Fifth National Local Government
Engineering Conference
Sydney 24 - 29 September 1989

A Comparison of Design Flood Estimation Methods

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SUMMARY Seven methods for design flood estimation were applied to two catchments, one of which had a 38 year streamflow record. Both catchments were treated as ungauged, and the accuracy of the estimates was assessed by comparing them to the actual flood frequency curve. Almost all methods over estimated the floods for short average recurrence intervals and underestimated for long recurrence intervals. Reasons for this are discussed and ways of correcting it are suggested. Flood estimates can vary because different models are used, and also because of the assumptions made by the different users. Even when the same model is used, the various assumptions made by the different users caused a spread in the design flood estimates. In the present study the estimates ranged approximately ± 13% about the mean value.

1 INTRODUCTION

In 1987 the Illawarra Regional Committee of the Water Research Foundation of Australia commenced assembly of a data base to assist calibration of flood hydrograph models for the Illawarra region (Rigby, 1984). The first application of the data base was a study of design flood estimation methods, and the results are presented in the present paper.

The study applied seven design flood estimation methods to two natural catchments. One catchment was treated as ungauged, although a flood record was available and this was used to assess the accuracy of the flood estimates. The other catchment was ungauged, but since its outlet was located further downstream on the same stream as the gauged catchment , a comparison between estimates made for the two catchments was possible.

The study involved a comparison of flood estimates made using the different models, and also a comparison of estimates made by the different users, using the same model. The results of the study therefore give an indication of the accuracy of the methods, and also of the likely spread of estimates.

Organisations involved in the study were the University of Wollongong, NSW Department of Main Roads (now the Road and Traffic Authority), NSW Public Works Department, Forbes Rigby and Associates, Shoalhaven City Council and Wollongong City Council.

2. DESCRIPTION OF CATCHMENTS

2.1 Physical and Climatic Data

Two catchments (Sunnybank and Princes Highway Bridge) were used, both on Macquarie Rivulet 15 km south of Wollongong at latitude 34° 34'S and longitude 150° 45'. The catchments extend from the steep slopes of the Illawarra escarpment near Robertson into Lake Illawarra near Albion Park. The total fall from headwaters to outlet is 680 metres. Macquarie Rivulet at Sunnybank (National Station number 214003) has an area of 35.0 km^2, stream length 10.5 km and equivalent main stream slope 31.9 m/km. Average annual rainfall is 1540 mm. The catchment is gauged with a streamflow record of 38 years. Macquarie Rivulet at Princes Highway Bridge is located further downstream, with area 105 km^2, stream length 22.5 km and stream slope 8.4 m/km. Average annual rainfall is 1287 mm. This catchment is ungauged. Both catchments are predominantly rural, mainly grassed but with some sub-tropical rainforest in the upper escarpment. Minor urban development has occurred in the lower reaches of the Princes Highway Bridge catchment.

2.2 Rainfall and Flood Frequency Data.

Design rainfall data for various storm durations were extracted from Australian Rainfall and Runoff (I.E. Aust., 1987) hereafter referred to as ARR. A flood frequency analysis was performed for the 38 years of flood records on the Sunnybank catchment, using the partial series method as described in ARR Chapter 10.

Figure 1 shows the resulting frequency curves for the gauged catchment. Note that the rainfall curves have the same approximate slope for all durations, and that the flood frequency curve has a much steeper slope, indicating that floods increases at a faster rate than rainfall intensities as the average recurrence interval (ARI) increases. This is typical of most catchments in New South Wales and indicates two things. Firstly, that losses may be quite important in converting design rainfalls into design flood discharges. For instance losses may need to be a greater proportion of the total rainfall for low ARI's but be a smaller proportion for high ARI events, so that rainfall excess depths and calculated flood peaks are increased as ARI increases. The current practice, as recommended in ARR, of using constant values of initial loss and continuing loss for all ARIs does provide this effect. However, it may be necessary to further increase the effect by using smaller losses for higher ARIs. Secondly, the greater proportional increase in flood discharge compared to rainfall intensity as ARI increases may indicate that nonlinear models will give better results than linear models. For example if a linear model such as the unit hydrograph is used together with the same proportional losses for each ARI, then the calculated flood frequency curve will be parallel to the rainfall frequency curve, and from Figure 1 this is seen to be incorrect. If either a nonlinear model is used, or smaller losses are used for higher ARIs, then the slope of the calculated flood frequency curve will become steeper and closer to the slope of the actual flood frequency curve.

3. MODELS USED IN THE STUDY

All models used are reasonably well known in Australia, and are described in ARR. The following brief descriptions are given.

(i) Rational Method (RM87) from 1987 ARR.

This is essentially a regional flood frequency method because the runoff coefficient values given in ARR were determined by fitting recorded flood frequency distributions from 308 gauged catchments in eastern Australia. The method involves calculating a storm duration from the catchment time of concentration

$$t_c = 0.76\,A^{0.38} \qquad (1)$$

A 10 year runoff coefficient C_{10} is read from a map, then converted to other recurrence intervals C_Y.

(ii) Rational Method (RM77) from 1977 ARR

Although this method is now superseded it was included to provide a comparison with the 1987 version. The major difference between the two methods is that the older version uses runoff coefficients depending on the soil type and rainfall intensity, but these coefficients were not based on recorded flood data so the method should be less accurate. The time of concentration is given by the Bransby-Williams formula

$$t_c = 58.5L\,/\,A^{0.1}\,S^{0.2} \qquad (2)$$

(iii) Cordery-Webb Unit Hydrograph (CWUH) (Cordery and Webb, 1974)

This method includes design losses as well as a unit hydrograph for each catchment. It was developed using data from 21 catchments in eastern NSW. Model parameters are given by

$$C = 0{\cdot}17\,(L/S)^{0.41} \qquad (3a)$$
$$K = 0{\cdot}66\,L^{0.57} \qquad (3b)$$

Various storm durations must be tried to determine the critical storm duration.

(iv) RORB Runoff Routing Model (Laurenson and Mein, 1985).

RORB model has been widely used throughout Australia. Relations have been derived between the model parameter K_c and catchment characteristics, and these are summarised in ARR. For eastern NSW,

$$K_c = 1{\cdot}22\,A^{0.46} \qquad (4a)$$
$$m = 0{\cdot}8 \qquad (4b)$$

(v) WBNM Runoff Routing Model (Boyd et al, 1987a, b)

This model is similar to RORB and includes many of its features, including storage reservoirs and urbanisation. The major differences are that in WBNM the data requirements and use of the model are simpler, a distinction is made between flow in the streams and flows on catchment surfaces, and optional forms of the storage-discharge relation to allow for different flow conditions are available. The model has been applied by various users to catchments ranging from 0·1 to 10,000 km^2.

Both RORB and WBNM are available on floppy disks for PCs. Both models require that a range of storm durations be examined to determine the critical duration. The models do not include design losses and these must be selected, based on recommended values in ARR.

(vi) PSRM Model

PSRM model was developed in the USA and has been applied in Australia by Rigby and Watts (1983). The model includes an allowance for losses, depending on the soil type and accumulated soil moisture. Runoff hydrographs are calculated using a procedure based on the kinematic wave theory.

(vii) Regional Flood Frequency (RFF) Method (Boyd, 1978)

The RFF method consists of a set of regression equations relating peak discharge to catchment area, stream length, stream slope and median annual rainfall. One equation is available for each ARI. The method was developed using recorded annual floods on 79 catchments in NSW. Because annual flood series was used, whereas the present study uses partial series, this method is strictly comparable for ARIs of 10 years and greater. For less than 10 years, the method should underestimate slightly. A simple conversion from annual series to partial series is possible using table 10.1 in ARR, and this was done for the 2 and 5 year ARIs in this study to allow results to be compared.

It is worth noting a basic difference between these models. Methods (i) and (vii) are the only ones which were developed using recorded flood frequency data. These should therefore be expected to give the better results. Methods (iii), (iv), (v) and (vi) were developed using recorded rainfall-flood hydrograph events. This means that the parameters of these models should correctly reproduce a flood hydrograph from an excess rainfall hyetograph. Their usefulness for design flood estimation however depends on the combination of design storm temporal pattern and design losses given in Chapters 3 and 6 of ARR. The results of the present study can give some indication of their accuracy.

4. METHOD USED IN THE INVESTIGATION

The two catchments, Macquarie Rivulet at Princes Highway Bridge and Macquarie Rivulet at Sunnybank were both treated in this part of the study as ungauged catchments, even though Sunnybank Station does have a 38 year streamflow record which was later used to assess the accuracy of the flood estimates for this catchment. The six organisations taking part in the study were given a catchment map and design rainfall intensity-frequency-duration data extracted from ARR 1987 for each catchment, but no other hydrologic information. Each user was asked to estimate the 2,5,10,20,50 and 100 year ARI floods using any flood estimation methods that they were familiar with, and to do so in general accordance with ARR procedures, although users were able to exercise their own judgement wherever necessary.

Results were assessed in two ways. Firstly a comparison of model performance, by comparing flood estimates made by each model with the flood frequency distribution established from the streamflow record. Secondly, a comparison of the spread of flood estimates made by the various users, for each of the models in turn.

5. RESULTS OF MODEL COMPARISON

Figure 2 shows flood frequency estimates made using the various methods, together with the actual flood frequency curve. Figure 2 is for the Sunnybank Station, but results for the larger Princes Highway catchment are very similar in the relative locations of the various estimates.

It is clear that the slopes of all flood frequency curves except the Regional Flood Frequency (RFF) method are flatter than the actual flood frequency curve for this station. This occurs because all methods except RFF use design rainfall data from ARR 1987 and consequently all curves have approximately the same slope as the rainfall frequency curve. Only the RFF method uses different rainfall data (the catchment median annual rainfall) and only this method produces a frequency curve close to the correct slope. While RM87 uses design rainfall data from ARR1987, derived values of the runoff coefficient C were recorded from flood frequency distributions. Consequently the difference in slopes is reflected in RM87 as an increase in C as the recurrence interval increases. Because of this slope of the frequency curve in figure 2 is slightly steeper than the other methods (except RFF).

Since the slope of the flood frequency curve is steeper than the rainfall frequency curve for most catchments, certainly in New South Wales , similar results can be expected on most catchments. This has implications for the choice of model and values of losses used for design, as discussed previously in Section 2.2 This matter is currently being investigated by Boyd and Cordery (1989).

Because of the different slopes of the rainfall and flood frequency curves, all methods overestimate flood discharges for low ARIs and underestimate for high ARIs.

The comparison between Rational Method results using 1977 (RM77) and 1987 (RM87) versions of Australian Rainfall and Runoff is interesting. Firstly, design rainfall intensities are considerably higher for 1987 ARR compared to 1977 ARR for this catchment. For 6 hour duration for example 1987 intensities are 1.5 times 1977 values. Secondly, for 1987, times of concentration using equation 1 are approximately one half the 1977 values calculated using the Bransby-Williams equation (2). Consequently, rainfall intensities used in the 1987 version are considerably higher than those used in the 1977 version. Because 1977 runoff coefficients depend critically on the rainfall intensity, it follows that they are also small, and for the lower ARIs actually become zero. The combination of all these factors causes 1987 Rational method flood peaks to be from 1.5 to 2.5 times greater than 1977 values for the Sunnybank Station, and more than 5 times greater for the Princes Highway Bridge Station.

The Cordery Webb Unit Hydrograph model (CWUH) and models RORB and WBNM have several features in common. They all use the design initial loss and continuing loss values given in ARR 1987. The critical duration storm was found to be between 6 and 9 hours for both Sunnybank and Princes Highway Bridge for all models. They use design parameter values from ARR in the form of equations (3) to (4) given earlier.

Note that the CWUH and RORB models require equations relating the model parameters to catchment characteristics, whereas WBNM requires only a single constant value of parameter C. This is because this model has lag-area relations built into it. A value of C near to 1.5 has been found to apply to a wide range of catchment sizes (0.1 to 10,000 km^2) in New South Wales. For this part of the study the parameter of WBNM was set at C = 1.5 and the non linearity parameter n was set at 0.23.

Another common feature of the models CWUH, RORB and WBNM is that they were all developed using recorded rainfall-flood events. It is interesting to note therefore that they all produce reasonably similar results, and that they lie toward the middle of the two rational method of flood estimates in Figure 2.

The model PSRM produces a flood frequency curve which is almost identical to RM87, for both Sunnybank and Princes Highway stations. This occurs even though several model parameters associated with soil type and losses must be estimated. Application of PSRM to more catchments is desirable to determine whether this result applies generally.

RM87 produces results which are somewhat higher than all other methods. This finding is consistent with a previous study by Webb and O'Loughlin (1981) in which the Pilgrim and McDermott (1982) version of the Rational Method (on which RM87 is based) consistently gave higher results for coastal NSW catchments.

Table I shows ratio of estimated to actual flood peaks for the data of Figure 2, for three ARIs. Errors in flood peaks are quite large, however, the errors in flood levels would be somewhat less. It should also be remembered that these results are for one catchment only.

TABLE 1
RATIO OF ESTIMATED TO ACTUAL FLOOD PEAKS AT SUNNYBANK

Model	Average Recurrence Interval (years) 2	10	100
RM77	1.58	0.83	0.40
RM87	2.18	1.63	0.99
CWUH	1.94	1.12	0.56
RORB	2.00	1.34	0.75
WBNM	2.01	1.25	0.67
PSRM	2.24	1.64	0.93
RFF	1.05	0.83	0.53

Finally, it is interesting to compare in Table II the ratio of flood estimates made by each model for the Princes Highway Bridge and Sunnybank Stations. The 10 year ARI floods were used for this. Estimates for the larger catchment should be larger than those for the smaller catchment, and a commonly used value is the square root of the ratio of catchment sizes ie $(105/35)^{0.5}$ = 1.73. While this ratio may not be strictly correct, it does give a basis for comparison.

TABLE II
RATIO OF PRINCES HIGHWAY BRIDGE TO SUNNYBANK FLOOD PEAKS

Model	Ratio Q_{10PH} / Q_{10SK}
RM77	0.67
RM87	2.17
CWUH	1.87
RORB	2.08
WBNM	2.17
PSRM	2.11
RFF	1.46

Most models scatter equally about the value 1.73. The exception is RM77 which actually predicts a smaller flood peak for the larger catchment. This anomaly occurs because the Bransby-Williams formula used in RM77 predicts a greatly increased time of concentration (from 4.1 to 9.3 hours) and consequently a much reduced design rainfall intensity (from 28.1 to 17.1 mm/hr). Because the RM77 runoff coefficient is critically dependent on rainfall intensity, it is greatly reduced (from 0.83 to 0.30) and consequently the predicted flood peak is reduced.

6. RESULTS OF USER COMPARISON

Although guidelines are given in ARR for the use of the models, users are still able to exercise some judgement and the different assumptions made lead to slightly different flood estimates by the various users, even when using the same model. Different assumptions can be made regarding the following:

(i) Storm duration A plot of calculated flood peak discharge versus storm duration typically rises from low discharges at short durations, to be reasonably horizontal over some range, before decreasing for the longer durations. The plot oscillates and ARR recommends that a smooth curve be drawn through the points. The maximum discharge tends to occur over a range of durations, and some variation in the selected critical duration is possible. For Sunnybank Station, users selected either 6 or 9 hours.

(ii) Losses Cordery and Webb (1974) give a detailed procedure for estimating design initial losses, depending on the catchment area and storm duration. ARR however omits these values and gives a more general statement that initial loss in eastern Australia can range from 10 to 35 mm. For the Sunnybank Station users selected initial loss values ranging from 5 to 13 mm. The well known continuing loss rate of 2.5 mm/hour appears to be accepted as a standard value, and all users adopted this.

(iii) The models RORB and WBNM require that the catchment be divided into sub-areas. The number of sub-areas and the location of their boundaries can be selected by the user, although guidelines are given by Boyd (1985). For Sunnybank Station users selected between 3 and 12 sub-areas.

(iv) Model Parameters When a model is first developed, regression equations relating the model parameters to catchment characteristics are usually provided. Later, other researchers may provide alternative equations for the same region or other regions. The user then has a choice of equations to use.

For the CWUH model, equations were originally given for NSW by Cordery and Webb (1974). ARR summarises equations for various regions within Australia, and an alternative equation for eastern Australia is given. For Sunnybank, values of parameter C in the range 1.82 to 1.93 hours, and values of parameter K from 2.51 to 2.67 hours can be used.

A similar position applies to RORB, and the various regression equations for different regions are summarised in ARR. For Sunnybank, values of K_c can vary between 6.26 to 6.51 according to the equations, but users adopted a wider range from 5.6 to 15.9. For RORB stream segment lengths and mode locations must be specified for all sub-areas and, depending on the values selected, this can also introduce variability into the flood estimates of various users.

For WBNM, the value of parameter C was originally recommended as C = 1.68. Subsequent studies by a range of researchers produced a lower value of C = 1.29. For Sunnybank, users adopted values of C in the range 1.00 to 1.68.

Figure 3 shows flood frequency curves estimated by the various users for Sunnybank Station, using WBNM. Results for WBNM are shown because more users used this model than CWUH and RORB, but similar results can be expected from those models. The various assumptions made by these users lead to a range of estimates of approximately ± 13% about the mean value. The coefficient of variation of the estimates (standard deviation/mean) is 0.091.

It is interesting to note that all users obtained identical results for the 1987 Rational Method. This is because the steps in this procedure are well defined, and also because the method has not yet been revised by the inclusion of additional data.

7. CONCLUSIONS

For the study catchments, it was found that the slope of the flood frequency curve was steeper than the design rainfall frequency curves. For those models which use design rainfall intensity data from Australian Rainfall and Runoff therefore, floods are overestimated for low average recurrence intervals and underestimated for high recurrence intervals. It may be possible to correct this difference in slopes by using nonlinear models, or by using smaller losses for the higher recurrence intervals. For the Sunnybank catchment studied here, the use of nonlinear models alone was not sufficient, and it would be necessary to modify the losses to give this correction.

Only one model, the Regional Flood Frequency method, did not use design rainfalls, and it was the only one to produce a flood frequency curve of similar slope to the actual curve.

There was a considerable difference between flood estimates made using the 1977 and 1987 versions of Australian Rainfall and Runoff. The 1987 version produced higher flood estimates than all other models, and this is consistent with other studies.

The models RORB, CWUH and WBNM all produced similar results, with WBNM lying near the mid point of these estimates.

The two models developed using actual flood frequency data, RM87 and RFF, are likely to produce the best estimates. It is interesting to note that PSRM estimates were very close to RM87 values for this catchment, but this result needs to be verified for other catchments.

When flood estimates are made by several users, all using the same model, the various different assumptions lead to a spread of estimated flood peaks. For this study, estimates ranged over ± 13% from the mean.

Finally, it should be remembered that these results are based on two catchments, only one of which is gauged. Some caution in accepting results is necessary. The study should give a good indication of the relative estimates made by the various methods, and also of the spread of estimates made by various users. The comparison of estimated and actual flood frequencies is necessarily limited to one catchment.

8. ACKNOWLEDGEMENT

The financial support of the Illawarra Regional Committee of the Water Research Foundation of Australia is acknowledged.

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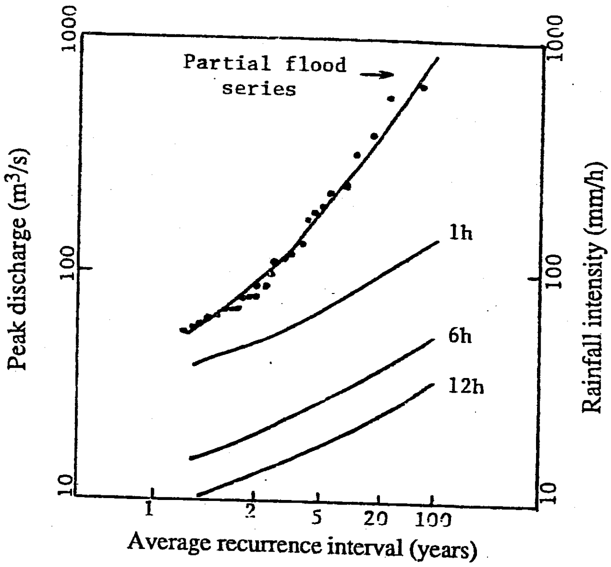

Figure 1 Rainfall and flood frequency curves - Macquarie Rivulet at Sunny Bank

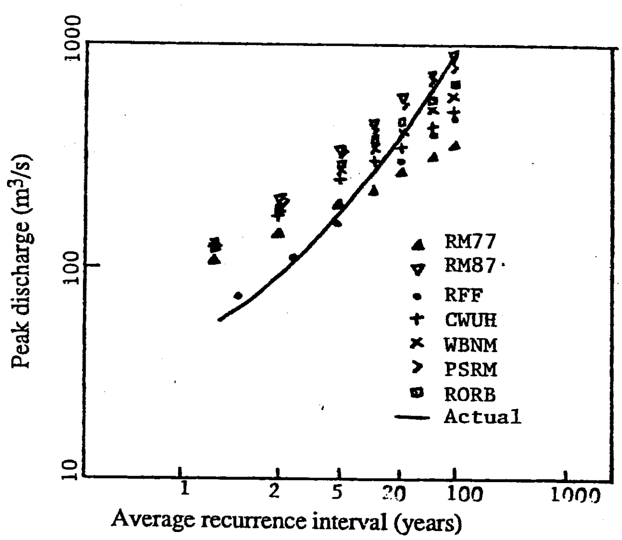

Figure 2 Estimated and actual flood frequency curves - Macquarie Rivulet at Sunny Bank

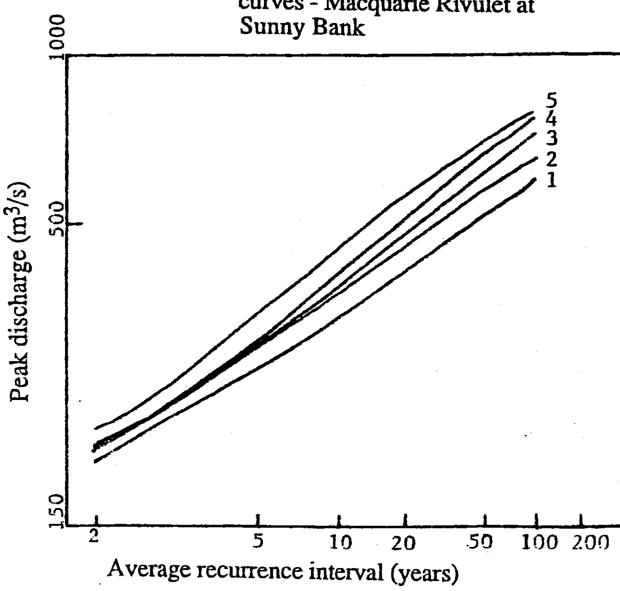

Figure 3 Comparison of flood estimates of various users (1-5) - Macquarie Rivulet at Sunny Bank