ESTIMATION OF DESIGN FLOODS USING CONTINUOUS SIMULATION

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Abstract

A common problem encountered by catchment managers is the estimation of design peak flow quantiles. Current practice, as discussed by Pilgrim (1987), is based either on the use of statistical approaches such as an at-site flood frequency analysis, or the use of a catchment modelling system to simulate catchment response to design rainfall. For many practical problems, the option of an at-site flood frequency analysis is not available due to the absence of recorded data at the desired location. In these situations, the second alternative (catchment simulation) must be employed to generate the information necessary for estimation of the design peak flow quantiles. While there are many alternative approaches to the generation of information for design flood flow quantile estimation, one approach that has been proposed previously (see, for example, Cameron *et al.*, 2001 and Droop and Broughton, 2003) is the use of continuous simulation techniques for generation of a flow sequence suitable for subsequent flood frequency analysis.

As part of the revision of ARR, continuous simulation techniques for design flood estimation in urban areas have been investigated. The focus of these investigations has been on techniques for prediction of flood quantiles together with the uncertainty of these predictions. Sources of the uncertainty considered were the rainfall sequences, parameter uncertainty, and the calibration metric. Presented herein will be the results of this investigation.

Introduction

Design flood estimation remains a problem for many catchment managers. Advice is required regarding design flood characteristics for the design of culverts and bridges necessary for cross drainage of transport routes, the design of urban drainage systems, the design of flood mitigation levees and other flood mitigation structures, design of dam spillways, and many other situations. The flood characteristic of most importance depends on the nature of the problem under consideration, but typically it is one of the following:

- Flood flow rate;
- Flood level;
- Flood rate of rise;
- Flood volume; or
- System failure.

While all of these flood characteristics have been noted as being of interest to flood designers, the dominant characteristic of concern has been the flood flow rate. This focus of the design flood problem is shown by Robinson (1987) who, in discussing selection of design floods, notes "*Hydrologic structures are required to perform in a predictable manner over a wide range of discharges. In Australia this can vary from zero to very large flows*".

As a result of the historical focus of flood designers, alternative approaches to design flood estimation have developed. These alternatives can be categorized as risk-based design and standards-based design. Most design flood management approaches in current practice, require a risk-based approach. With a risk-based approach, it is necessary to estimate both the magnitude and frequency of the flood characteristic of interest; in other words, the magnitude and frequency of design flood flows require estimation. Hence, the common design problem is one of predicting flood flows over a range of magnitudes and frequencies.

There are two alternative situations when design flood characteristics are required; these are:

- Suitable historical information (monitored data) is available; and
- Suitable historical information is not available.

It is the later situation that is of interest herein as the purpose of the catchment modelling is to develop data suitable for the prediction of flood flows over a range of frequencies and magnitudes. There are many alternative catchment modelling approaches that have been used for generation of information necessary for design flood flow prediction. Continuous simulation is one approach that has been proposed previously (see, for example, Cameron et al, 2001 and Droop and Broughton, 2003) with the aim of this approach being the generation of a flow sequence suitable for subsequent flood frequency analysis.

As part of the revision of Australian Rainfall and Runoff (ARR), continuous simulation techniques for design flood estimation in urban areas have been investigated. These investigations form ARR Research Project 8. The focus of these investigations has been on techniques for prediction of design flood quantiles together with the uncertainty of these predictions. Sources of the uncertainty considered were the rainfall sequences, parameter uncertainty, and the calibration metric. Presented herein will be the results of this investigation.

Approaches for Estimation of Design Flood Quantiles

As mentioned previously, there are two alternative situations when design flood characteristics are required; these situations are based on the availability of sufficient data. As shown in Figure 1, where adequate historical information is available, prediction of the desired flood flows can be undertaken using *at-site flood frequency analysis* (FFA) methods. Suitable approaches for FFA are presented by, for example, Jin and Stedinger (1989) and Kuczera (1999). Additionally, a draft of the recommendations for FFA methods (Kuczera and Franks, undated) is available to the profession through the ARR website (www.arr.org.au). The aim of FFA techniques is to develop a relationship between the peak flow of a flood hydrograph and its annual exceedance probability; an example of this relationship is shown in Figure 2.

For the alternative situation, where sufficient data is not available, two generic techniques have been applied for prediction of the desired flood flow magnitudes and frequencies. These two generic techniques, as shown in Figure 1, are

- Regional Transformation; and
- Catchment Simulation.

In general, those techniques classified as *Regional Transformations* are *Regional Flood Frequency Estimation* approaches and rely on analysis of monitored data from other catchments for prediction of design peak flows with a range of frequencies; examples of these techniques are presented by Mittelstadt *et al*. (1987) and Haddad and Rahman (2011). The aim of these techniques is the prediction of the relationship between the peak flow of a flood hydrograph and its annual exceedance probability (see Figure 2) for a location where insufficient data exists for direct determination of the relationship.

The second of these two categories are those techniques referred to as catchment simulation. The general basis of these procedures is the prediction of the catchment

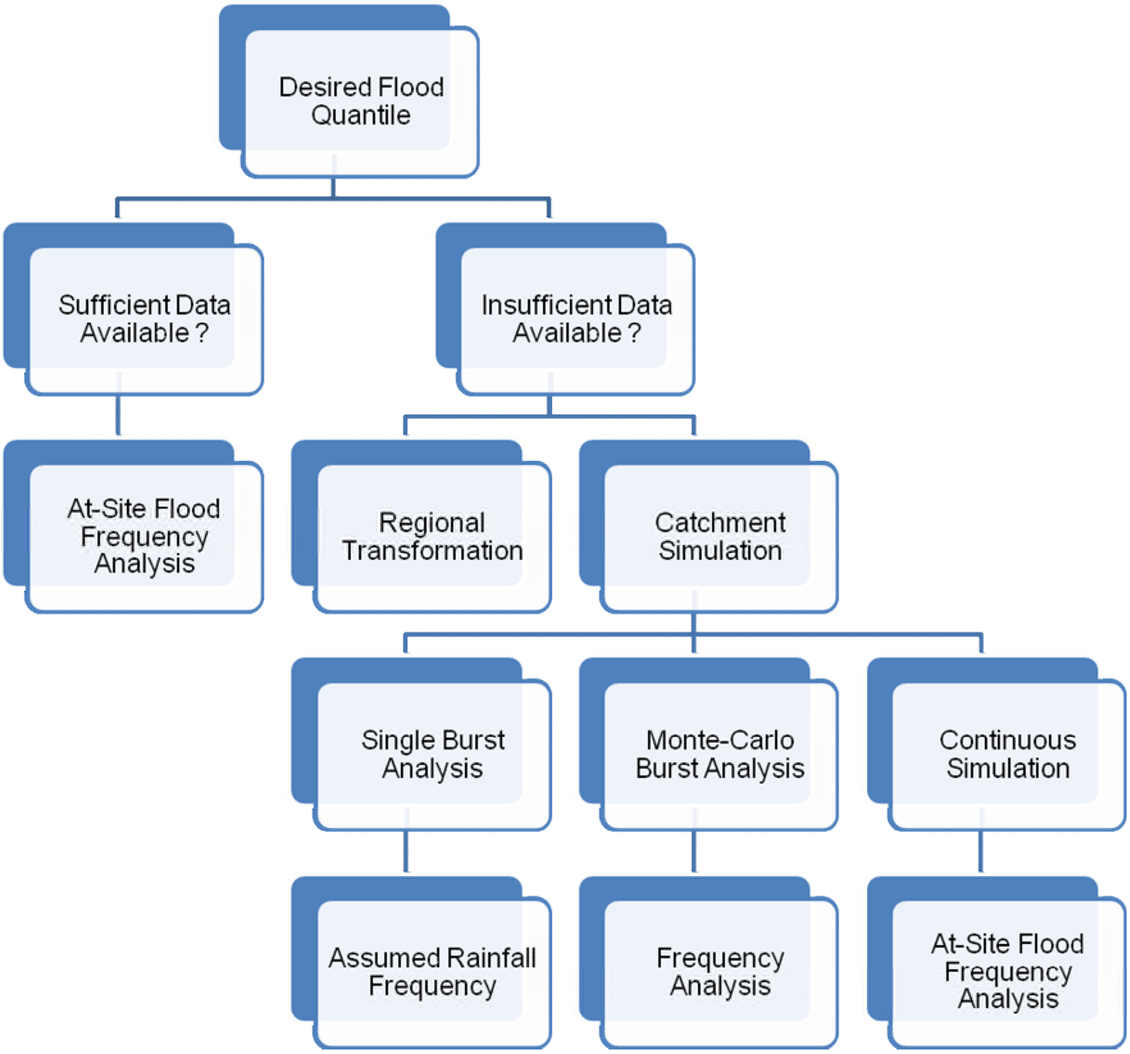

Figure 1 Design Flood Estimation Approaches

response to storm bursts or events. There have been numerous models proposed for prediction of this catchment response. Additionally, alternative approaches for their use in prediction of the desired relationship between the peak flow of a flood hydrograph and its annual exceedance probability. It is possible to categorise (see Figure 1) these alternative catchment simulation approaches into the following subcategories:

- Single Burst Analysis;
- Monte-Carlo Burst Analysis; and
- Continuous Simulation.

While approaches fitting within all three subcategories have been shown to be feasible for the prediction of the relationship between the peak flow of a flood hydrograph and its annual exceedance probability, the focus of the discussion herein is on the last of these subcategories, namely Continuous Simulation approaches. Hence only approaches in this category will be discussed further.

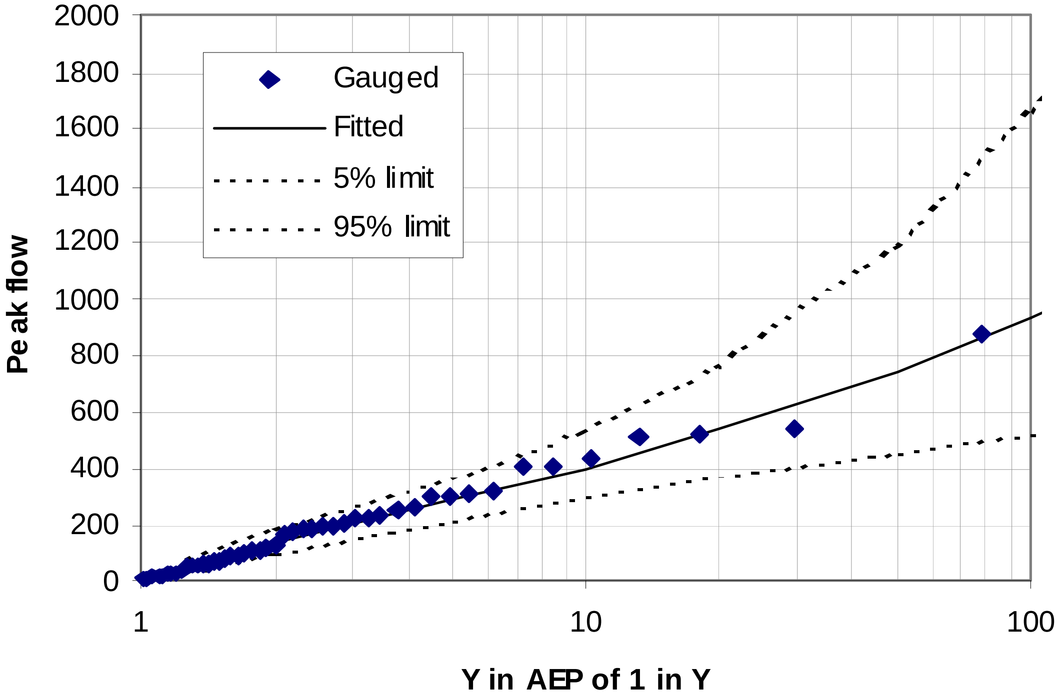

Figure 2 Probability plot for Styx River at Jeogla

Boughton and Droop (2003), Boughton *et al*. (1999), Cameron *et al*. (2001), Droop and Boughton (2003), Jones and Kay (2007), Jung and Bae (2005) and Tan *et al*. (2007) have proposed Continuous Simulation approaches suitable for design flood estimation. The fundamental basis for use of continuous simulation for prediction of design flood flows and their frequency is the prediction of flows at the point of interest that would have been recorded if monitoring program was undertaken at that point. For design flood estimation, these predicted flows need further analysis through implementation of an FFA approach resulting in relationship between the peak flow of a flood hydrograph and its annual exceedance probability as shown in Figure 2.

Test Catchment

Two catchments were investigated as part of this investigation. These catchments were:

- Powells Creek located at Strathfield in the Inner Western Suburbs of Sydney, NSW; and

- Gungahlin located in the north west of Canberra, ACT.

As results obtained from the two catchments are similar, only results from Powells Creek will be presented.

The Powells Creek catchment is a medium sized fully urban catchment located approximately 10km west of the Central Business District of Sydney. The catchment lies within the Sydney suburbs of Homebush West, North Strathfield, Rookwood and Strathfield, and is administered by the local government areas of Strathfield, Canada Bay and Auburn.

The total catchment area is approximately 841ha. However, only 236ha of the catchment drains to the gauging station located at Elva Avenue, Strathfield. Streamflow and rainfall data was collected at the gauging station from 1958 till 2005 by UNSW. The primary use of the collected data from the gauged catchment has been for many research projects; examples of these projects are

- Stream gauging of rapidly varying flows (Tilley *et al*., 2000);
- Catchment lag (Dewar and Robinson, 1988); and
- Prediction error correlation (Westra, 2003).

The catchment, as previously noted, is fully urbanised and has been fully urbanised over the gauging period. While redevelopment within the portion of the catchment monitored has occurred, it is reasonable to assume stationarity of the catchment flows over the gauged period.

After quality checking the data, data for a 40 year period between 1958 and 1997 was selected for determining the relationship between peak flow of the flood hydrograph and the annual exceedance probability. This relationship was determined using a GEV distribution and Bayesian methodology as implemented in the software package FLIKE; this approach is consistent with the draft chapter of ARR (Kuczera and Franks, undated). This relationship is shown in Figure 3 while predicted flow quantiles from this relationship are shown in Table 1.

Stormwater Management Model

The availability of computational resources has resulted in many alternative software systems being developed for simulation of both historical and design flows in urban catchments. Since a comparison between these packages was beyond the scope of

Table 1 Design Flood Quantiles for Powells Creek Gauging Station

AEP (%)	**Peak Flow** (m^3/s)	**Confidence Limits** (m^3/s)	
50	15.7	13.6	18.0
20	23.9	20.7	28.3
10	30.1	25.3	37.7
5	36.6	29.9	49.9
2	46.0	35.2	71.4
1	53.8	39.0	93.4

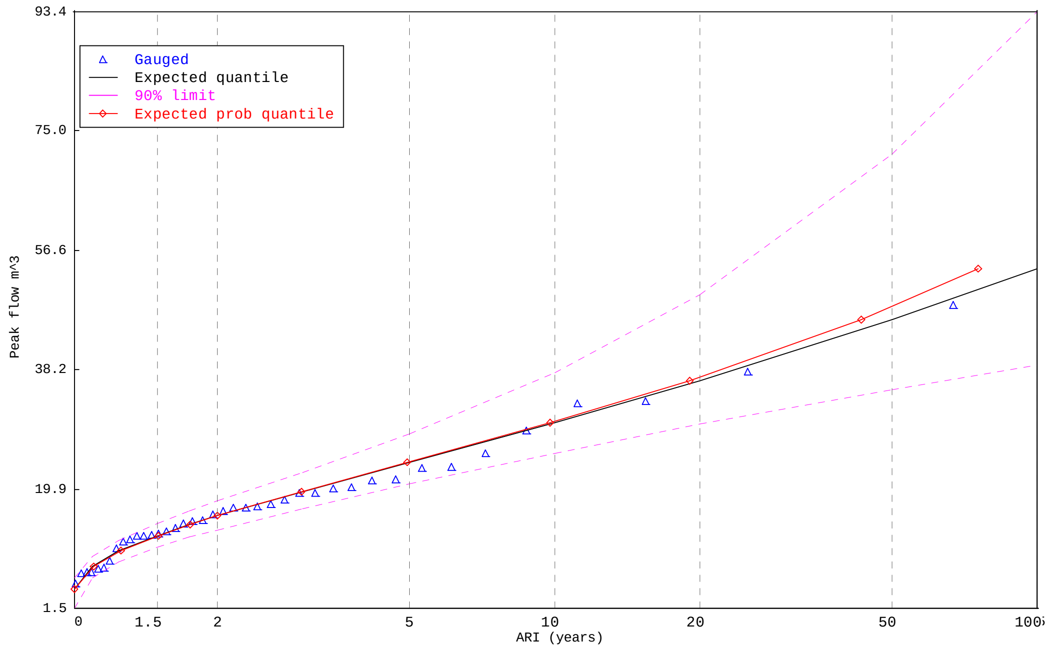

Figure 3 Flood Frequency Relationship for Powells Creek Catchment

this investigation, selection of the software package was based on the availability of historical models subject to the constraint that the software package was capable of undertaking continuous simulation; in other words, selection was based on the availability of models used in previous studies. A number of students have applied the Stormwater management Model (SWMM) to the Powells Creek catchment, and, hence, this software was selected for use in this investigation.

SWMM (Huber and Dickinson, 1988) is a distributed physically based catchment modelling system which is used widely for the assessment of catchment response in terms of both the quantity and quality of stormwater runoff from urban areas. Furthermore, the system is capable of simulation of the catchment response from both single bursts of rainfall and continuous sequences of rainfall; in other words, both continuous and event simulations are feasible with this catchment modelling system.

SWMM consists of a number of computational modules, in which the RUNOFF and TRANSPORT are two of the core blocks for simulating runoff quantity. As a distributed catchment modelling system, application of SWMM requires users to deal with a large number of spatially variable parameters. Using the concept presented by Choi and Ball (2002), it is possible to classify these spatially variable parameters into two categories, namely measured parameters and inferred parameters. The measured parameters, such as the subcatchment areas, the length and slope of open channels and pipes, and the dimensions of the open channels and pipes, are assumed to be error free during calibration. The second category of parameters is the inferred parameters which are parameters that cannot be physically measured and usually are estimated during the calibration process.

Modelling System Calibration and Validation

There are numerous steps in the implementation of a catchment simulation approach to prediction of design flood flows. Among these steps is the need for calibration and validation of the catchment modelling system.

Calibration is the process which aims at identifying appropriate values of the parameters so that the catchment modelling system can be used effectively to predict the catchment response. Traditional calibration approaches tend to identify a unique optimal parameter set or near optimal parameter set which represents the generic catchment characteristics. However, many studies have demonstrated extreme difficulties, if not the impossibility of finding a unique optimal parameter set due to uncertainty of model structure, simplifications of process, measurement errors associated with both the input and observed data, and interactions between parameters; see, for example, Kuczera, (1983), Sorooshian *et al.*, (1983), Beven and Binley, (1992), and Gan and Biftu, (1996). Validation, on the other hand, tests that the selected parameter values, or range of parameter values, will result in reasonable predictions for data not used as part of the calibration process.

Both calibration and validation require metrics for assessment of the alternative parameter sets and, hence, the belief that can be applied to the predictions obtained. Sefe and Boughton (1982) showed that the selected set of parameter values for a catchment model were dependent on the metric used to assess the performance of the catchment modelling system. This arises from the alternative metrics emphasising different portions of the flood hydrograph. Hence, as there are many alternative metrics that can be used, it is important therefore that the selected metric reflect the purpose of the modelling and emphasise the appropriate portion of the hydrograph.

The need for careful consideration of the metric used to assess the suitability of a set of parameter values is shown in Figure 4. In this figure, the results from a number of studies presented by Boughton and Droop (2003) are summarised in non-dimensional terms. The catchment modelling systems used in these studies were calibrated to individual events (events models) or the flow sequence (continuous models). Predicted flood quantiles were then derived using standard techniques from the generated data. These predicted flood quantiles have been normalised by the flood quantile derived from a frequency analysis.

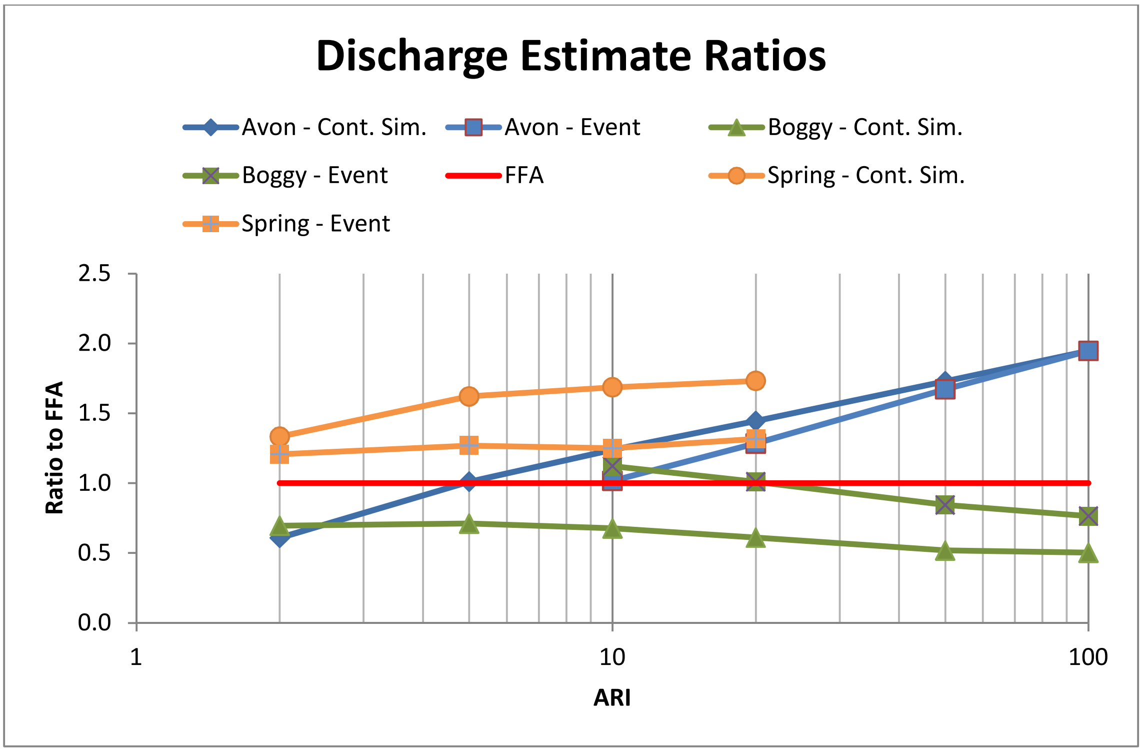

Figure 4 Non-dimensional Predicted Flood Quantiles

As shown in Figure 4, the resultant relationship between flood flow and AEP developed from the modelling results does not coincide with the relationship derived from the recorded data. For the continuous simulation results, the predicted flood quantile for one catchment (Boggy Creek) is consistently under-predicted but with a consistent bias. For the other catchment (Spring Creek), the predicted flood quantile is over-predicted with the magnitude of the over-prediction appearing to be a function of the AEP. Hence, while the catchment modelling systems used for the continuous simulation were calibrated and validated, the metric applied during the calibration was not appropriate for reliable prediction of the flood frequency relationship.

A flood frequency relationship is developed using the maximum instantaneous flow in any year (Annual Maxima Series - AMS) or those peak flows that exceed a threshold (Peak over Threshold Series – PoTS). An analysis of this form using data from catchment simulation does not require accuracy in those flows that are not part of the AMS or PoTS.

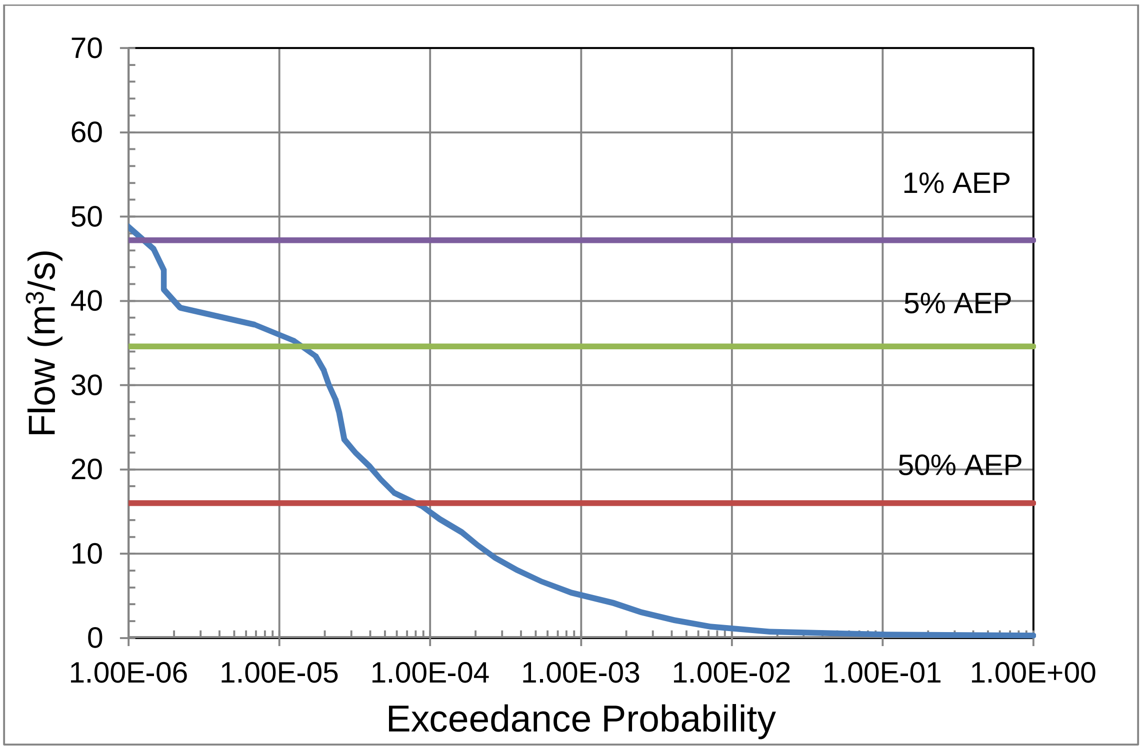

Figure 5 Flow Exceedance Probability for Powells Creek

Shown in Figure 5 is the flow exceedance probability for Powells Creek over the 40 year period used in this investigation. Also shown in this figure are the 1%, 5% AND 50% AEP design flood quantiles. As shown in this figure, should the complete generated flow sequence be used for calibration and validation of the catchment modelling system then a significant portion of the flows influencing the calibration will not be part of the subsequent analysis; only 0.1% of the recorded flows exceed 4m3/s and only 0.01% of the recorded flows exceed the design 50%AEP flow. Use of these low flows has the potential to bias the calibration due to their frequency of occurrence; the result will be similar effects to those shown in Figure 4.

As previously noted, the aim of undertaking a catchment simulation using continuous simulation approaches is the generation of sequences of flow data that replicate the data that would have been collected if a monitoring program had been employed. Using this concept, it was considered that the appropriate metric for assessing the performance of the catchment modelling system was one that reflected the flood frequency relationship and the catchment response.

Hence, a multi-criteria metric was used. This metric had two parts which were:

- Prediction of flows greater than a defined threshold – analogous to a PoTS; and
- Prediction of the three parameters defining a GEV distribution – analogous to fitting to the flood frequency relationship.

For the results presented herein, an arbitrary threshold of $0.4m^3/s$ was adopted. However, the sensitivity of this value is the subject of ongoing investigation. The second component of the metric was based on the difference between the GEV parameters for the predicted (see Table 2) and recorded flood frequency relationship.

Table 2 GEV Parameters for Flood Frequency Relationship at Powells Creek

Parameter	**Most Probable Value**
Location - μ	13.36
loge (Scale - α)	1.818
Shape - κ	-0.095

It is worth noting that application of either of the two parts independently did not result in suitable calibration of the catchment modelling system. While space limitations preclude a detailed discussion herein, a detailed discussion is included in the ARR Research Project 8 Report (in preparation).

Given difficulties in the identification of a single unique optimal set of parameters, identification of suitable parameter sets was based on the concept of behavioural and non-behavioural sets of parameter values. Behavioural sets were those where the prediction metrics were within a defined tolerance of the calibration metric. For this case, the defined tolerance was a normalised residual of 10%.

Using this approach, approximately 500 behavioural sets of parameter values were identified; these were selected from approximately 50,000 trials. It is the analysis of the predictions from these 500 behavioural sets of parameter values that was used for assessing prediction uncertainty.

Predicted Flood Frequency Relationship

When a continuous catchment modelling system is implemented, the aim is the generation of a flow sequence that has similar characteristics to those flows that would have been recorded if monitoring were available. Assessment of the predicted flows, therefore, should focus on the statistical characteristics of the predicted flow.

For each identified behavioural set of parameter values, the predicted flow sequences were analysed using FFA techniques. In other words, the AMS of the predicted flow sequences for each set of behavioural parameter values was analysed using FLIKE to obtain a relationship between flood flow and AEP.

The ratio of the predicted flows to those obtained from analysis of the recorded flows was obtained for the 50, 20, 10, 5, 2, and 1% AEP flows. To illustrate the generic characteristics of the results obtained, the average ratio for each AEP was calculated. Shown in Figure 6 is the average ratio of the design flood flow predicted from the modelling data to the design flood flow from the recorded data.

From consideration of Figure 6, some generic results were

- Frequent flood flows tended to be overestimated;
- Rarer flood flows tended to be underestimated;
- The growth curve tended to be underestimated; and
- The variation in the predicted design flows for alternative sets of behavioural parameter values was similar in magnitude to the extent of the Confidence Limits obtained for the monitored data.

Some discussion of these results is warranted. The catchment area upstream of the gauging station on Powells Creek is $2.4km^2$. Additionally, the catchment area was subdivided into 38 subcatchments.

For each subcatchment modelled using SWMM, there are a number of parameters influencing the catchment response. Furthermore, there are parameters which influence the response of the impervious areas, others that influence the response of the pervious areas, and others that relate to the pipes and channels linking the subcatchments to the catchment outlet. As a result, there are approximately 20 parameters per subcatchment that can be modified to improve the calibration with

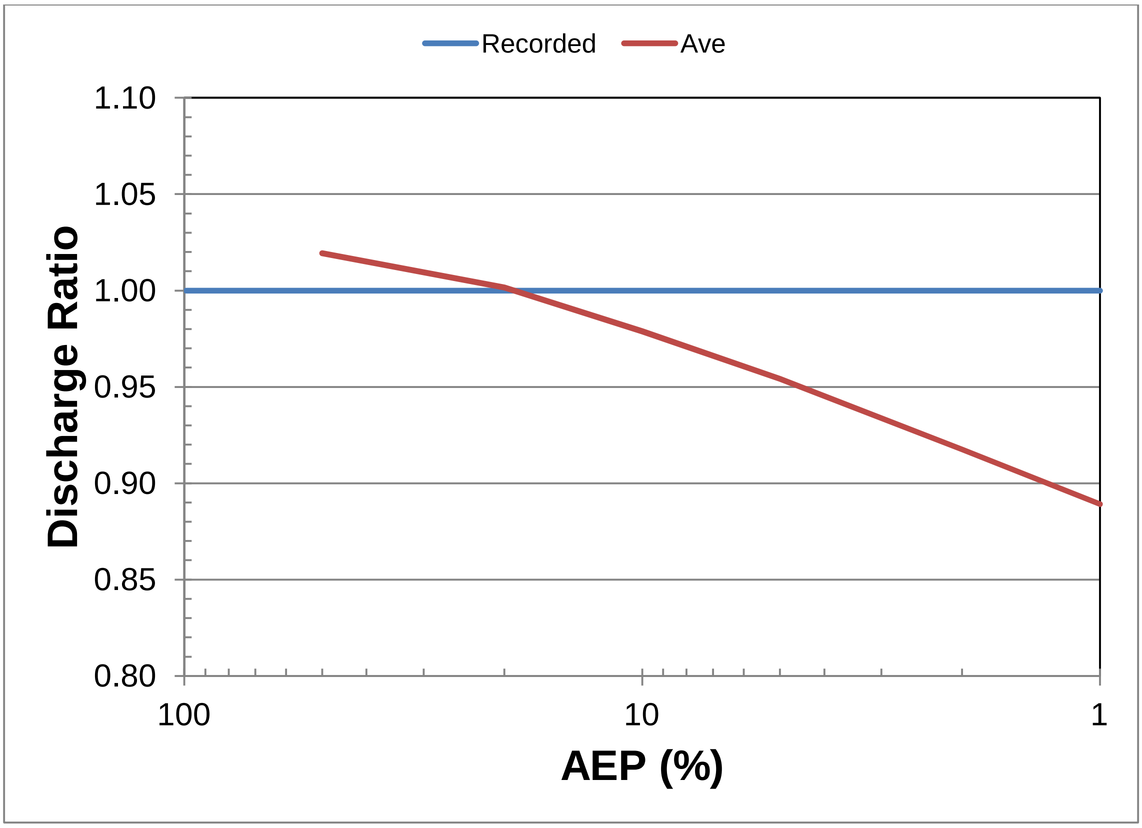

Figure 6 Average Ratio of Predicted Peak Flood Flow

many of these parameters being correlated. In this study, parameter values were sought for each subcatchment; in other words, the parameter values were spatially distributed.

The rainfall model applied during this study, however, was lumped; in other words, a spatially averaged and spatially constant rainfall was applied for prediction of catchment response. Furthermore, the rainfall was assumed to be stationary during the simulations. These assumptions were necessary as monitored rainfall from only one gauge was used to represent the rainfall occurring over the catchment during the period of simulation.

These assumptions are not consistent with the recorded rainfall data for the catchment. While there were two rain gauges monitoring rainfall occurring within the catchment, it was found that only the more intense storm events were consistent between the two gauges over the period when the two gauges were operational.

It is suspected that the result of using a spatially lumped model is an over-estimation of the rainfall resulting in frequent events and hence an over-estimation of the resultant flow. While the influence of the rainfall model was investigated by Umakhanthan and Ball (2005), the focus of that investigation was on individual events rather than continuous sequences. Nonetheless, that study highlighted considerable variability between individual storms which would not be reflected in the lumped model used herein. Hence, further research in the influence of rainfall models on the relationship between flood flow and AEP is needed.

Finally, as noted previously, the magnitude of the variation in the different relationship between flood flow and AEP obtained using alternative behavioural sets of parameter values was similar to the magnitude of the Confidence Limits. This predicted variation needs to be interpreted as a lower bound to the potential uncertainty as the primary source of this variation is limited to parameter values. Additional sources of uncertainty are introduced by the rainfall model (inclusive of the recorded rainfall sequence, the spatial extent of the rainfall, etc.), the model structure (particularly the pervious – impervious area simulation), the reliability of the recorded data used for calibration and validation of the catchment modelling system, and inclusion of the CLs from the FFA for individual sets of parameter values.

Conclusion

Reported herein have been the results of an investigation into the use of continuous catchment simulation for the prediction of the relationship between flood flow and AEP for an urban catchment. As a result of this investigation it was found that

- Censoring of the recorded data is necessary during the calibration phase of the modelling to ensure that the calibration is not biased by the frequency of flows that are not relevant to the problem being investigated. In this study less than 0.1% of the flows were relevant for development of the desired relationship.
- The rainfall model has a significant influence on the predicted flows with the assumption of a spatial average value for frequent events likely to be the source of the over-estimation of the more frequent flows.
- The variability in the predicted relationship is likely to be greater than that obtained from an FFA.

Furthermore, while it was found that this relationship could be obtained from continuous simulation, there are many areas where further research is required to enable wide-spread application of the approach.

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