Research on surface-water drainage

by

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The Chairman, Mr H. J. B. Harding, thanked Mr Watkins for his Paper and referred to Conclusion 5:

‘Subject to some qualifications in exceptional circumstances, the whole area of paved surface in an urban area should be considered impermeable in a sewer design calculation, and the unpaved areas should be considered completely pervious.’

The Chairman said that two things occurred to him in relation to this conclusion. Suppose a municipal authority, trying to be as economical as possible, worked things out on those lines and then Clore and Cotton suddenly turned an unpaved area into a paved area where the authority least expected it, how would that affect the calculations? Secondly, how would it be worked out in the circumstances of a heavy storm of rain or a foot of snow in a sudden brisk thaw?

53. The Chairman said that many years ago he was living in a house in Warwick Gardens when there was a cloudburst and the L.C.C. sewer could not cope with it; the basement was flooded to a depth of 4 ft. In the case of this sort of design was there any factor of safety, as was used in steelwork design?

Mr P. Ackers (Senior Principal Scientific Officer, Hydraulics Research Station) said that it had been a great pleasure to him to be associated with Mr Watkins in the research reported in his Paper. He had had a personal interest in the subject for many years, quite apart from his official duties in connexion with the work of the Joint Committee on Rainfall and Run-Off, which had been closely concerned with this project. The research carried out by the Road Research Laboratory—10 years’ work—represented a great effort, and that it had proved fruitful was amply demonstrated by the Paper.

55. One of the approaches to urban drainage that had been adopted in North America recently was what might be termed a ‘microscopic’ analysis, in which separate consideration was given to each element of the run-off process and subsequent conduit flow.¹⁰ In such an analysis the precipitation was first reduced to account for surface wetting and evaporation loss, and the resultant effective rainfall was then considered element by element and section by section in its passage to the outfall, including overland flow, open-channel flow in the gutters, through the gulley connexions to join the branch sewer, and so into the main sewer, each minor contributory surface being gradually added in a complex analysis to give the cumulative outflow from the system. The R.R.L. approach was on a much broader basis, accepting the general principles implicit in the time/area diagram and then comparing extensive experimental data with this basic theory in studying the deficiencies of the traditional methods of design. This, as explained by the Author, had high-lighted the attenuating influence of pipe storage, and a relatively simple method had been

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proposed for taking account of this. A subsequent speaker would be giving a brief account on research carried out at the Hydraulics Research Station which had confirmed the reality of the attenuation process where free surface flow in a pipe-line was involved.

56. It would be apparent that the design of drainage systems in rural areas, as opposed to urban areas, must be based on quite different principles. The results from Harlow cited in §§ 7-11 showed how the soil-moisture balance affected the run-off from rural, i.e. non-paved, areas. In extreme cases of saturation, very high run-off percentages had occurred in small rural catchments; for example, the 1960 floods at Exmouth resulted from about 100% run-off from a hilly area of 2000 acres, following 8½ in. of rain in 10 days, culminating in a 2½-in. rainfall in the late autumn of a very wet year. This was a point to bear in mind if one had a mixed type of area, which might have a very large rural proportion in relation to the paved area.

57. The Hydraulics Research Station assisted in the research programme by advising on the design of flow-metering devices, wherever they could be used. An interesting problem was presented at Brighouse, however, where the steepness of the sewers precluded the use of a flume or weir. It was essential to the research project to determine the stage/discharge relationship for the storm sewer, so that the recorded stages could be converted to flows, and this had to be accomplished automatically during storm conditions in order to cover an adequate range of depths. The salt-velocity method was considered to be the best approach, and an entirely automatic system was devised as a co-operative venture between the two stations of D.S.I.R. Great difficulty was experienced in maintaining the equipment in operating order over the protracted periods of inactivity between storms, but eventually sufficient records were obtained for the purpose.

58. This calibration at Brighouse provided a roughness value for that particular sewer (which had been in use for a number of years), and following this up, an extensive programme of research had since been carried out on the roughness of sewers after a period of use, with special reference to the reduction in carrying capacity due to the resultant sliming. A report on this was shortly to be submitted to the Institution for publication, and it would not be appropriate to go into further detail at this point, although a knowledge of sewer roughness was obviously an essential element of sewerage design. It was necessary to apply an appropriate value of the roughness coefficient k_s . The results of the research on old sewers were incorporated in a set of tables, recently published as a Hydraulics Research Station paper.¹¹ These gave discharges and velocities in pipes from 6 in. in diameter to 96 in., over a wide range of slopes and for eight roughness values. The tables were based on the Colebrook-White equation, and the programme and computations for the purpose were prepared by staff of the Road Research Laboratory on their Pegasus computer. However, if full use were made of the computer facilities (also utilizing the Colebrook-White equation) in the design project as a whole, then in many cases it would not be necessary to refer to these new tables for pipe flow.

Mr L. B. Escrib (Principal Assistant, Professional, London County Council) said that it was not possible to judge the paper after merely reading it: many statements were made which were not supported. It was necessary to read the previous literature of the Road Research Laboratory and then convincing support for many of the statements still could not be found. What one did find was that much of the experimental work was too questionable for use in scientific research: assumption was built on assumption: unsound mathematics were used; there were inaccuracies of arithmetic, plotting, fact and reference to the literature, and there were significant omissions. There was too much to be criticized in the time allowed for discussion but these matters would be dealt with in a paper before the Institution of Public Health Engineers in May.¹²

60. One point would be dealt with because, in this, a contribution could be made. After comparing actual recorded hydrographs of run-off from sewers with those calculated from rainfall, the Laboratory had noticed that the peaks of the former were much lower than the peaks of the latter. They then assumed that the principal factor causing this difference was storage in the sewerage system and, to adjust for this, made an arbitrary assumption regarding the amount of this storage.

61. It was not always appreciated that time-of-concentration methods, which included the Lloyd-Davies method and the hydrograph method used by the Laboratory in their research, were means of determining the effect of storage on the run-off from sewerage systems. The outgo from a sewerage system was a function of the time of concentration and the storage: thus it was irrational to use a time-of-concentration method and then make an adjustment for storage in the sewers. Furthermore, the amount of storage allowed by the Laboratory was purely arbitrary, not based on any reasonable calculation: in fact, it could be disproved by hydraulic calculations.

62. There was another and much more reasonable explanation of the difference between recorded and calculated hydrographs. Several writers, including Lloyd-Davies, had observed that impermeability (using the word in the extended sense known to surface-water sewerage engineers) increased during rainfall, and it could be suggested that this was the main cause. Examination of the hydrographs showed that not only were there differences between peak flows, but much greater differences at the beginning of run-off: this supported the suggestion. Working from a selected storm at one site Mr Escritt had derived an approximate formula for this impermeability change, and this, when applied by hydrograph method to more complex storms at other sites, was found to give very good agreement, as shown in Fig. 15.

63. He had suggested to the Laboratory that their storage theory could be checked by recording the run-off from a catchment which discharged direct into a measuring vessel for, if there was no intermediate drainage system, there could be no storage in it. They had not replied to this suggestion. He had therefore carried out experiments himself, using the most impermeable and clean-draining surface imaginable—a sheet of plate glass laid at a gradient of 1 in 15.

(a) BLACKPOOL, 12 AUGUST 1954

(b) KIDBROOKE, 18 JULY 1953

(c) OXHEY, 17 SEPTEMBER 1953

FIG. 15

64. In Fig. 16 was shown the curve of the formulae he had derived from the Laboratory's field experiments and, on this, were plotted some data points of the plate glass experiments. These experiments showed that, even when plate glass was used as a catchment, marked change of impermeability occurred.

65. Change of impermeability was of considerable practical importance and should be taken into account in design. Fig. 17 showed the curve for Bilham's formula for storms likely to occur once a year and, below that, the curve for rainfall run-off to sewers likely to occur once a year according to the provisional change of impermeability formula. It showed that, below 11 minutes' duration, there was a reduction of intensity in run-off to sewers, which supported the practice of many engineers of not allowing for rainfall intensity greater than that of the 10-minute storm.

66. Referring to § 46 in which the Author referred to the modified tangent method, he considered this an error of nomenclature. The original tangent method, invented by Reid¹³ for the purpose of selecting the storm conforming to the Ministry of Health curve that would produce the greatest run-off for any time/area graph, was corrected for mathematical imperfections by Riley¹⁴ and, for many years, Riley's method had been generally known as the tangent method. Mr Escritt devised the modified tangent method¹⁵ for use with rainfall formulae, such as Bilham's formula,

FIG. 16

in which duration of storm was expressed to a fractional power, therefore calling for a modified method. This was generally known as the modified tangent method but was not described in any of the Author's writings.

FIG. 17

Mr A. J. M. Harrison (Senior Scientific Officer, Hydraulics Research Station) said that the work described in the Paper represented a period of over 10 years' research into the relation between run-off and rainfall in several catchment areas. A thorough study had been made in a number of catchments of different characteristics and for each storm the measured run-off had been compared with that calculated from the same rainfall by several different methods. Perhaps the most important conclusion which could be drawn from the results was that a theory based on the assumption of steady uniform flow could not be used to represent correctly what was in fact an example of non-steady non-uniform flow. The attenuation of a flood wave in a river as it passed downstream had been recognized and studied by engineers for over a century, so it was surprising that in this country the design of sewers was still in general based on methods such as Lloyd-Davies's which took no account of the non-steady nature of the phenomenon.

68. To study in more detail the influence of the 'pipe storage' on the design of storm-water sewers, an experimental investigation had been in progress at the Hydraulics Research Station in the past 3 years into the unsteady, free-surface flow that occurred in a circular-section conduit under an advancing flood wave. Fig. 18 showed the experimental arrangement: there was a 300-ft length of 3-in.-diameter pipe-line of adjustable slope; multiprobe depth recorders were set at 60-ft intervals, water levels being recorded by a multiple pen recorder in the hut. The flood waves were injected by a cam-operated butterfly valve and discharges were measured by a propeller-type meter giving a continuous graphical record.

69. Fig. 19 gave a close-up of the flow meter and butterfly control valve. By means of a number of interchangeable cams and a range of available speeds the slope,

FIG. 18

FIG. 19

height and length of peak of the waves could be varied. A by-pass arrangement was provided so that these waves could be superimposed on base flows of various magnitudes.

70. One hundred and forty-four waves were studied at five different pipe slopes. A concise method of presenting the results was required and after a number of trials the method shown in Fig. 20 was evolved. For a given base flow a dimensionless depth of wave peak parameter was plotted against a dimensionless distance parameter, the other dimensions involved being pipe diameter D , wave volume V and pipe-full flow Q_t . The origins of distance x and time t were taken as the point (in space and time) where the wave peak height was midway between the base flow depth and the pipe soffit. The dimensionless depth/time relationship was shown in Fig. 21. Altogether 27 runs were plotted in each figure. The correlation showed that for a given base flow and diameter of pipe the attenuation of a flood wave with regard to time was a function only of the volume of the wave, the wave profile having no significant influence on the process within the range of the experiments. The attenuation with regard to distance was a function also of the pipe slope and roughness (implicit in Q_t).

71. It was interesting to compare the correlations of this analysis with the Author's method. The depth/distance correlation could be written

$$\begin{aligned} \frac{h}{D} &= f\left(\frac{x\sqrt{gD^3}}{VQ_t}\right) \\ &= f\left(\frac{x D^3 \sqrt{g D^3}}{V Q_t}\right) \end{aligned} \quad \dots \dots \dots (1)$$

The first term in parentheses was a storage function and was in fact proportional to the ratio of pipe volume to wave volume, i.e. it was directly related to the R.R.L. hydro-graph routing method. The second term was a form of Froude number, which took account of the pipe slope; a comparable term, however, did not appear in the R.R.L. method.]

FIG. 20: DECAY OF PEAK WITH DISTANCE: $h_0/D = 0.09$

72. Again, the distance/time relation could be written

$$\begin{aligned}\frac{h}{D} &= f\left(\frac{t\sqrt{gD^5}}{V}\right) \\ &= f\left(\frac{tQ_r}{V} \frac{\sqrt{gD^5}}{Q_r}\right) \dots \dots \dots (2)\end{aligned}$$

and the terms in parentheses were again the storage function and the Froude number.

73. Looking at equation (1), it appeared that a wave of a given height and shape would attenuate more rapidly with distance in a pipe of low gradient than of steep gradient. Assuming that this basic case of an unbranched pipe-line with single input formed a special case of the more general sewerage problem, the R.R.L. method should by implication tend either to over-estimate the run-off at low slopes or to under-estimate the run-off at steep slopes. Fig. 22 did in fact confirm this trend. The mean errors (taking account of the sign) of the Lloyd-Davies and R.R.L. methods had been plotted for each area against the mean ground gradient. However, among the narrower band of R.R.L. points a distinct tendency to under-estimate was evident at steep slopes, as would be expected from the application of the findings of their basic research.

74. Despite the neglect of the slope factor the R.R.L. method of design showed a marked improvement over the other available techniques. It recognized the non-steady nature of the complex flow phenomena of a storm-drain system and as such was an advance on the simplified methods. It might be that some refinement could be made to increase its accuracy even further, at the expense of further complication

FIG. 21: DECAY OF PEAK WITH TIME: $h_0/D = 0.09$

in the method of application. However, it was considered that this would need additional research and full analysis of the complexities of the practical case of branched systems, and it would be unfortunate if on this account the gain in accuracy obtainable from the R.R.L. method were not made use of immediately.

FIG. 22

Mr D. J. Holland (Meteorological Office) said that at the Meteorological Office, as would be known, there was long-term research work supporting that of the R.R.L. that had been mentioned in the Paper. His remarks would be confined to some of the work that his Office had been doing during the past year. The work came under two headings, one part being concerned with relating rainfall duration and frequency at individual points, while the other was an investigation of the change in that relationship when averaged over various sizes of area.

76. Under the first heading, the Bilham formula was the one most widely spoken of, and it was the one favoured by the Office. It dated from the middle 'thirties but had stood the test of time. That had been demonstrated several times in the course of the years. For example, a review of all relevant material collected in the Meteorological Office in a period 36 years since Bilham's own material began, showed that the formula had stood the test of time right up to 1960. The observed frequency of falls of 1 in. of rain in 24 hours matched the Bilham formula even more accurately, when taken over 30 years or so, than in Bilham's own day, when the data covered only 10 years.

77. Considering comparatively small amounts and small durations, until recent years the smallest duration for which an answer was fairly confidently known was about $\frac{1}{4}$ hour, and the observed frequency for a fall of $\frac{1}{4}$ in. of rain in $\frac{1}{4}$ hour again closely fitted the Bilham formula.

78. In recent years the development of the open-scale technique of rain recording, in which there was a chart running at the rate of $5\frac{1}{2}$ in./h. along the time scale, had made it possible to see what happened in detail over still shorter durations. In that connexion there was a network of stations up and down the country, all using the open-scale technique of rain recording with a view to carrying on for a long term to try to reveal whether there was a systematic variation across the country from one side to the other.

79. The Bilham formula represented a regional mean for Britain as a whole, but there were broad hints of a systematic variation from one side of the country to the other. The technique had only been running for a few years so that it was too early to expect anything conclusive, but it might be of interest that, in addition to 11 Meteorological Office stations which were still operating rain recorders using this open-scale technique, there were about 70 operated by local authorities. The northernmost was at Aberdeen, the southernmost at Paignton. Two of the Meteorological Office staff who handled the information had personally visited about 50 of these authorities during the course of the past year, and would be visiting the rest in 1963. This had enabled them to see every set-up at first hand, and it had been a good thing on both sides. It had put the Meteorological Office in the picture regarding each station's set-up, and it had shown the local authorities that the Office was taking an interest.

80. Under the second heading were the investigations into the effect of the size of area. One was at Cardington in Bedfordshire, the other at Winchcombe in the Cotswolds. The last batch of data, which completed the material for Cardington, had been received by the Office about a month before the Meeting. Material for the investigation had been received in various forms, some as plotted maps, every map representing the pattern of rainfall over the Cardington network for a 2-minute step. There were nearly 4000 of those maps, and it was proposed to analyse them, mapping out the rainfall by means of curves and using them in turn to assess the rainfall over various specific areas of different size. With such a big job, it was obvious that statistical results were not expected before 1964, but the job had high priority. The basic material was all in 2-minute steps, and it was hoped ultimately to be able to give statistics for durations that were multiples of 2 minutes. There were now enough data to give an idea of the size of sample, and to put all the statistics on a sound footing. At Winchcombe a similar scheme was operating with a basic network so far of 16 sites, which would be handled in the same way. That scheme was started in the middle of 1962 so that the analysis of the results would not be in hand for some time.

Mr Granville Berry (City Engineer and Surveyor, Coventry), represented by Mr B. D. Steele, said that in post-war years, with the rising cost of sewerage works, there had been an increasing feeling amongst engineers that there should be further research into the existing methods of design which were perhaps not always economic. Valuable research had been carried out by the Road Research Laboratory, the Hydraulics Research Laboratory and the Meteorological Office and there was no person who could better deal with this subject than the Author, who had been Secretary of the Joint Committee on Rainfall and Run-off of the Road Research Laboratory and the Ministry of Housing and Local Government. He considered that this work constituted a major break-through in the field of main drainage design and felt sure that generations of engineers in the future would consider the Paper to be no less significant than that presented to the Institution by Lloyd-Davies in 1906.

82. In many towns and cities today where the main trunk sewers had outlived their usefulness and needed replacing or duplicating, the new method would be of great value in investigating existing sewerage schemes. The new hydrograph method

appeared to be more reliable in the case of the larger sizes of sewers than the rational or Lloyd-Davies formula in common use, although there was still a future for the Lloyd-Davies basis of design for calculating the run-off from small drainage areas.

83. Many advantages of the R.R.L. hydrograph method were immediately apparent: the design argument was derived from first principles and avoided empirical assumptions to a large degree. It considered the changing situation over a drainage area at regular short intervals of a given storm, usually of 1 minute; it was concerned with a selected rainfall profile rather than with average intensity. Thus the engineer would be able to make full use of current research into rainfall distribution and storm profiles which were subjects on which he had had so little information in the past. In addition, when the new method was programmed for an electronic computer, it became very flexible, as variations could be more readily made in the design by changing the design parameters: the effects of different hypothetical flooding frequencies or of different hydraulic conditions in pipe-lines could be considered for the whole of a design or for particular sections of it. While it could not be claimed that these facilities had not been available to the engineer in the past, it was probably true to say that no one method had before combined them all. In short, it might be said that the theory was attractive in its scientific and precise analysis and the application was capable of embracing new knowledge and offered great flexibility of design.

84. Probably two of the main bones of contention that evening would be those two hardy annuals of main drainage design—impermeability and storage. On the question of impermeability he merely wished to say that the assumption of any particular impermeability factor did not affect the method of calculation, although it would certainly affect the computed maximum run-off. An engineer wishing to make less than a 100% allowance for some good reason over a large or small paved area would merely make the appropriate numerical adjustment of area in the tabulated data for the lengths to which the area drained; if, as a result, his design were less accurate, he had only himself to blame. The question of storage was one which appeared to arouse more interest—if not emotion—than any other subject in this field. No one would doubt that sewers formed a huge reservoir beneath the cities and that this must affect peak run-off. Whether other methods did or did not allow for this effect was perhaps not entirely relevant to the discussion of the Paper. Certainly the Author had made a valuable contribution to the thoughts on this subject, and his method of evaluating the storage effects from the recorded hydrograph of an existing system was both accurate and ingenious. In making the step of applying this to systems under design he made an assumption which he did not claim to be precise but which all practising engineers would know was reasonable for a newly designed system. Experience in the application of the method would confirm the validity of this basic assumption. Some experience had in fact already been obtained in Coventry.

85. In the course of the past 15 months his Department had been in active co-operation with the Author and his colleagues in the practical application and development of the computer programme for the design of sewers by the R.R.L. hydrograph method. The flexibility of the method was perhaps illustrated by the fact that a computer programme originally written for the design of new storm sewers was readily adapted for checking the designs of duplication schemes for foul sewers on the partially separate system containing several storm water overflows. The first scheme so checked was the Allesley foul-sewer duplication, comprising 5 miles of new sewers from 12 to 36 in. in diameter in parallel with the old system draining approximately 4 sq. miles of the city. Traditional designs by the Lloyd-Davies and the tangent methods were available. Assuming that the drainage area survey and abstraction of impermeable areas, which were required for all methods, had been completed, the tabulation of the data for the computer was a matter of a few days' work for a junior assistant, compared with a number of weeks' work by a senior and junior assistant using the traditional methods. A comparison of the designs might be of

some interest to members. On this particular scheme, the rational method designed peak rates of flow on average about 20% higher than the R.R.L. hydrograph method; the tangent method calculation of the total flow was over 50% in excess of the hydrograph calculation. In terms of designed pipe sizes these differences were reduced because pipes were available only in 3-in. increments of diameter; the capacity of a 36-in. pipe exceeded that of a 33-in. by over 25% at ordinary gradients and this percentage increased as the pipe size was reduced until a change from a 9-in. to 12-in. pipe more than doubled the capacity. Thus on average a very considerable economy of design was required to reduce the pipe size and any such tendency would be reflected more in the larger sized pipes. Generally, in terms of pipe sizes, the R.R.L. method gave similar results to the rational method except at the lower end where the new method designed pipes one size smaller than the rational method and one or two sizes less than the tangent method.

86. In the course of their discussions with the Road Research Laboratory it was suggested that for the design of a major trunk sewer the inclusion of a full data tabulation for every one of the hundreds of small sewers within the drainage area might be somewhat onerous. A limited form of data tabulation was therefore evolved which allowed any sub-area forming a relatively small proportion of the total to be treated as a single unit, so that its full effect on the main computation would be felt without the necessity of designing each sewer within the sub-area. The Butts sewerage scheme at Coventry was used to test this method, which proved to be sufficiently accurate for major schemes and would allow considerable economies of time both in the data tabulation and in the computation of the design. The interest of the Butts, however, lay in the fact that it was the first scheme submitted to the Ministry of Housing and Local Government as a purely computer design by the R.R.L. hydrograph method. The storm sewers were submitted as a fully detailed design and the partially separate foul sewers were designed with limited data only. Loan sanction had recently been received and this mark of Ministerial approval was an important precedent of which members might be glad to be aware.

87. The limited data method for sub-areas was being extensively used in the Sowe Valley sewer duplication scheme on which those at Coventry were currently co-operating with the Road Research Laboratory as a further research project in parallel with the traditional design which was continuing in Mr Berry's office. The major trunk sewer considered for this design was approximately 12 miles in length and drained an area of 22 sq. miles through 63 separate drainage areas containing 520 acres of impermeable area. The re-design of the sewer along its present route involved a time of concentration of over 300 minutes. This scheme was perhaps a sewerage project of near maximum size for this country and would provide a rigorous test of the computer programmes. In addition it raised interesting problems of storm intensity and distribution, and he awaited with very great interest the comparison between the R.R.L. design by computer and that already completed by the tangent method.

88. With regard to the use of computers generally, it seemed certain that within a few years engineers would become fully aware of the wide opportunities offered by these machines, and in main drainage departments they would be used not only for the calculation of maximum run-off but also for the structural design of pipe-lines, for their hydraulic design and perhaps even for producing estimates and bills of quantity. His authority must be among many others who were in the course of acquiring a modern computer. The position could be foreseen in the future when the data for all the main sewers in a city would be held on tape. By making additions or amendments to the appropriate data tape the probable effects of any development or redevelopment in a drainage area could be quickly determined, and flooding problems resulting from storms of unusual intensity could be investigated. Thus the whole science of main drainage design in a large conurbation would become more

precise, allowing a calculation of flooding risks and a rapid evaluation of proposed changes in impermeability.

89. The new design method and the new computer techniques offered the engineer a powerful tool which would be used in parallel with traditional methods for some time but would, he felt sure, ultimately replace them to a large extent.

Mr A. J. M. Young (Chief Engineer's Department, London County Council) said that in § 34 it was stated that the 'rational' or Lloyd-Davies method was less accurate *on the average* than the R.R.L. method. This statement was not supported by the data. Table A in Appendix 1 of Road Research Technical Paper No. 55¹ showed that errors of minus sign had been added to errors of plus sign, and the signs had been ignored. This was surely unsound mathematics and produced incorrect results.

91. To find the average accuracy of the Lloyd-Davies method, this could be done in the normal way, taking account of the plus and minus signs, but it was necessary first of all to delete all data which were obviously too suspect to be considered.

92. Perhaps the circumstances of the twelve different sites might be enlarged upon by way of explanation. Area 1 was the roadway at Oxhey. Here the results were influenced by run-off from grassland areas of undetermined size, one side of the road being in shallow cutting. Area 2 was the small factory area at Stevenage. Here resurfacing of the roadways took place during the progress of the experiments and it was noted that it did cause a marked change in the percentage run-off. Incidentally, there was also some doubt there whether the road surfaces drained properly to the gulleys. In Area 3, the small factory area at Kidbrooke, an appreciable part of the paved area which had been assumed to drain into the drainage system was in fact never designed to do so. In Areas 4 and 7, the small housing areas at Stevenage, there was an abnormally high leakage of the sewers, and although the quantity of leakage must have been *variable*, a *constant* adjustment factor had been allowed. With regard to Area 9, the old mixed development at Brighouse, it had been stated—and mentioned that evening, he understood—that the accuracy of the gauging arrangements was somewhat doubtful. Area 10, Kensington, was one where excessively large old sewers served as laterals, and the run-off was measured at one point only, while there must have been some unmeasured flow escaping at other points in the system except at times of very low flow. The results obtained from this area were sufficiently strange to show that something was amiss somewhere. Area 12 was a large undeveloped area at Harlow and should not really be included in the same category as the other sites investigated. This left only four areas giving altogether reliable data: 5, 6, 8, and 11.

93. If the true average for these four areas were taken, namely, taking account of signs, then the Lloyd-Davies method was found to give a result which was 3% low. If, however, it was considered that only the most questionable areas should be omitted, namely, areas 9, 10, and 12, the average for the Lloyd-Davies method on the remainder worked out at 3.2% high. Thus it could be said that, as far as could be ascertained from the data, the Lloyd-Davies method was accurate and could not be improved upon, *on the average*.

94. In Table A of reference 1, the figures in column 7 appeared to be derived from columns 4 and 6. If that were so then there seemed to be numerous mathematical inaccuracies.

95. Finally, in the interpretation of rainfall/run-off data there were various factors for which allowances could not be made. For example, if a storm moved in the direction of flow in the sewers, then the run-off would be greater than for a storm of the same magnitude but moving in the opposite direction to the flow in the sewers. It was therefore necessary to consider averages only and not individual cases.

Mr D. J. Maclean (Head of Soils Section, Road Research Laboratory) said that he would first like to explain why the R.R.L. adopted the experimental approach described by Mr Watkins in his Paper, and secondly to make a suggestion about the lines on which further research might be carried out on this subject.

97. When the research was originally planned the possibility was considered of concentrating the investigation at one or two large drainage areas. Each drainage area would have been broken down into a number of small sub-areas and the rate of flow in the sewer draining each sub-area would have been accurately recorded.

98. This method of approach appeared to be quite attractive since it would have shown how the rate of run-off at the outfall was built up by contributions from each of the sub-areas and it would also have provided information on the design of sewers for small sub-areas.

99. It proved necessary, however, for a number of reasons to abandon this method of investigation. First, there were practical difficulties associated with the accurate measurement of the rate of flow in a sewer pipe. This required specially designed flumes and it was evident that the installation of a number of these flumes in the same area in the course of a normal sewer contract would have proved highly impracticable and unduly expensive.

100. It was also realized that the accuracy in the design of sewer sizes was far more important economically towards the downstream end of a sewer system and that it would therefore be preferable to concentrate on a study of the factors affecting the rate of run-off at the outfall of a sewer system as being representative of these downstream conditions.

101. Another aspect that influenced their approach to these investigations was the necessity to study the effects on the rainfall/run-off relation of variations in rainfall conditions associated with geographical situations and of the greater variations in types of development than would have existed in a single drainage area. They were thus led to the opinion that the greatest benefit would be derived from measurements of the rate of flow at the outfalls of a range of urban drainage areas of differing size, topography and development, rather than from making a detailed study of the flow conditions in one or two drainage areas. It seemed likely that the latter approach would have provided a smaller benefit to present practice and at greater cost than the method adopted.

102. With regard to the need for further research, the final proof of the findings of these investigations, together with the important contributions which had been made by the Meteorological Office and by the Hydraulics Research Station, would be obtained from their application to normal practice. It was encouraging to see the interest already shown by practising engineers in this respect, and sewer designs had already been prepared for a number of drainage areas.

103. Mr Maclean suggested that a useful further line of investigations would be to study the tendency of such sewer systems to approach a surcharge condition during heavy rainstorms. The experimental measurements would be relatively simple to carry out and the results would not only be a useful check on the accuracy of the new design method but would also provide a sounder basis for selecting the most appropriate frequency of storm to use in design calculations and for making suitable allowances for the extension of urban development within the existing drainage area. These two factors might have a considerable effect on the designed size of sewer, and it was suggested that they could be profitably studied now that greater precision was available in the design method.

Mr J. H. Walton (Consultant in Public Health Engineering to the National Coal Board) said that he had risen to speak because he had been impressed by the fact that the majority of the contributors to the discussion so far had been research workers and not practising engineers. Perhaps the latter were to come later.

105. There was a paper in the Institution *Proceedings* many years ago in which a very eminent engineer advised the members to find a method of dealing with the different branches of their work and to stick to it. There was, he felt, a lot to be said for sticking to Lloyd-Davies. It had taken a long time to establish that method, and he did not think that the work in Mr Watkins' Paper had demolished the basic principle in any way. It was clear to him (as Mr Escritt had already said) that there was no necessity to consider storage in sewers with the Lloyd-Davies principle. This was automatically taken into account by the increase in time of concentration and the corresponding decrease in the rate of rainfall as each length of sewer was designed.

106. Referring to the tangent method, Mr Walton said that there was a method of using it with the Ministry rainfall formula in which the tangent was drawn from a point measured out from the most hollow part of the time/area curve. This had always seemed to him utterly wrong, because surely the rate then obtained—which was higher than if the tangent were drawn from minus 10 or 20 minutes on the time scale—was upstream of the point for which one was designing; and the work of Ackers at the Hydraulics Research Laboratory, which had been explained by Harrison, had shown that waves in a sewer diminished in height as they travelled downstream. This would happen also with the rate determined by using the tangent method from the most hollow part of the curve.

107. Mr Harrison had suggested that the wave theory which had been developed at the Hydraulics Research Laboratory on a relatively short small-bore pipe-line could be taken as some proof of the Author's contentions. Mr Walton suggested that whilst the principle no doubt held, there was doubt about the details because Mr Harrison had said that his experiments were valid within the wave volumes he had used. The volumes of the waves in the Author's examples were surely very many times greater. When a sewer was over 2 ft in diameter then the wave might be several thousands of feet long and, Mr Walton submitted, the Hydraulics Research Station experiments had not indicated what the results might be in that size.

108. It was a great pity to mix up the terms 'rational method' and 'Lloyd-Davies method'. The rational method should be confined, he thought, to the method used in the United States, where it was usual to reduce the rate of rainfall by the rate of soakage before applying the difference to calculating the size of sewer. The Americans first used the term and should be allowed to retain it for their method.

109. The question of change of impermeability during a storm had been mentioned. He had in the past had to design quite a number of schemes for large air-fields, where there were very highly compacted grassed areas on either side of the runway from which considerable run-off could occur. Many years ago, after reading the American rational method, he had made measurements of the rate of soakage and had found it to be fairly constant over large areas after any particular amount of rain had fallen. In other words, rate of soakage depended on the amount of water in the ground at the time when the design storm fell. A design rate of soakage could be chosen from a time/soakage curve and used in design. As an example, the design rate of soakage might be $\frac{1}{4}$ in./h. If the design rate of rainfall for the time of concentration was then $\frac{1}{4}$ in./h or less, all the water soaked away and impermeability was zero, but if the time of concentration gave say, $\frac{1}{2}$ in./h then there would be $\frac{1}{4}$ in./h of run-off giving 50% impermeability, so that the latter was dependent on the rate of rainfall, amongst other things.

110. Mr Walton said that he would like to congratulate the Author on two points. His measurement of hydrographs on existing schemes was extremely valuable, and he hoped there would be very full details of these measurements available so that people could see for themselves how they would arrive at a size of sewer in the cases where the Author had made these measurements. Rainfall details and the full data were needed so that this could be done. Secondly, the Author's preparation of the

problem for solution by computer was a pointer to the execution of future methods on whatever theory they might be based.

Mr H. D. Manning (Messrs J. D. and D. M. Watson) said that in view of Mr Walton's challenging remarks he felt he ought to say something as another engineer responsible for a certain amount of design in this field. He was, however, a 'polluted' witness in that he had been a member of the Committee, so that he could say at once that he supported the findings of the Author, whose method of calculation was a very good one.

112. The speaker said that his firm had checked three surface-water designs with the help of the Road Research Board, using their method and using their computer, and the results were interesting and useful, and showed that the method was practical and extremely flexible, as had been said before. In the case of larger schemes, or where dealing with a large number of schemes, it was a very economical method of design.

113. His personal view was that on such practical applications as he had been able to see so far the method was a very valuable tool.

Mr E. H. Ely (Messrs J. D. and D. M. Watson) asked the Author how their 'old friend' the Ministry of Health curve came out in the light of the many detailed and excellent studies of various rainfalls.

The following contributions were received in writing:

Mr Oakley (Partner, Messrs J. D. and D. M. Watson) hoped that practical engineers would not lose their sense of perspective in enjoyment of the debate between supporters of the rival methods of calculation. The differences quoted in the Paper and in the discussion would not often amount to much as a proportion of the total cost, and were of small magnitude compared with uncertainties which were inherent in the design assumptions.

116. The present research had in one sense put the cart before the horse since refined methods of calculation were only of academic interest so long as the basic meteorological data were suspect. However, it seemed to be generally accepted that Bilham's formula was reasonably accurate within a limited range, and this stated that the intensity of rainfall for a '10-year' storm was over twice that for a '1-year' storm, and that less frequent intensities of up to five times the '1-year' storm could be expected. Other than custom, there was little guidance regarding what frequency of occurrence should be taken in any particular instance; perhaps an engineer-economist would present the Institution with a rational assessment of the right balance between risk and cost for flood problems in urban areas.

117. Again, it was quite impossible to foresee what changes might take place in the impermeable area within the effective life of a sewerage system, and any assumption of less than 100% impermeability throughout would be open to risk.

118. This was not to denigrate the Road Research Laboratory's approach which offered a flexible and powerful method of calculation which would be of importance if it could be made convenient for general use. It should, however, be realized that except on the largest and most complex areas the potential saving in time and effort was small compared with that needed to obtain the basic data, make the first broad engineering appreciation and assess the importance of any deviation in the particular area from the assumptions on which the method was based.

Mr J. E. Nash (Department of Civil Engineering, University College, Galway, Ireland) wrote that the Author was to be congratulated on the work described briefly in the Paper and more fully in reference 1.

120. There had been a small number of attempts to apply unit hydrograph techniques to the relation between rainfall and the discharge of sewers but, so far as Mr Nash was aware, this was the first attempt to provide a general method analogous to the synthetic unit hydrograph method as used on natural catchments for the determination of design discharges, sewer sizes, etc. at the design stage of sewerage schemes.

121. It was certainly extraordinary that progress in this field should have been made earlier in the case of natural catchments than in the very much more determinate case of impervious urban catchments.

122. The Author's work might be looked upon as taking the design of sewerage schemes out of the doldrums of the rational method, a service provided for natural catchments by Sherman and others a quarter of a century ago.

123. The object of the method described was to determine the discharge hydrograph and particularly the peak discharge for a given rainfall pattern $i=i(t)$ on a given catchment of impervious areas drained by a system of sewers. One might almost expect that a complete analysis based on the well-known laws of hydraulics of flow on such surfaces and in such channels as occurred might be possible but the physical complexity was such, and the equations so difficult to solve, that this method, involving as it were following each particle of water from its origin in the catchment to the outfall, was not yet feasible. As yet, the determination of the hydrograph of discharge from a plane surface subject to continuous uniform rainfall had not been satisfactorily solved.

124. The Author's work provided an approximate method, justified empirically by the agreement obtained between the measured and calculated hydrographs on the catchments which formed the Author's data. This now constituted what was undoubtedly the best available method of obtaining the necessary sizes of sewers, discharges etc. at the design stage of an urban drainage system. The details of the method would be recognized by hydrologists as a variant of what was now known as Clarke's method¹⁶ whereby an area/time diagram was formed and the convolution of this with the rainfall, namely $\int_0^t i(t)v(t-T)dT$, provided an inflow which was routed through a single element of reservoir storage to produce an outflow.

125. In the original Clarke method, and in most variants of it, the routing was performed first on an elementary inflow whose ordinates were proportional to those of the area/time diagram and the convolution with the rainfall was then made. If the storage/discharge relationship of the assumed reservoir was linear, the order of convolution and routing was irrelevant to the final result. The Author's choice of order reduced the total amount of work slightly and enabled him to use a non-linear storage/discharge relationship without difficulty. The use of such a non-linear element before the convolution would greatly complicate the subsequent calculations.

126. The construction of the area/time diagram by taking the time of flow as being equal to the length divided by the velocity when the sewer was flowing full could be argued against, but a more rational alternative would involve difficulties. As the method was essentially empirical, and therefore justified by the results obtained, consistency in such matters was all that was required and therefore this objection was not important. The storage/discharge characteristics for the subsequent routing were obtained by consideration of the volume in the sewers corresponding to a given discharge (except that for Harlow the actual measured recession provided the required information). This method of obtaining the storage/discharge relationship was an essential part of the Author's work and as the method obviously could not be applied to a natural catchment, it might have been better to leave Harlow out of consideration entirely. Furthermore, it was not surprising that the unit hydrograph for Harlow could be determined fairly accurately when one parameter was available in the given recession. This agreement could not be looked upon as providing any support for the Author's method.

127. The Author's method was linear except in the storage/discharge relationship

which might in a particular case be non-linear. Would the Author consider a restriction in this also to a linear approximation unduly restrictive? If not, and Mr Nash believed that such an approximation would make virtually no difference, then the method became a particular case of the unit hydrograph method and a generalization could be obtained by determining empirically the unit hydrographs of the catchments used and relating parameters of these to the characteristics of the catchments. This would have provided a method of much greater generality than the Author's, in that the restriction imposed by a preconceived idea about the relationship between the unit hydrograph and the catchment would have been avoided. It also seemed likely that the final relationship obtained would have been easier to apply. Nobody had yet shown that the characteristics of the area/time diagram persisted significantly in the unit hydrograph, indeed the greater the time lag of the storage/discharge relationship (K in $S = KQ$) relative to T (the time of concentration) the less the unit hydrograph would depend on the shape of the area/time diagram. The Author regrettably did not give enough data to prove this point in relation to his catchments.

128. The discovery that surfaced areas alone contributed significantly to storm run-off in sewers was an encouraging one. It was equivalent to saying that pure surface run-off on natural catchments was negligible. Sewers collected pure surface run-off; natural channels collected all sorts of 'interflow' as well as pure surface run-off. The writer had often contended that good results in the prediction of river discharges could be obtained, except perhaps during the most intense storms, without considering pure surface run-off. Neglect of surface run-off simplified the problem enormously in that the soil-moisture condition became the dominant factor determining how much run-off took place during a given storm. Soil-moisture condition could be measured continuously or could often be calculated in the analysis of past records. In the absence of pure surface run-off, it should not be necessary to consider time of year, duration of storm, antecedent conditions, etc. Obviously if this were true, a much simpler analysis was possible than that current in contemporary American work.

129. Some years ago the Author very kindly made available to Mr Nash the records collected at Harlow. Mr Nash's analysis showed¹⁷ that the run-off could indeed be predicted accurately from the calculated soil-moisture deficiency and the rainfall volume, except when the calculation of soil-moisture deficiency was made difficult by periods intervening since the last previous saturation in which the deficiency grew to an extent where it might restrict the evapo-transpiration rate.

130. While the Author's work undoubtedly went a long way to providing a method of determining the discharge hydrograph for a given storm on a given catchment, the problem of the relationship between the frequency of the discharge peak and that of the rainfall remained.

131. Finally, Mr Nash suggested that, if possible, the preparation of the data for the programme for the computer might be described in detail so that practising engineers might be encouraged to make the fullest use of the Author's method.

Dr E. J. Sarginson (Lecturer in Civil Engineering, University of Sheffield) wrote that his contribution was confined to raising some points concerning the effect of retention on the discharge from a sewer.

133. The Author had given examples of areas where the existing sewers were oversize, so that the effect of storage based on the assumption of uniform proportional depth was in error. Dr Sarginson had developed a theory of storage in sewers,^{18,19} and this showed that for a given run-off hydrograph, the discharge from the sewer was only slightly affected by its diameter, provided that the sewer did not surcharge. The following example illustrated the point:

134. The full line in Fig. 23 represented the run-off from a catchment. The sewer was 1000 ft long and laid at a gradient of 1 in 500. Manning's formula

($n=0.012$) showed that a 12-in.-diameter sewer was required to pass the maximum discharge, neglecting the effect of storage. The two dotted lines showed the discharges from a 12-in. and a 24-in.-diameter sewer. The two discharge hydrographs were very little different, despite the fact that the maximum proportional depths in the 12-in. and 24-in. sewers were 0.48 and 0.18 respectively. It was therefore suggested that in an area where some of the existing sewers were oversize, they could be assumed to be replaced by sewers of the correct size for the purpose of calculation, and then a retention curve based on the assumption of uniform proportional depth could be used.

FIG. 23: THE EFFECT OF THE PIPE SIZE ON THE DISCHARGE FROM A SEWER
(The input hydrograph is arbitrary.)

135. The assumption of uniform proportional depth of flow over the whole sewer system for the purpose of computing retention curves was likely to lead to error on a large system with a high time of concentration. The sewers in the higher parts of the network would be designed for a short intense storm; consequently they would be somewhat oversize for the longer, less intense storm appropriate to the whole area. It followed that the proportional depth of flow in the upstream sewers must be less than lower sewers so that the effect of storage was over-estimated. The Author had obtained good agreement on an area of 600 acres with a time of concentration of 20 minutes but Dr Sarginson had in mind a much larger area.

Mr F. V. Appleby (Consulting Engineer) wrote that the Author's research was directed to design procedures and was indeed welcome in a field in which so little practical work had been done. The rational method made no pretence to reflect the complex interrelations of hydrologic factors in general; it was anchored firm in simplicity, it was safe and according to the Author's analysis, not greatly in error.

137. There was a mass of useful information in the Paper. For example, Table 2 gave a distribution analysis of run-off from 264 storms on a large variety of surface types. The analysis showed an almost normal (statistical) distribution with a maximum expectation of 75% run-off from surfaces all nominally 100% impervious. No

doubt in some areas the designer would consider that possible antecedent conditions would justify a 100% value. The rational method was very dependent on a correct estimate of this factor and the information given by the Author would repay critical study.

138. The times of concentration for Areas 1 to 7 inclusive were all less than 10 minutes—the design critical storms were therefore of the order of 1.50 in./h or more; it should be noted that 80% of the storms used were of smaller intensity. The information needed some further analysis on this count. Some examination of the possibility of correlation between intensity, percentage run-off and antecedent conditions would be useful from the range of data available.

139. In § 24 the Author referred to the Harlow time of entry being high in proportion to the time of concentration, thus justifying a straight line area/time diagram. This statement needed some justification. At what value would this proportion similarly affect an urban area? In reference 1 Mr Watkins adopted 2 minutes for entrance time for all urban areas. For the four housing areas the entrance time was therefore very nearly 30% of the time of concentration.

140. Lateral channels, surface and depression storage effects as factors modifying the rainfall were not discussed. Hydrologically the lateral and surface system formed, with the rainfall, a complex of interrelated phenomena, where the work of transforming the rainfall took place and was completed. The sewerage pipes and channel network acted only as a transport system, receiving to itself a run-off, greatly modified, from the 'straight from the rain gauge' situation envisaged in the Paper.

141. To some extent the notion of entrance time and percentage run-off could take account of this. The intensity histogram could be modified by a process suggested by Mr P. Ackers, and also by Mr Appleby in the Discussion on a paper by the late C. D. C. Braine.²⁰

142. In § 24, as a fourth step in producing his area/time hydrograph the Author combined, in order, the (rain-gauge) rainfall based on its particular duration and corrected for actual percentage run-off (supposed known) with the area/time variations, based on section times of concentration. Such then was the area/time hydrograph inflow to be related to the channel network as the reservoir. By converting the area/time sub-sections into a histogram of 'rate of contribution of area' units, some interesting mathematical developments became possible, high-lighting the question of phasing. Urban areas were time sensitive and phasing could be a source of substantial variations in peak flows. The Author took account of that automatically for particular storms, but the designer had no such information and the Author did not discuss that matter.

143. The Author also left the designer to choose for himself the rainfall time base and the form of intensity distribution with possible effects not discussed in the Paper. Usually the time base for the storm was the total time of concentration—a dynamically meaningless dimension but a useful practical convention. This inflow area/time graph was then routed through a variable storage characteristic of the sewerage network yet to be designed, the concentration times for which would vary from initially high values to a minimum in the region of the peak.

144. The Author based his theory on the unique relationship between storage in transit S , and outflow rate q . This matter, referred to in § 28, had been studied by hydrologists for a long time, following Horton's pioneer work in 1936.²¹ The matter was discussed in relation to urban networks by Mr Appleby in 1954.²²

145. The ratio S/q , of time dimensions, was the value of the mean time of concentration—a response time—and was shown to be the principal parameter controlling the recession characteristic. Its value was sensitive to immediate antecedent conditions: the question of variation in mean times of recession was further dealt with in some detail in the Discussion on Mr Andrews's recent Paper to the Institution.²³

146. The Author made it quite clear that he was depending on a foreknowledge of a given situation, and it seemed all the more necessary that his arguments should lead to some working generalizations. For example, whilst we could agree with his statement in § 32 on proportional depths, he did not make it clear how he applied this to his synthesis of the recession curve. Recession of run-off must also involve residual surface run-off as well as the contents of the network. Did the Author allow for this?

147. In § 44 the Author said that the designer could calculate the retention relation from the dimensions of the sewer system; the Author had by no means clearly demonstrated that this was the case. The only evidence he submitted was in Fig. 5 which did not, in Mr Appleby's opinion, show the satisfactory relationship between the calculated and the actual recession curves that the Author claimed. Mr Appleby thought that Fig. 5 demonstrated quite the contrary: that the S/q relation was subject to wide variation. For the same value of q at 4 minutes the storage S for the 19 July, 1957 recession was 75% greater than that for 30 June, 1957.

148. In § 33 the Author seemed to indicate in arriving at his results that he had used (or that it was easy to use) a calculated recession characteristic. This point was important to a proper understanding of the results. Would the Author make the matter clear? If he had used a standard calculated curve then the accuracy of the results in relation to the actual recession curves should have been discussed. Clearly the closer the actual recession was to the chosen one the better would be the result.

149. If actual recession curves in each case had been used one would have expected the calculations to show less divergence than they did. The smaller the value of S/q the less the storage channel effect: the more sensitive the conditions and the closer would the peak value approximate to the non-storage area/time value as corrected for percentage run-off only, and the more dominant the surface effects.

150. In Fig. 5, the calculated curve was closer in form to the July storm than to that of June for which the R.R.L. calculation was 29% low: the storage routing method generally claimed better results. Errors arising from the use of a recession curve not truly representing optimum design conditions could be as great as those supposed to be inherent in the rational method and it would be helpful if the Author would discuss the question illustrated with one example of a calculation of peak value using the different curves of Fig. 5 for Area 3. To avoid large negative errors a design recession characteristic should have the smallest value for S/q , when seeking critical peak values. It was tacitly assumed by the Author that the falling storage characteristic (recession) could be applied to the rising phase of the hydrograph; this was an open question, but the convention would seem to lead to further negative errors.

Mr G. Hedley (Chief Assistant, Main Drainage, County Borough of Newport) wrote that the research culminating in the Author's Paper had exposed many of the deficiencies of the generally accepted methods of surface-water calculation. The R.R.L. method, whilst admirable in part, also contained limitations.

152. The labour and detail required in calculation would be considerably reduced once a programme for a computer had been developed; and that, therefore, constituted only a minor limitation. The major limitation lay in the accurate prediction of the volume/discharge or retention curve. Over-estimation of this led to under-estimation of the rate of run-off, as was dramatically shown in Fig. 7 for the Kensington area.

153. The assumption that the proportional depth of water would be the same throughout any well-designed system was fair. This would, however, exclude most existing town systems and thereby alterations or additions to them. It could also exclude systems where actual flows fell short of design flows, this applying particularly to systems where pipe diameters exceeded 24 in.

154. The volume/discharge curves shown would appear to apply only to systems

without surcharge. Once the system was surcharged the relationship was lost and modification could not be made to the rational hydrograph. It seemed that the method provided an accurate assessment of a system operating without surcharge, and no indication of the behaviour under surcharge when an increased discharge was obtained.

155. Measurement of flows in existing sewers could of course be undertaken and from these a volume/discharge obtained. In addition to the time and labour involved, where a relief sewer was proposed this measurement could not be made satisfactorily as information was required about the proposed rather than the existing system.

156. The Author referred to the importance of selecting a frequency of flooding when calculations were accurately made. This might be described as a 'research truism', which an engineer would find difficult to explain to his principals, particularly if they lived in or represented the area concerned!

157. The most general basis for design was a 1-year storm. This, coupled with over-design of sewers, had probably provided a design frequency of once in 5 years. If the previous rather perfunctory consideration of storm frequency was replaced by careful consideration, it would probably result in accurate design based on a 5-year storm.

158. The Author was to be congratulated on his Paper which provided a most valuable contribution on the subject and would undoubtedly lead to more accurate design of surface-water systems.

The Author wrote in reply that although most contributors to the discussion appeared to accept the basic principles of the new R.R.L. hydrograph method of sewer design, there was a minority who did not. His main impression on studying the discussion had been, however, that there was little real difference between the principles of sewer design described in his Paper and those stated by those contributors who opposed the introduction of the new method. Most of the differences of opinion appeared, in fact, to be little more than diverse views as to which factors in the relation between rainfall and run-off require detailed calculation and which could be adequately incorporated into the calculations by assumptions.

160. The main basic processes of rainfall and run-off could not be in dispute, and were as follows:

- (a) rain falls at a rate which varies with time and with the area covered;
- (b) water runs off the different surfaces to the sewer entries, the rate of flow having been affected by retention on the surfaces, by infiltration through the surfaces, and by the hydraulic characteristics of the surface channels and gully inlets; and
- (c) water flows along the sewer at a varying rate of flow, and the volume of water contained in the sewer also varies with time.

161. There was no doubt that all these processes must be precisely calculated if a method of design was to be absolutely precise under all conditions, and this had been the broad aim of investigations such as those carried out by Tholing and Keifer and referred to by Mr Ackers. However, such a design method must be exceedingly complex and cumbersome, and one must question whether the accuracy that might be attainable would justify the complexity of the method and the considerable research effort that would be required for its development. At the start of the research at the Road Research Laboratory, it was decided that the aim should be to provide a design method that, whilst being satisfactorily accurate in practice, was also reasonably simple to apply and was sufficiently flexible to accommodate later additions to knowledge, both hydraulic and meteorological. In order to achieve this, it was necessary in the derivation of the method to calculate fully only those factors which were found

by experience to have first order effects, and to treat the remainder by simplifying assumptions.

162. The 'rational' (Lloyd-Davies) formula made many simplifying assumptions. The rate of rainfall was assumed constant, and as regards retention, although it was argued by Mr Escritt that the method took retention into account, it did so only by implication in that a gross volume was implicit in the determination of the dimensions of a sewer, while the variation in retention during the storm was completely ignored. However, the Paper stated that the Lloyd-Davies formula was sufficiently accurate and reliable for the design of relatively small new sewer systems. This was a significant conclusion, because such designs represented a considerable part of a drainage engineer's work.

163. The R.R.L. hydrograph method selected for detailed calculation the variation with time of the rate of rainfall and of the area/time diagram, and the retention/discharge relation of the sewer system. The method left the effect of retention on the surfaces to be dealt with by a simple time-of-entry allowance and in this connexion it should be recognized that the experiment with a sheet of glass described by Mr Escritt was a demonstration of the surface retention effect and not of varying impermeability, since, as Mr Escritt remarked, one could hardly imagine a less permeable surface.

164. Mr Appleby criticized the hydrograph method on the grounds that the retention curve employed was not strictly accurate. The Author agreed that the retention curve was an approximation, but considered that experience had shown that it was sufficiently accurate for practical purposes and that a further complication of the method would not be justified by the possibility of a further small increase in accuracy. Mr Appleby had proposed an investigation into the accuracy of the retention curve, using different recession curves with one recorded storm. Although detailed examination of individual storms was at first sight attractive, one of the lessons that had been learned during the research was that this procedure was open to serious doubt since results obtained from one such investigation could not necessarily be used to draw a generalized conclusion; the Author believed that a better demonstration of the reliability of the R.R.L. hydrograph method had already been provided by the analysis of the 286 storms discussed in the Paper.

165. The Author could not support Mr Nash's suggestion that the retention/discharge curve might as well be assumed to be linear. For circular sewers the relation was markedly non-linear, and when a computer was employed the use of the actual curve gave rise to no practical difficulty (the computer would still be necessary even if the relation were assumed to be linear).

166. Both Mr Nash and Mr Appleby had commented on the Harlow investigation, but in the Author's opinion the real significance of the work at Harlow was in the information that it gave about the rates of flow in a sewer system resulting from run-off from the unpaved surface in a drainage area.

167. Mr Ackers and Mr Harrison had described the research carried out at the Hydraulics Research Station on various aspects of the hydraulics of sewers and sewerage structures, many of the results of which were employed in the practical applications of the R.R.L. hydrograph method. Mr Harrison's investigations of the behaviour of a flood-wave in a pipe-line gave valuable confirmation of the reliability of the R.R.L. hydrograph method. Mr Walton had attributed to Mr Harrison the suggestion that his results were only valid within the actual wave volumes employed in the investigations, but the Author had been able to find no such suggestion in Mr Harrison's contribution and was satisfied that the results were capable of general application. Mr Harrison's observations on the effect of gradient on the accuracy of the method were interesting, and consideration could usefully be given to whether a further refinement to take this effect into account would result in a worth-while improvement in accuracy.

168. One of the greatest difficulties in the whole problem of storm sewer design was

the selection of a suitable frequency for the design storm, and this was remarked on by Mr Oakley, Mr Hedley, and others. This was not a new problem that had been brought about by the introduction of the new method; on the contrary, it had always been present, but had been largely ignored since the traditional methods of calculation were not sufficiently flexible to enable different frequencies to be considered, and were also so unreliable that the frequency of surcharging was unlikely to be the same as, or even directly related to, the selected frequency of the design storm. The new method high-lighted the problem only because it was made possible for the first time for the frequency factor to be examined in detail and the most satisfactory and economical design selected. Accurate and reliable rainfall statistics and storm profiles were required for this purpose, and in this connexion the contribution of Mr Holland was especially valuable. It was to be hoped that the Meteorological Office would pursue their studies of rainstorms with all practicable speed and that improved rainfall data would be made available for engineers in the near future. It was this research that would, *inter alia*, provide the answer to Mr Ely's question about the reliability of the Ministry of Health rainfall formulae.

169. Mr Young had surely made a fundamental error of logic in his comments on the statistical analysis of data described in the Paper. The Author maintained that it was absolutely necessary to omit the plus and minus signs in the consideration of the errors, otherwise one might have been led to a conclusion such as, for example, a method being said to be completely accurate if it gave a +100% error one day and a -100% error the next day.

170. Mr Young's criticisms of the drainage arrangements in the experimental areas were mostly valid; however, it was clearly not possible to construct perfect areas for examination and in any case the results would probably have been less useful had this been done. It was only necessary factually to note these imperfections and to take them correctly into account in the analysis of data, and this the Author considered had been done in the Paper.

171. Now that the research at the Road Research Laboratory on this topic was finished, attention was being directed to carrying out practical applications of the method, and Mr Granville Berry had given an account of some of the work in this direction carried out by the Coventry City Engineer's Department in collaboration with the Road Research Laboratory. This had led to the production of computer programmes that were capable of solving most of the problems that arise in storm-sewer design, and Mr Nash would be interested to know that a note giving a guide to the preparation and tabulation of data for the computer analysis had been published by H.M. Stationery Office.²⁴

172. It had been suggested by Dr Sarginson that the R.R.L. hydrograph method might over-estimate retention in those large areas where uniform proportional depth was assumed. This doubt was presumably connected with the traditional use of a rectangular storm profile for design purposes, whereas the storm profile employed in the computer programmes was more realistic in that it combined a high peak rate of rainfall that filled the upstream sewers at the same time that the downstream sewers were filled by the whole storm. For the examination of existing systems, where the assumption of uniform proportional depth could not be justified, the actual retention curve was calculated in a manner rather like that suggested by Dr Sarginson.

173. In his opening remarks, the Chairman had mentioned the allowance of safety factors for future development and exceptionally heavy rainfall, and in doing so had hit upon one of the key factors determining the usefulness of the methods of sewer design available to engineers. Judging from the general discussion the only methods now under serious consideration were the 'rational' (Lloyd-Davies) method and the R.R.L. hydrograph method. Whilst the Lloyd-Davies method, when applied to large areas, could in some circumstances introduce an arbitrary factor of safety without any positive decision on the part of the engineer, this approach to the matter was surely not satisfactory engineering practice. It was far better that a method

should be employed that correctly calculated rates of run-off from rates of rainfall, the factors of safety having been introduced by the engineer in the forms of increased impermeable areas to allow for future development and wisely chosen design storm frequencies. The R.R.L. hydrograph method gave an engineer the means of doing this, and the use of a computer gave him additional flexibility so that alternative designs could be readily calculated and assessed and the most satisfactory design selected.

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