

A new type of structure for flow measurement in steep streams

by

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AUTHORS' PRESENTATION

Introducing the Paper, the Authors said that although it might be thought that the need to measure flow continuously occurred only rarely in the circumstances for which the structure was developed, the conclusions to be drawn from the Paper nevertheless had quite a wide application.

59. In the Paper, it had been shown that the various errors in gauging were related principally to the Froude number, which in turn depended on the river slope. Examination of Tables 1 and 2 suggested a classification system for rivers, based on the errors likely to be experienced at gauging structures:

- (a) rivers with Froude numbers less than 0.25, i.e. slopes less than about 1:1000, could be called *rivers of gentle slope*; the calibrations of gauging structures in these rivers were unlikely to be significantly affected by the factors considered in the Paper;
- (b) rivers with Froude numbers between 0.25 and 0.5, or slopes between about 1:1000 and 1:250 could be called *rivers of moderate slope*; small, though significant errors might arise in gauging;
- (c) rivers with Froude numbers greater than 0.5, or slopes greater than 1:250 could be termed *rivers of steep slope*, in which large gauging errors would arise.

60. To assess the relevance of these problems to flow measurement in the United Kingdom, the Authors had recently analysed the river slopes at the 106 weir sites recorded in the Surface Water Year Book for 1964. They found that at 20 sites the rivers had slopes in the steep classification, 41 had moderate slopes and only 45 were in the gentle slope category. Thus it may be concluded that at the majority of new or existing flow gauging sites some thought should be given to the effect of river slope on the calibration of structures.

Mr A. Gérard Boulton (Water Resources Board) said that it had been clear for many years to those concerned that there was a very great need for a structure to tackle the problem of sediment flow. According to the Authors, sediment seemed to vary from particles of rather large size to very small stones. It was not usual to use the word 'stone' in this context in engineering.

62. In the days of the Surface Water Survey checks of monthly rainfall and runoff had been made every year at flow measurement stations. The results were plotted in the form of a running chart, which was very useful. Structures behaving in an unusual way were thus identified. There was in Scotland one gauging station consisting of two side-weirs and a central flume, where the runoff gradually began to catch up with the rainfall until eventually it was more than the rainfall. It was a site where there was a considerable amount of gravel brought down by the winter

rains. Every spring, when it was judged that the winter rains were more or less over, the engineer sent in a bulldozer to push all the gravel onto the downstream side of the structure, and there it remained throughout the summer, backing up the level of the water in the flume so that the discharge recorded rose more and more on account of the artificially high water level.

63. The previous week he had been looking at the River Quarne on the southern slopes of Exmoor and the River Wye at Cefn Brwyn. Both rivers had similar problems in that material came down and piled up on the upstream side of the structure. In both cases the material appeared to be very similar, consisting generally of flat plates of stone measuring about $7\text{ cm} \times 5\text{ cm} \times 1\text{ cm}$, and the plates seemed to lie until high flows swept over them. This was a problem common to a number of structures, and one wondered how it could be solved. It could not always be dealt with in the manner suggested by the Authors, unfortunately, because the velocities involved in a structure of this type were fairly high and would impede the passage of migratory fish. It might be that some of these difficult streams could best be dealt with by a control in conjunction with the dilution method.

64. Turning to the Paper he noticed that in § 29 it was stated that loose gravel was used on the model. He would like to ask the Authors whether this was from Plynlimon. The specific gravity of the material must have some bearing on the design, and, of course, the specific gravity of rocks varied very considerably, that of chalk being about 1.94 and that of granite about 2.9.

65. In looking at Fig. 10 he wondered how it was that there were a number of curves drawn which did not appear to have any experimental points to justify them.

Dr J. S. G. McCulloch (Hydrological Research Unit) explained the background to the Unit's search for an experimental catchment to investigate the effect of land use changes on hydrological behaviour. It was specified that the catchments be upland and water-tight and not so rugged that assessment of rainfall would be impossible. No requirements were laid down as regards flow measurement since it was assumed that the Hydraulics Research Station would be able to solve any problems that might arise. In fact the catchments chosen at Plynlimon proved to be too steep and stony for conventional means of flow measurement to be used and the assistance of the Hydraulics Research Station had resulted in the Paper which had been presented. It should however be stressed that, in catchment area research, the one parameter which was integrated over the catchment and measured as a whole was stream flow: other parameters such as rainfall, evaporation or soil moisture were sampled with a sampling area which was minute compared with the area of the catchment as a whole. Hence every effort should be made, for research purposes, to measure flow as accurately as possible.

67. It was hoped that the research would prove of value to River Authorities with similar problems on upstream catchments; a further report on the performance of the structures in practice should be available in a few years' time.

Mr R. Bidgood (Associate, Robert F. Earley and Partners) said that his interest in the Paper arose from problems concerning the measurement of fast-flowing rain-rivers (wadis) in the semi-tropical countries, and he wondered if the structure suggested by the Authors would be of use under these conditions. Dry for some nine months of the year, wadis then experienced flash floods for the remaining three months, on and off. There was no persistent flow. Slopes varied, but up to 1 in 150 was not uncommon, and bed conditions were rough. Much debris was brought down. Flows ranged from 50 cumecs to 150 cumecs, sometimes more.

69. Would the Authors' suggested structure promote scour; would the usual anti-scour devices (e.g. falling aprons) be necessary? Could the Authors give any indication of the budgetary cost of a structure under such conditions?

70. The other possible application he had in mind, and on which the Authors'

views would be welcomed, was in the case of measuring flows up to 300 cumecs at the end of side-channel spillways. There would be no debris flowing, but flows varied widely. He had found that the high flows and high velocities involved, with deep rather than wide channels of this nature, made the usual measurements of the head across a sill unreliable. Small errors in head reading lead to large errors of the flow. Again, would the suggested structure be suitable in this case?

Dr D. T. Plinston (Hydrological Research Unit, Wallingford) said that the gauging structure at Cefn Brwyn on the River Wye had been mentioned as one subject to fluctuations in bed level during floods. He had buried layers of coloured pebbles and a vertical chain in the shoal upstream of the left-hand flanking crest to determine the bed level at peak flows. Since observations began, three significant floods of 1000 cusecs, 550 cusecs and 360 cusecs had occurred which had caused movement of material. In each case the shoal returned to substantially the same level after erosion and deposition during the flood.

72. The Authors had shown that for a constant weir coefficient, energy coefficient and Froude number, the ratio H/P would be constant. At peak discharges the evidence from Cefn Brwyn suggested that this was so. This suggested that a better estimate of discharge might be obtained by assuming a constant value of H/P above the critical discharge causing material movement, rather than assuming a constant value of P . For Cefn Brwyn the limiting H/P was about 3.6 and he had worked back from this to deduce a critical discharge of 350 cusecs above which erosion took place.

73. Though one could say that there could be a considerable error in discharge above this critical discharge, it was useful to consider the effect of this error on the parameter one was trying to measure. He had made an approximate frequency analysis of the flows at Cefn Brwyn and the proportion of the total annual runoff occurring at a discharge greater than 350 cusecs, for instance, was between 2% and 4%. Thus the effect of the errors in discharge above 350 cusecs had a very much reduced effect on such a parameter as the total annual runoff.

74. He wished to comment on the design problems of the new structures. Six were to be built on the smaller streams on the Hydrological Research Unit's Plynlimon catchments. The estimate of bank-full conditions appeared a difficult task for these streams, as there were numerous falls, pools and abrupt changes of direction. On the basis of measurements on one of the streams he had tried to estimate the probable error in his estimate of bank-full discharge and Froude number. The hydraulic radius and area of flow were the mean values from measurements taken at seven cross sections and the probable errors of these means was of the order of $\pm 15\%$. He used Manning's equation to estimate velocity and hence obtained bank-full discharge and Froude number. The probable error of estimate of both factors was about $\pm 20\%$.

75. As a consequence, the dimensions of the approach section of the structure could be in error by $\pm 40\%$. This could lead on the one hand to deposition of sediment in the approach channel if the stream velocity was under-estimated, and on the other hand to a larger, and hence more costly structure than was necessary if the Froude number was over-estimated.

Mr R. W. Herschy (Water Resources Board) said that in Fig. 10 of the Paper the Authors had plotted the experimental data, which had already been referred to, along with theoretical curves, which were based on various assumptions. He wondered whether the Authors would be prepared to suggest from this a working equation for the flume.

77. From the point of view of field application it would also be necessary to set the limits of application. For instance, from the details given it would appear that the tapping point could be placed at about H max upstream of the throat transition. Other limits such as L , La , h/b , h , b/B_1 and b/B_2 would be necessary for field application.

78. With regard to the constructional difficulties which might ensue with this type of flume, evidently it would be constructed in a rocky stream with a rocky bed, and

therefore, any excavation would be very expensive. On the other hand, if the flume were built in a raised position, this might lead to some objection from the amenity point of view, as had happened in some instances with Crump weirs for example.

79. He wished to ask the Authors whether they could suggest dimensions for the roughness strips. There was a problem with extremely wild streams in that these strips would come in for some very rough treatment.

80. Finally, he wished to ask the Authors whether they meant to check the calibration of the flume in the field.

Mr M. Mansell-Moullin (Messrs Binnie and Partners) said that he imagined that the flume would be extremely costly in cases where there was a large range of flows to be measured, as in many tropical regions, and that for this reason its application might be limited.

82. The Americans had recently developed a weir, the drop-box weir, which, although very different in design from the flume described in the Paper, was intended to operate under similar conditions. It had been described in a recent paper by Johnson, Copp and Tinney.¹² He asked the Authors whether they would like to comment on that design, which would certainly be very much cheaper than the flume which they had proposed.

The Chairman (Mr J. T. Calvert) said that he wished to ask one or two practical questions. One of his cardinal principles was never to put two meters in parallel, and it was both an advantage and disadvantage that field work on flow measurement was very difficult to check. A certain amount of checking could be done, but hardly on a continuous reading basis.

84. In some of the steep streams there were waterfalls, and it seemed to him that these waterfalls and similar areas themselves formed control sections. He wondered what the possibility was of determining flow from such natural control sections rather than by constructing special structures. Obviously this would be cheaper. He thought that in the course of time they must achieve generally stable conditions, and he could not imagine a waterfall being seriously affected by deposition immediately upstream.

85. Secondly, in the steeply sloping section of the flume the Authors had placed baffles to dissipate the energy. He wondered to what extent the construction of these would affect the calibration. How critical was it? Was it really necessary to have them, and if so, how were they to be designed?

86. Thirdly, he knew that the diagrams and experimental work could be deceptive, but when it was all converted into large-scale structures, what sort of throat width was one going to have? From the diagrams, it appeared that there was quite a danger of tree trunks, large boulders, etc., getting into the throat. He wondered whether the Authors were only dealing with streams or structures which were free from this danger.

Written contributions:

Professor E. Markland (Queens University of Belfast) congratulated the Authors on a notable contribution to a notoriously difficult problem. There was clearly great difficulty in providing reliable gauging in steep rough streams by means which allowed free passage of bed material. To ensure this, attention had been paid to keeping the velocity substantially constant in the approach section. However, the exit from the throat was in the form of a sudden enlargement in width. Was this adopted on grounds of economy and expedience, or was it a desirable design feature? Had there been any evidence in the model of shoaling, and was the modular limit likely to be affected by the detail at the exit?

88. The experimental measurements of discharge coefficients were valuable in their own right, but when compared with theoretical values as in Fig. 10, they became

especially interesting. The continuing rise of the measured values as the head increased was puzzling, especially as the trend of the experimental curve rose above that representing the thinnest possible boundary layer. Presumably this must be due to changing conditions in the approach length, which was about 2 ft long at the maximum flow condition. Could the Authors supply information on the variation of energy coefficient α in the approach length with flow, and would they care to express an opinion on the suggestion that the variation of C_d indicated in Fig. 10 reflected upstream effects as well as those of boundary layer development?

89. It was, perhaps, somewhat optimistic to expect flat plate boundary-layer calculations to be applicable directly to the more complex situation of the model. There must be some amount of three-dimensional effect due to the change of wall directions at the ramp, and particularly at the transition. If the measurements of boundary layer described in § 43 were extended to include the whole periphery, the value of displacement thickness δ^* might well be found to vary. Since the expected secondary flow was outwards along the base of the section of the throat, and upwards along the vertical walls, a thickening of the boundary layer might be found near the bottom corners and the surface, so that the mean displacement thickness might well be considerably greater than that indicated by a single measurement in the vertical wall.

Mr P. G. Holland (Ministry of Development for Northern Ireland) congratulated the Authors on tackling the problems of higher Froude numbers in a most logical manner, to the extent that accurate measurement of flow in steep streams became a distinct possibility. Inevitably a somewhat complicated structure was indicated, and Fig. 5 pointed to a full-scale prototype some 60 ft long in a natural stream about 15 ft wide, allowing a bank-full depth of stream flow of roughly 4 ft. Bearing in mind the commissioning of the work by the Natural Environment Research Council (through the Council's Hydrological Research Unit) for the application of this type of structure to the Plynlimon experimental catchments, it seemed that the Authors had in mind the smaller, somewhat inaccessible catchment areas which might be suitable for small or medium impounding reservoirs.

91. In a completed impounding scheme a gauging structure which permitted the continual monitoring of stream flows immediately downstream of the dam was usually included. Such a structure was not usually sited in a steep reach, and the Authors' structure would appear to be more applicable to the monitoring of stream flows prior to impounding, for the purpose of assessing design yields and other design criteria. If this was so, it could be that the initial gauging structure would not be sited to suit the final dam location. Mr Holland wondered if the Authors' structure could be prefabricated to ease construction, particularly as permanent access to the gauging section was unlikely to exist at the time of investigating an impounding scheme.

92. It was not clear from the Paper to what degree of accuracy it would be necessary to construct any roughness strips in the ramp, and Mr Holland asked for the Authors' comments on (a) the types of constructional material which would be suitable (e.g. could glass fibre be used?), and (b) the extent to which prefabrication could be used.

The Authors, in reply, first wished to thank all those who had contributed to the discussion and brought out a number of useful points. Particular emphasis seemed to have been laid on the practical points of the design. This was only to be expected since, as research engineers, the Authors developed new designs which practical engineers subsequently had to build, maintain and operate satisfactorily.

94. The Authors were grateful to Dr McCulloch for explaining the background of the hydrological research programme which had prompted their work on flow measurement. Lack of space had prevented them from doing so in the Paper. He had also stressed the need for high accuracy in stream gauging when carrying out

hydrological experiments. The Authors agreed with Dr Plinston that if the total annual runoff was the parameter being measured, high accuracy was needed only at medium and low flows. However, if the form of the flood hydrograph was being studied, then high accuracy was necessary over the complete range of flow. In the case of the Plynlimon catchments the range of flow was over one thousand-fold, and the Authors had designed the structure to be accurate over this range.

95. In connexion with the effect of sediment on weir calibrations, Mr Boulton and Dr Plinston had mentioned the Crump weir at Cefn Brwyn, on one of the Plynlimon catchments. The results obtained so far by Dr Plinston were very gratifying, as it appeared that at the peaks of the higher floods there was a constant H/P value or a constant Froude number in the approach channel. The Authors were a little surprised however, as they had always assumed that there was a lag in sediment movement relative to water movement in floods, whereas at Cefn Brwyn it appeared that at the maximum discharge the bed was at its 'regime' level. Thus, as Dr Plinston had pointed out, it seemed that an allowance could be made for fluctuating bed levels in calibrating a weir. However, Dr Plinston had only been able to study the bed level at peak flow, when the flow was virtually steady, and the Authors would still expect some lag effect during rising and falling stages. However there would be many problems in carrying out research to investigate this in the field.

96. Several speakers had raised points concerned with the design of the structure. Mr Herschy had asked for details of the limits of various dimensions; these were given in Appendix II of a Hydraulics Research Station Report,⁶ where a detailed, step-by-step, design procedure was set out. As Dr Plinston had pointed out, the most difficult part of the design was in estimating the stream velocity, bank-full depth and Froude number. These could not be determined accurately and in the end some compromise had to be made between a safer, more expensive design and a cheaper, less reliable one. In fact the design of the structure itself was probably slightly conservative, since the floor was smooth, and sediment would move more easily than on the rough bed of the stream.

97. Mr Boulton had asked what effect the specific gravity of the sediment had on the design of the structure. The answer was none at all, since the structure had been designed, on the basis of the principles set out in § 17, to ensure that at any discharge, any sediment moving in the natural stream, of whatever size, shape or specific gravity, would also move through the structure.

98. Professor Markland and Mr Bidgood had asked whether the structure would promote scour downstream. On the Plynlimon sites, the stream beds were mostly of rock, and because little scour was expected no tests were performed to study this problem. An exit expansion was tested in an attempt to determine the reason for the high coefficient at high flows (see § 44), but no determinations of the modular limit were made in this case. Since the modular limit for a flume of this type could not be less than two-thirds, the modular limit could only have been increased with the expansion installed. However, the range of depths upstream of the flume throat was much greater than the range of tailwater levels, so the possibility of drowning had only to be considered at low flows. Thus the expansion was omitted from the design, since there would be little gain for the increased cost. A shoal some distance downstream from the structure might cause the flow to become drowned at low discharges, but this could easily be remedied.

99. Messrs Herschy and Holland had raised points concerning the siting and construction of the structure. As Mr Herschy had pointed out, the site of the structure had either to be excavated to the required depth, or the structure had to be built in a raised position, when there might be amenity objections. The Authors thought that the best site, if it existed, would be at a waterfall, preferably with a height equal to the step height, t , of the structure, but there might be amenity objections to such a location. Mr Holland had asked whether the structure could be prefabricated for easy erection on remote sites. The Authors felt they were not

qualified to comment on this. In reply to Mr Calvert, typical dimensions of the structures to be used in the Plynlimon catchments were: length 60 ft, flume throat width 4 ft. There was admittedly some danger of trees blocking the structure, but this was unavoidable on most structures.

100. The number of curves on Fig. 10 had slightly confused Mr Boulton and Mr Herschy and they wondered which curve to take as a design calibration curve. In § 36 it had been pointed out that the Reynolds number at the downstream end of the throat in the full-scale structure would be large enough, even at minimum discharge, for the boundary layer thickness to be virtually independent of the Reynolds number. Several of the curves on Fig. 10 were thus of interest only in analysing the model's performance. In a typical design it would only be necessary to evaluate L/k , and take a typical transition Reynolds number of 3×10^5 , to obtain the design curve. A detailed, step-by-step method of obtaining the calibration was also included in Appendix III of the Report referred to above.⁶

101. In reply to Mr Herschy, field checks on the calibration would probably be carried out by chemical dilution techniques, since the nature of these streams ensured rapid mixing. The energy coefficient curve (Fig. 14), would also be checked by current meter, by the method described in § 27. However, no attempt would be made to use these current meter readings to check the calibration, since the Authors did not believe the method to be accurate enough for that purpose.

102. Two speakers had commented on the high cost of these structures, about £4500 each in the case of those in Plynlimon. Mr Mansell-Moullin had suggested that the drop-box weir¹² might be cheaper. This seemed to be true, but the Authors felt there were several objections to this weir. The Authors of that Paper had recommended that, if possible, the weir should be designed to operate wholly within the range $H/D < 0.8$ (where H was a piezometric head and D the depth of the V-notch) since, they claimed, the dimensionless calibration curve was universal in this range. However, close examination of their Figs 13 and 14 indicated a scatter in the experimental discharge parameter of some $\pm 15-20\%$ for a given value of H/D within the above range. Outside that range the scatter could be up to $\pm 40\%$. Furthermore, as the calibration of this weir was entirely empirical, it was necessary to have an accurate laboratory calibration curve covering the whole range of flow and to show that this could be applied with confidence to the prototype structure. However, in the recommended range of H/D the experimental results covered a range of flow of only tenfold.

103. For Mr Bidgood's problem of measuring flash floods in wadis, the drop-box weir might be an acceptable form of structure because, presumably, he did not need to measure with a high degree of accuracy over a large range of flow.

104. Mr Calvert had suggested that gauging might be carried out cheaply at a natural waterfall. Such a site had either to be calibrated in the field over a long period of time, or calibrated in a model. If the section was unstable the calibration had to be repeated at intervals. The total cost of this work might well exceed the capital cost of a structure. Furthermore it was doubtful if comparable accuracy could be achieved in a steep river, where standing waves, located at different points at different flows, could cause unknown errors in measuring water levels.

105. Mr Bidgood asked for the Authors' views on using the structure to measure flow at the end of side-channel spillways. They had grave doubts about the wisdom of flow gauging in such a position, and suggested that it would be advisable to measure the flow either by means of the spillways crest, or by placing a conventional weir at the end of a horizontal channel at the head of the spillway.

106. Professor Markland had raised several important points concerning the unexplained rise in discharge coefficient at high discharges. While agreeing with his suggestion that the discharge coefficient was probably a function of upstream conditions, the Authors felt that the effects of upstream conditions would be noticeable only in a change in the energy coefficient, and the turbulence level, with consequent

change in transition Reynolds number. The energy coefficient had been measured, and thus accounted for; its variation with head, and thus with flow was given in Fig. 14. The boundary layer measurements had indicated a fully turbulent boundary layer at maximum flow, but with an exceptionally low displacement thickness, which a change in transition Reynolds number could not explain. As Professor Markland had mentioned, the value of the boundary layer displacement thickness was probably not constant around the perimeter, but it was hard to believe that the value measured at approximately half depth on one of the walls would differ significantly from the average value. Moreover, the fact that the discharge coefficient calculated from the measured boundary layer displacement thickness agreed so well with the measured discharge coefficient tended to support this belief. In this case no assumptions were made about the development of the boundary layer.

107. To obtain a full explanation of the unexpectedly high value of discharge coefficient at maximum flow the Authors would have liked to conduct a full investigation of the development of the boundary layer along the throat and its distribution around the perimeter of the throat. Unfortunately the physical size of the throat, together with its unusual shape, rendered this impossible without a great deal of further expense and time. Because of this, the Authors could put forward two possible explanations, without being able to substantiate them. For instance, the relatively high value of δ_*/b of 0.008 might have restricted the growth of the boundary layer along the wall. Alternatively there might have been a shape effect. This could take the form of an uneven distribution of total energy across the width of the throat, whereas the theoretically derived discharge coefficient contained the assumption of a uniform distribution. The magnitude and direction of secondary currents also depended on the throat shape.

108. Finally, the Authors would like to point out three corrections to the Paper. In § 14(a), 'ten times' should read 'one-tenth of', and on Fig. 13 the relative roughness value $L/k = \infty$ should point to the lowest line in each group. On this figure, the Reynolds number should also read $R = vx/\nu$. Although the original intention in plotting Fig. 14 was to show α as a function of H/L_a , it had in fact been plotted as a function of H/L , which should therefore replace H/L_a .

REFERENCE

12. JOHNSON C. W. *et al.* Drop-box weir for sediment-laden flow measurements. *J. of the Hyd. Div., Am. Soc. civ. Engrs, Proc. Paper 4916*, 1966, **92**, No. HY5 (Sept.) 165-190.