers regarding its characteristic run-off pattern, and for some the linear relation between excess rain and run-off, implied in unit hydrograph theory, was not strictly true. But the vital points were:—

- (i) There was no other method of predicting “design flood” from “design rain” which in accuracy approached this procedure.
- (ii) “Derived” unit hydrographs were much more accurate than those “synthesized” from catchment characteristics.

Dr Roderick Agnew (Lecturer in Hydraulics, Queen's University, Belfast) suggested that the Author's equation (16) be re-written with the terms in ascending order, thus:

$$i = s + a_0 \cdot q + a_1 \cdot \frac{dq}{dt} + a_2 \cdot \frac{d^2q}{dt^2} + \dots + a_m \cdot \frac{d^mq}{dt^m}$$

It would then be clear that neglect of all terms above zero order implied that rainfall = storage + run-off. The higher order terms allowed for past events (such as antecedent precipitation causing water-logged ground, hence quicker run-off), the rate at which those events occurred, etc.; a few terms of higher order were adequate. This approach was reminiscent of von Karman's similarity theorem for turbulent velocity fluctuations:

$$u' \propto l \cdot \frac{du}{dz} \propto l^2 \cdot \frac{d^2u}{dz^2}$$

With the Author's treatment of terms in descending order, what was their physical significance when n was not an integer?

137. In a recent Paper, O'Donnell¹³ had shown that his IUH derived by harmonic analysis produced an earlier and higher peak than the Author's exponential IUH for the Ashbrook catchment, with run-off values differing by about 10%. How did the present analysis compare with O'Donnell's harmonic method?

Mr E. E. Dawson (retired; formerly District Engineer, Tanganyika Railways) observed that the Author had made no reference to overbank spill. Those catchments in which heavy rainfall might be expected to give appreciable spill were presumably omitted from the study; or was the IUH assumed to reflect the effect of such spill? Possibly spill was included in “other neglected factors” mentioned in § 3.

139. The theory of the unit hydrograph implied that a stream when in spate flowed no faster than when in its normal state; since this was contrary to common observation the evidence was distinctly against linearity. In view of this could the Author be persuaded to consider a more realistic theory?

The Author, in reply, thanked Mr Wolf for his able presentation of the Paper, and for his closing remarks. In a few paragraphs Mr Wolf had clearly and precisely described the unit hydrograph idea and the relation thereto of the work described in the Paper.

141. Mr Wolf, Professor Munro, and Mr O'Donnell had all stressed the fact that synthetic unit hydrographs were to be used only in the absence of suitable records, and Professor Munro had stated emphatically that such absence should be tolerated only in minor schemes. These speakers had also emphasized the fundamental simplicity of the use of unit hydrographs. The Author was completely in agreement, and the only reason why he had not made these points in the Paper was that he had assumed universal agreement on them. Excellent accounts of the use of unit hydrographs were given in many text books and it had not seemed desirable to repeat these in a new Paper on the subject.

142. Mr Bowen and Mr O'Donnell had discussed the base flow separation and

Dr Sutcliffe had suggested the use of the total hydrograph without any separation. This suggestion greatly appealed to the Author. The separation of base flow was necessary only to avoid long tails on the unit hydrographs and consequent difficulties in numerical computation. It was profitless to discuss whether a particular method of separation was a good one or a bad one unless a physical definition of the two components of the hydrograph was understood. Such a definition was hardly possible, since, because of the various kinds of interflow, the total hydrograph was a continuum rather than the sum of two or three qualitatively distinct parts. It seemed that the only really satisfactory approach would be to adopt Dr Sutcliffe's suggestion and use the whole hydrograph; a considerable advantage of this course would be that the input to the catchment would be the total rainfall less the evaporation and transpiration losses—so avoiding the necessity of defining effective rainfall. However, a non-linear element would certainly be required to represent the ability of the soil to retain water below the saturation level. In the present study the method of separation must be looked upon as the definition of storm run-off and base flow without any implications as to the physical origin of the two parts. The method was simple in definition, though, as Mr O'Donnell had pointed out, it involved a trial-and-error calculation in practice. However, it was not either subjective or capable of leading to absurdly different separations depending on very small differences in the hydrograph, as were many of the methods which depended on expressing the total recession as the sum of two or three logarithmic parts. Mr Bowen had drawn attention to the small fraction of the rainfall which had become effective at Swallowfield (Fig. 20c). Unfortunately the Author could not at the present time check the computations which had led to Fig. 20c, but it appeared that something might be wrong. It should be noted, however, that an error in the scales of rainfall or discharge would make virtually no difference to the values of the UH parameters obtained.

143. Once the "input" and "output" had been defined the next question was to find the relation between them. Mr Appleby, Mr Dawson and Mr Bowen had expressed doubts on the suitability of a linear system—Mr Dawson had kindly given the Author privately proof that the increased velocities attendant on high discharges implied non-linearity. It was doubtful, however, if the present data were sufficiently precise to warrant a non-linear treatment, which must necessarily be very much more difficult than the present study. Some recent experimental work done by the Author tended to indicate, though not very clearly, the constancy of the product of time and velocity which agreed with Mr Appleby's basic premise.¹⁵ Professor Dooge in a penetrating analysis, had accepted the usefulness of a linear system and the correlation of m_1 with the catchment characteristics but had argued: (i) that the correlation for m_2 was not good enough; (ii) that a three-parameter equation was justified; and (iii) that the method of equating moments was inapplicable in determining the values of the parameters of equation (33), because the data were on a finite time base and the equation implied an infinite time base.

144. The correlation for m_2 was indeed poor, but nevertheless significant. Because it was significant it would be inappropriate to neglect it. The Author did not share the view that the bad correlation was due to the choice of catchment characteristics, but believed that it was due to the difficulty of measuring m_2 accurately in the data. Since m_2 was a second order quantity, small errors in the data and inadequacies of the linear theory made m_2 as measured rather variable even among the floods on a single catchment. Similarly, m_3 was even more subject to this variation. Holding this view, the Author had felt that a poor correlation for m_2 made it profitless to seek a correlation for m_3 .

145. With reference to point (ii) there appeared to be a slight misunderstanding. The insertion of "at least" in § 35 was accepted. The number of parameters which could usefully be employed in the general IUH equation was equal to the number of independent correlations obtained between the IUH and the catchment characteristics. It was certainly true, as Professor Dooge had demonstrated, that a three-parameter equation could represent the IUH's better than a two-parameter one. Similarly, a

four-parameter equation could do even better. But was this really relevant? Since only two correlations were available it would not be possible to determine the appropriate values of three parameters in a practical case if a three-parameter equation had been chosen. The justification of equation (33) depended, of course, on the restriction to a two-parameter equation, and Figs 11 and 12 were used simply to judge between several two-parameter equations. It had not been intended to suggest that Figs 11 and 12 justified a two-parameter equation rather than a three-parameter one. The general differential equation with constant coefficients had been referred to merely to show that it was not really as general as it seemed (see Fig. 14). Professor Dooge's point (iii) was accepted. Because of this point, the Author, during the analysis, had "truncated" the curves corresponding to the theoretical equation at a point $t = 3m_1$ from the origin and had calculated the moments of the part of the curve above a line from the origin to this point of truncation. That was to say that the theoretical curve had been treated in the same way as the data, which was in fact Professor Dooge's suggestion in § 101. The moments of the truncated curve had then been expressed in terms of n and K as before, but instead of simple relations like equations (34), (35), and (36), quite difficult relations had been obtained. These modified equations had been used to determine n and K for some of the floods used in the study, and the reproduced floods were compared with the originals. In a majority of cases the reproduction obtained had been less good with the modified than with the unmodified equations. While this could scarcely be considered conclusive it had suggested that the modification was scarcely worth the trouble. This part of the work had not been described in the Paper because of the amount of space it would have required and because the Author had felt that the theoretical rigidity had not justified the abandonment of the extremely simple form of equations (34), (35), and (36).

146. In § 99 Professor Dooge had expressed a preference for what had come to be called "routed time-area diagrams" (i.e. an inflow in the same form as the time-area diagram was routed through an element of linear storage to produce the IUH). If the constant K of the storage element was of the same order as the time of concentration, the IUH produced retained very little of the characteristics of the time-area diagram. This applied even more to the UH's of finite duration. Consequently, it was virtually impossible to test any of these methods properly, and until such a test could be made it seemed a needless complication to introduce the time-area diagram. The shape of the time-area diagram and hence of the catchment would have to be very unusual indeed to produce, when routed, a two-peak IUH as had been suggested by Mr Hartley. It seemed that the catchment would have to consist of two areas connected by a long neck of negligible area. The time-area diagram did of course represent a catchment characteristic which could easily be used in a correlation, and Mr Hartley's objection that a catchment could be turned back to front without altering the values of the characteristics used in the Paper, was equally true of most such characteristics. The even limited success of such correlations indicated that all catchment characteristics were not truly independent of one another. A catchment turned back to front would not be in a state of morphological equilibrium, and would probably be quite impossible.

147. Mr O'Donnell and Professor Munro had discussed the utility of deriving UH's by the method of moments rather than the standard method of solution of a set of simultaneous linear algebraic equations or the harmonic analysis method developed by Mr O'Donnell. These methods referred to the derivation of UH's from catchment characteristics. There could be no doubt that either of these methods would produce a UH which, when the convolution with the effective rainfall was performed, would reproduce the flood from which it was derived, better than the method suggested by the Author. These methods did not presuppose an IUH restricted in any way but their very generality was their weakness. For use in a correlation the number of degrees of freedom of the IUH must be restricted. Therefore, even if the IUH's were obtained by an exact method some measures of the IUH's must be chosen for use in the correlations. If the moments were chosen as parameters no purpose would be served in finding the IUH's by any method, as the moments of the IUH could be found directly from the

original data. However, if the UH's were required for some other purpose, such as flood estimation, either of these methods might be preferable to the use of equation (33) with the parameters determined by equating moments, provided suitable computing facilities were available. However, there were practical difficulties due to "hunting" in the solution of the set of algebraic equations. These difficulties did not arise in Mr O'Donnell's method which implied closer and closer approximation to the algebraic solution by taking account of higher and higher harmonics. This effectively restricted the IUH from hunting.

148. Dr Agnew had rewritten equation (16) in ascending order and had concluded that neglect of terms of higher order than zero implied rainfall = storage + run-off. This terminology must not be confused with that of the Paper. In the Paper the relation being studied was between effective rainfall (as input) and storm run-off (as output).

149. Dr Agnew's use of the term "storage" was quite different from that of the Author. Dr Agnew's "storage" was a rate of loss. Writing equation (16), modified for the continuity requirement, in ascending order yielded $i(t) = (1 + a_1 D + a_2 D^2 + \dots) q(t)$ in which neglect of terms of order greater than zero implied that $i(t) = q(t)$. Neglect of second order quantities yielded the standard level pool linear flood routing equation $i(t) = q(t) + K Dq(t)$. The higher terms therefore represented the differences between a system of channels and a single reservoir.

150. If n was an integer, the catchment had an analogue in a system of n equal linear reservoirs. If, however, n was not integral there was no obvious analogue to the assumed performance of the catchment.

151. While Professor Dooge had expressed some satisfaction with the results expressed in the Paper, and had compared the correlation for m_1 with other similar correlations obtained elsewhere, the Author was more inclined to the views of Mr Dawson and Mr Appleby who hoped for an improved knowledge of the relation between rainfall and run-off in the abandonment of the assumption of linearity. However, a prior necessity was to define clearly what constituted the input and output of the system. This, it seemed, could best be done by abandoning the unscientific division of the hydrograph into two or more inadequately defined parts. Failure to progress sufficiently fast in this field was probably due mainly to failure to abandon this pernicious tradition.

152. The Author regretted the errors in Figs 17 and 18, pointed out by Mr Appleby in § 119, and hoped that they had not caused difficulties for readers.

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OBITUARY

JOHN DAVID BOOTH, aged 24, JOHN ROBERTSON FRASER, aged 25, and PETER SMITH, aged 23, Students of the Institution, lost their lives on 25 June, 1961, while taking part in a glaciological and geological survey expedition to Jan Mayen Island, organized by Imperial College and Birkbeck College, London.

Mr Booth won a State Scholarship from Harrow Grammar School in 1955. He took first-class honours in civil engineering in 1958 and was carrying out research in structures for a Ph.D. at Imperial College. In 1958 he was awarded an Exhibition by the Governing Body of the College to attend the annual meeting of the British Association. He was awarded an Institution Medal and Premium in 1958 for a Paper "The Channel Tunnel".

Mr Fraser, after attending Kirkcaldy High School, graduated at the University of Edinburgh with second-class honours in civil engineering. After two years of practical experience he was appointed a research assistant at Imperial College and was preparing for a degree of M.Sc.(Eng.) by an investigation into the behaviour of arch dams.

Mr Peter Smith, the deputy leader of the expedition, went to Imperial College in 1956 on a County Scholarship from Heywood Grammar School in Lancashire. He was awarded the Faber Prize at Imperial College in the session 1958-59 and took his degree in civil engineering in 1959. In the same year he was awarded a Bursary by the Rees Jeffreys Road Fund and in 1960 he obtained a Diploma of the Imperial College in Highway Engineering. He took part in the Imperial College Icelandic Expedition of 1958.

The accident occurred when a party of six men were returning in a small boat to the main base camp after they had been working for a week on the Sorbreen, a large glacier on the southern flank of the Beerenberg, where they had been very successful in their work. A sudden disturbance of the sea, probably caused by the calving of an iceberg from the glacier, capsized the boat. Only one of the occupants managed to reach the shore.

Another student of Imperial College, Mr C. M. Smith, aged 26, who was working for a Ph.D. in Organic Chemistry, and Mr J. Cole, aged 39, a radio officer from the Post Office experimental research station at Dollis Hill, were also drowned.