Design flood estimation for bridges, culverts and channel improvement works on small rural catchments

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Mr R. B. Bulman, Consultant

In § 4 the Authors recognize one of the weaknesses of the *FSR* method¹ in that some unspecified catchments will be underestimated and others overestimated. By introducing their design factor, F_n , they have reduced the underestimates to 5% of cases. Where safety is a main consideration this is still not entirely satisfactory since inhabitants living below an unspecified 5% of the works will be at risk. On the other hand, where economics is a consideration 94% of the works will be overdesigned and wasteful of capital investment.

11. In order to illustrate the range of errors possible in the use of the method described, consider two catchments both of 20 km² area, alike in mean effective slope and all other respects except the drainage pattern as indicated in Fig. 3.

12. Since each channel of catchment B only drains about half the area of A, the mean velocity along the channels in B in response to a given storm will be less than the mean velocity along the channel in A. The mean velocity along the channels in B in response to a median annual storm will be about 0.81 of the corresponding velocity in the channel in A. If the period of concentration in A in response to the median annual storm is, say, 1 h then the period of concentration in B will be about 37 min.

13. From Table 3.8 of the *Flood studies report*, II, it would appear that the mean intensity of rainfall during a critical storm on catchment B will be some 36% higher than the corresponding mean intensity on catchment A. It follows that the peak discharge from catchment B in response to a median annual storm will be some 36% greater than the corresponding peak discharge from catchment A, whereas the Authors' equation would predict the two as equal.

14. Up to an annual non-exceedance probability of, say, 0.9, the period of concentration may give the appearance of being a constant for the catchment with acceptable scatter. At the rarer frequencies, however, the critical duration decreases, moving the catchment response on to a higher point in the rainfall intensity-duration curve.

15. When peak discharge is required at rarer frequencies the critical duration

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Fig. 3

must first be estimated for the frequency in question. The method described in § 6 will only exaggerate any error inherent in the estimate of average annual flood.

16. The proposed equation takes no account of other factors which can affect the peak flood discharge, such as mean effective slope of the catchment. Other factors being equal, the slope affects the period of concentration and hence the mean intensity of rainfall during the critical period.

17. The general altitude of the catchment area also affects the intensity of rainfall at a given probability. For durations greater than 2–3 days rainfall can be correlated with altitude, but for intense rainfall of short duration there is usually a negative correlation with altitude. By adopting a base rainfall period of two days the *Flood studies report* has masked altitude effects.

18. Both of these factors should be taken into account in a definitive estimate of floods for an important catchment.

19. Engineering time spent in the determination of the design flood is usually small in relation to the time spent in the structural design of the works based on it. The cost of this determination is usually very small in relation to the cost of the actual works. The cost of failure may be many times the original cost of the works. The marginal cost of overdesigned works may be many times the additional cost of undertaking a rigorous estimate of the design flood rather than a rapid estimate.

20. Armstrong⁵ has drawn attention to the value of ‘relief from anxiety’ as an economic factor when assessing flood alleviation. If, in a sample of flood alleviation works for 100 areas, five unspecified areas are not fully protected, then any economic value of relief from anxiety is lost in all the 100 cases.

21. It is therefore very difficult to make out a case for any short cuts to design flood estimation unless high accuracy can be guaranteed. The proposed equation may have advantages over the *FSR* method as a first approximation but its use definitively may be just as dangerous.

Mr M. A. Beran, Institute of Hydrology

Just as the Authors have been concerned with the estimation of design flood magnitude for small catchments, so also has the Applied Hydrology group at the Institute of Hydrology.

23. The *Flood studies report* itself (§ 1.4.3.7) described some simple tests to investigate the reliability of applying a nationally derived equation to the small catchment subset. The conclusions were that the equation could not be perceptibly improved but that the estimation accuracy for small catchments was poorer.

24. Since then steps have been taken to increase the sample size by adding

extra years of data and introducing other catchments not used at the time of the Flood Studies. A total of 53 catchments with areas less than 20 km² was assembled, about half of these having areas less than 10 km². Because of a tendency to gauge small upland and large lowland catchments, it cannot be claimed that this subset is very representative; for example only eleven have slopes below 10 m/km and only twelve have SOIL indices below 0.45. New gauging stations are needed on small flat lowland catchments.

25. Regressions were performed with this data set, as were tests for differences in the flood frequency relationship and unit hydrograph shape. The details of the analysis are given in supplementary report 6,⁶ but the following sample conclusions are offered here.

- (a) Best three-variable regression equation is

$$\bar{Q} = 0.00066 \text{AREA}^{0.92} \text{SAAR}^{1.22} \text{SOIL}^{2.0}$$

(factorial standard error 1.58)

where SAAR is annual average rainfall and other variables are as defined in § 3.

- (b) The growth curve for small catchments is not distinguishable from that for all catchments.
- (c) The rainfall runoff approach via the unit hydrograph appeared to be the more accurate procedure for treating small catchments.

26. The equation above is generally similar to that found by the Authors, although the writer recommends that an abbreviated form of prediction equation is used only when time-saving is important.

27. The inclusion of the design factor concept is interesting, although the Authors have committed a statistical *faux pas* in stating that 68% and 95% of estimates fall below 1 and 2 standard deviations above the mean (§ 5). In fact, because of the need to consider only one tail of the distribution, their F_n values will enclose 84% and 98%, a much more conservative criterion than that expressed. The desired values of F_n corresponding to 68% and 95% are 1.26 and 2.26.

28. In this connection it would be of interest to discover how 'normal' the Authors found the errors to be. In the experience of the researcher who was responsible for the investigations outlined above (P. P. Lynn), much of the error tends to reside in a few catchments, often urbanized ones or those having low SOIL indices.

Mr J. D. Blood, Midland Road Construction Unit, Warwickshire County Council Sub Unit

The equations developed by the Institute of Hydrology and published in the *Flood studies report* have provided a most useful method of flood prediction for rural catchments, with or without continuous flow records. The no-data six-variable equation is in use in this office for river and stream calculations associated with major road schemes. Many of the catchments come into the 'small' category, and it is of interest to me to see the Authors' work particularly aimed at these areas.

30. It appears from the Note that the data analysed was drawn from that used in FSR. I would like the Authors to indicate if this is so, and/or comment on other data used.

Table 1

Catchments	Area, km ²		Ratio Q_3/Q_6	
	Range	Mean (and standard deviation)	Range	Mean (and standard deviation)
31 in Warwickshire	0.1-4.6	1.3 (SD = 0.9)	0.7-2.0	1.1 (SD = 0.3)
17 in Derbyshire	0.1-3.1	0.9 (SD = 0.8)	0.6-1.2	1.0 (SD = 0.1)

31. There is sometimes a problem in identifying from Ordnance Survey sheets the data for the variables STMFRQ and S1085 in small part-catchments, and there is therefore attraction in the proposed equation, which does not require detailed assessment of unmarked channels etc.

32. I have examined a number of small catchments associated with highway schemes under design, 31 in Warwickshire and 17 in Derbyshire, and compared the predicted mean annual flood using both the full *FSR* equation (Q_6) and the Authors' three-variable equation (Q_3). The results are shown in Table 1.

33. A similar examination of the Warwickshire catchments, but comparing the full *FSR* equation (Q_6) with the Institute of Hydrology's short equation for small catchments (Q_{3a}), resulted in ratios Q_{3a}/Q_6 of 0.8-2.0, mean 1.2 (SD = 0.3).

34. There is a satisfactory relationship between the results using the shortened equations and the full *FSR* equation. Given the predictive ability of the *FSR* method, based as it is on detailed examination of many rural catchments, then the shortened equation(s) can be a most useful method for designers to use with confidence. There is reluctance on the part of some engineers to accept fully the *FSR* methods for peak floods and this is understandable. However, I believe that the catchments must be examined realistically, and any culvert or bridge introduced into a watercourse should be based on a wholly reasonable assessment of flood risk and effect. The engineer's judgement as to flood risk is still important and the standard of provision of flood openings should be economically justifiable.

Mr Poots and Mr Cochrane

We found that Mr Blood's comparison of $\bar{Q}$ estimates using our three-variable equation with those obtained using the full *FSR* six-variable equation particularly interesting. By his comparisons for 48 small catchments in Warwickshire and Derbyshire, he confirms that our equation provides a useful and simple tool for use in flood predictions in small rural catchments.

36. We agree with Mr Blood that the use of STMFRQ and S1085 variables often presents problems in the application of the *FSR* six-variable equation, and indeed little advantage is gained by their use in many instances.

37. We confirm that the data used for the 42 selected calibration catchments was included in the *FSR*, and as Mr Beran points out, there is, in the data, a well defined lack of range in the S1085 and SOIL variables. We support Mr Beran's view that there is an urgent need for floods data from small, less

steep, more permeable catchments, which we suggest would permit a better all-round four-variable equation to be developed which would include S1085 as the fourth variable.

38. **Mr Bulman** discusses catchment response to rainfall mainly from a time of concentration/rainfall intensity/return period point of view, which can be compared with the *FSR* unit hydrograph method, and as Mr Beran suggests, and we should agree, the unit hydrograph analysis is probably more accurate than $\bar{Q}$ equations used with regional Q - T growth curves for flood estimation. However, the unit hydrograph method is not particularly simple to apply, and substantial estimation errors may still result due to errors in calculated values for T_p (the time to peak), the estimate of percentage quick response rainfall, and also important assumptions about the linearity of flood response to rainfall. For countless small culverts, bridge openings and river channel improvements on minor rivers, our method is thought to be particularly suitable in its simplicity, and when combined with the use of a suitable factor of safety, will not produce dangerous underprovision.

39. The *FSR* base rainfall term for $\bar{Q}$ equations is RSMD, which is a net one-day rainfall and not a two-day rainfall as suggested by Mr Bulman. Our investigations showed, like the *FSR*, that the use of 60 min. rainfall did not give as good flood estimation accuracy as RSMD except perhaps in small urban catchments. Again this could be due to the lack of small lowland catchments in the calibration set and certainly there seem good enough reasons for examining whether there is a more appropriate shorter duration of rainfall for small rural catchment studies than one-day rainfall.

40. As Mr Bulman points out, catchment shapes, tributary patterns and river gradients are all important catchment characteristics affecting flood magnitude, as are indeed flood plain storage, bridge and culvert restrictions, channel roughness and tortuosity etc. The problem is how to incorporate these many factors into a simple design tool. Much research remains to be done, but in the meantime approximate estimating procedures will have to be used together with a suitably chosen factor of safety or ignorance, such as F_n as proposed in our Note.

41. Mr Beran's comments are particularly useful in defining the limitations of the data available for the calibration of such three- or four-variable $\bar{Q}$ equations, and he identifies the need for data from more varied small catchments before significant improvement can be made. Until such data is available we have suggested factoring up the flood estimate to allow for possible estimation inaccuracy. What particular safety factor to apply is still the subject of debate and precise values are somewhat meaningless at this stage of development.

42. The logarithmic residuals obtained using our three-variable $\bar{Q}$ equation are sensibly normally distributed, and therefore we agree that theoretically the values of 68% and 95% should be replaced by 84% and 98%. However, it should be remembered that estimation errors also exist when using the *FSR* regional growth curves, especially for large values of T , the return period. It is therefore recommended that serious consideration be given to the use of a factor of safety (F_n) between 1.5 and 3.0 depending on the designer's assessment of the seriousness of the possible consequences of underestimation.

43. The Authors would like to thank the contributors to the discussion for their constructive comments. Mr Beran has in fact given the Authors generous guidance in hydrological matters over a period of several years, and in producing a 'simple to apply' design tool for minor river works we have worked principally

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from the methods developed in the *FSR* by Dr Sutcliffe and his team at the Institute of Hydrology. We are already encouraged by the response to date, but we emphasize that continuing improvements in flood estimation procedures are required to reduce both wasteful overprovision and the chance of dangerous underprovision in flood protection works.

References

5. ARMSTRONG K. G. Whither engineering economics? *Proc. Instn Civ. Engrs*, Part 1, 1979, **66**, May, 247–260
6. INSTITUTE OF HYDROLOGY. *Flood predictions for small catchments*. Institute of Hydrology, Wallingford, 1978, Flood Studies supplementary report 6.