Revised Guidance on Selection of Approaches to Flood Estimation

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Abstract

Hydrologists are required to estimate flood magnitudes for the design of culverts and bridges for roads and railways, 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 it is often necessary to estimate peak flow, peak level, flood volume, and flood rise.
Design objectives are most commonly specified using risk-based criteria, and thus the focus of the revised ARR guidance (for Chapter 3 of Book 1) is on the use of methods that provide estimates of flood characteristics for a specified probability of exceedance. A key difference between the proposed guidance and earlier versions of ARR is the focus on "probability-neutrality". This concept is particularly relevant to rainfall-based techniques where it is necessary to ensure that the transformation of design rainfalls into design floods is undertaken in a fashion that minimises bias in the resulting exceedance probabilities. Accordingly, the proposed guidance introduces the use of more computationally intensive procedures (such as ensemble event, Monte Carlo event, and continuous simulation approaches) in an attempt to minimise bias in the resulting flood quantiles.
This paper summarises the proposed ARR recommendations covering the selection and application of methods available to the flood practitioner. The methods discussed are divided into two broad classes of procedures based on: (i) the direct analysis of observed flood and related data and (ii) the use of simulation models to transform rainfall into flood maxima. All methods involve the use of some kind of statistical model (or transfer function) to extrapolate information in space or time, and the paper includes discussion of their strengths and limitations and how they vary in their suitability to different types of data and design contexts.

1. INTRODUCTION

Design flood estimation is a focus for many engineering hydrologists. In many situations, advice is required on flood magnitudes for the design of culverts and bridges for roads and railways, 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 it is often necessary to estimate peak flow, peak level, flood volume, and flood rise. The analysis might be focussed on a single location – such as a bridge waterway or township levee – or it may be necessary to consider the performance of the whole catchment as a system, as required in urban drainage design.

Design objectives are most commonly specified using risk-based criteria, and thus the focus of this guidance is on the use of methods that provide estimates of flood characteristics for a specified probability of exceedance.

The general nature of the estimation problem is illustrated in Figure 1. This figure shows the annual flood maxima (blue circular symbols) from 75 years of available gauged records. These flood maxima have been ranked from largest to smallest and are plotted against an estimate of their sample exceedance probability. Such information can be used directly to identify the underlying probability model of flood behaviour at the site which the data was collected. The flood peaks are usually considered to be independent random variables, and it is often assumed that each flood is a random realisation of a single probability model.

The best estimate of the relationship between flood magnitude and annual exceedance probability obtained by fitting a probability model is shown by the solid red curve in Figure 1. The gauged data represent a finite sample of a given size, and thus any estimate of flood risk using a fitted probability model is subject to uncertainty, as illustrated by the increasingly divergent dashed red curves. The computation of such confidence limits usually only reflects the limits of the available sample, or perhaps the increasing uncertainty involved in the extrapolation of the relationship between recorded stage and estimated flood peak. However, it needs to be recognised that these factors only represent the uncertainties most easily characterised; other factors, such as the influence of a non-stationary climate, changing land-use during the period of record, and the changing nature of flood response with event magnitude, confound attempts to identify the most appropriate probability model. Accordingly, the true uncertainty around such estimates will be larger than that based solely on consideration of the size of the available sample. Of course, data are rarely available at the location of design interest, and additional uncertainty is involved in the scaling and/or transposition of flood risk estimates to the required site.

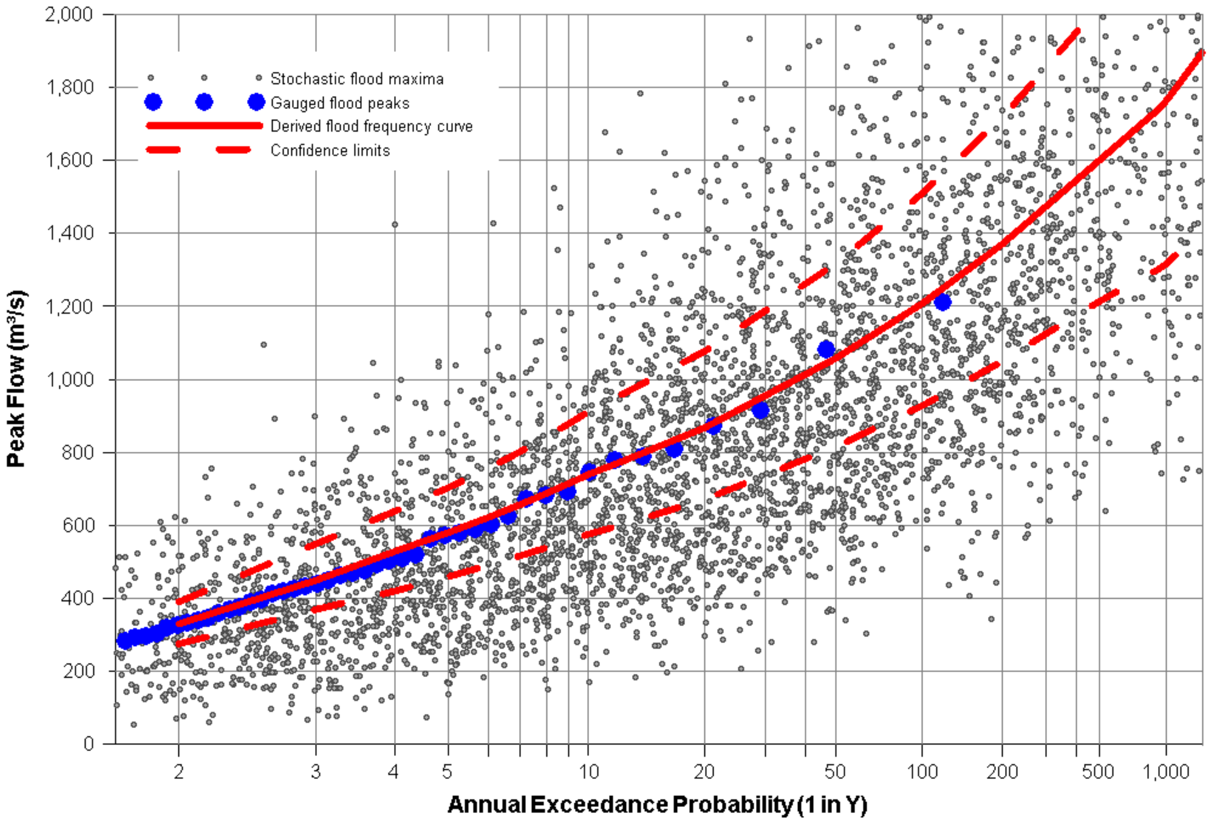

Figure 1 Illustration of stochastic influence of hydrologic factors on flood peaks and the uncertainty in flood risk estimates associated with observed flood data.

Figure 1 also illustrates the influence of natural variability on flood generation processes, and is based on the stochastic simulation of flood processes using 10,000 years of rainfall data under the assumption of a stationary climate. The stochastic flood maxima were obtained by varying key factors that influence the production of flood runoff, namely rainfall depth, initial and continuing losses, and the spatial and temporal patterns of catchment rainfalls. The flood peaks in this figure are plotted against the AEP of the causative rainfall, and the scatter of the stochastic maxima illustrates the natural variability inherent in the production of flood runoff. While these maxima have been derived from mathematical modelling of event rainfall bursts, an indication of this variability can be seen in the relationship between observed rainfalls and runoff in gauged catchments (though of course with real-world data we do not have 10,000 years of observations).

The scatter of stochastic flood maxima resulting from different combination of flood producing factors illustrates the inherent difficulty in removing bias from “design event” methods. Such methods use a flood model to transform probabilistic bursts of rainfall (the “design rainfalls”) to corresponding estimates of floods. For example it is seen from Figure 1 that the flood peaks resulting from 1% AEP rainfalls range in magnitude between around 500 m^3/s and 2000 m^3/s; it is also seen that the AEP of rainfall that might generate a flood with a 1,000 m^3/s peak might vary between around 20% and 0.1%. Traditional practice has been to adopt fixed values of losses and rainfall patterns for use with design rainfalls to derive a single flood that is assumed to have the same AEP as its causative rainfall. If chosen carefully it is possible to select a set of values that yields an unbiased estimate of the design flood, but without taking steps to explicitly cater for the joint probabilities involved, there is a considerable margin for error (Weinmann et al, 2002; Kuczera et al., 2006).

Accordingly, a key difference between the new edition of ARR and earlier versions is the focus on how best to achieve “probability-neutrality” when using rainfall-based techniques. A number of more computationally intensive procedures are introduced (such as ensemble event, Monte Carlo event, and continuous simulation approaches) to help ensure that the method used to transform rainfalls into design floods is undertaken in a fashion that minimises bias in the resulting exceedance probabilities.

The methods discussed here are divided into two broad classes of procedures based on: (i) the direct analysis of observed flood and related data (Section 2) and (ii) the use of simulation models to transform rainfall into flood maxima (Section 3). All methods involve the use of some kind of statistical model (or transfer function) to extrapolate information in space or time. Each method also has its strengths and limitations and they vary in their suitability to different types of data and design contexts, and this is discussed in Section 4.

2. FLOOD DATA BASED PROCEDURES

On overview of the procedures commonly used to analyse flood data directly is provided in Table 1. Flood frequency techniques are used to estimate the probability of flood exceedances directly from observed flood maxima, and are often used to extrapolate to probabilities beyond that inferred by the length of available record. Flood frequency analyses are most commonly applied using only the data at the site of interest using peaks-over-threshold and annual maxima series (“at-site analyses”), but the resulting estimates of flood risk can be much improved by the consideration of flood behaviour at multiple sites that are judged to have similar flood frequency distributions (“at-site/regional analyses”). This concept of pooling information from multiple sites is often referred to as “trading space for time” for, with appropriate care, the information on flood exceedances across a region can improve the fit of the probability model at a single site with a short period of record.

One drawback of frequency analyses is that it can only provide quantile estimates at sites where data is available. Accordingly, a range of procedures have been developed to estimate flood risk at sites with little or no data. These procedures generally involve the use of regression models to estimate the parameters of probability models (or the flood quantiles) using physical and meteorological characteristics, although simpler scaling functions can sometimes be used for local analyses. Rahman et al (2015) provide details of a regional flood model (RFFE) for different Australian regions in which the three parameters of the probability model are estimated from catchment characteristics using a Bayesian regression approach. The developed procedure provides a quick means to estimate the magnitude of peak flows for AEPs ranging between 50% to 1%, with the additional attraction that uncertainty bounds are provided. The regression equations presented in Book 3 were developed using parameters obtained from at-site/regional flood frequency analyses, and thus represent a rigorous example of regional flood frequency analysis based on parameter regression.

Table 1. Summary of common procedures used to directly analyse flood data

	Frequency analysis of small floods	Frequency analysis of large floods	At-site/regional flood frequency analysis	Regional Flood Frequency Estimation
Inputs	Peak-over-Threshold series	Annual maxima series at single site of interest	Gauged flood maxima at multiple sites with similar flood behaviour	Catchment characteristics and flood quantiles (or parameters) derived from frequency analyses
Analysis	Selected probability model is fitted to flood maxima (eg exponential distribution fitted by L-Moments)	Selected probability model is fitted to flood maxima (eg LPIII/GEV distributions fitted by L-Moments)	Information from multiple catchments is used to improve fit of probability model (eg regional L-Moments or Bayesian inference)	Regression on model parameters or flood quantiles (eg RFFE method), or local scaling functions based on catchment characteristics
Outputs	Flood quantiles for AEPs > 10% at a gauged site	Flood quantiles for AEPs < 10% at gauged site	Improved flood quantiles at multiple sites of interest	Flood quantiles at ungauged sites

3. RAINFALL BASED PROCEDURES

Rainfall-based models are commonly used to extrapolate flood behaviour at a particular location using information from a short period of observed data; this can be done using either event-based or continuous simulation approaches. The parameters of such models can also be transposed to a different location (or modified to represent different catchment conditions) and used to estimate flood characteristics for which no gauging information is available.

Table 2 summarises the different characteristics of the event-based and continuous simulation approaches. The three broad approaches to event-based simulation all use the same hydrologic model to convert design rainfall inputs into hydrograph outputs, the main difference is in the level of sophistication used to minimise bias in the probability-neutrality of the transformation. Continuous simulation approaches utilise model structures which generally differ markedly from those used in event-based models.

Table 2. Summary of recommended rainfall-based procedures

	Simple Event	Ensemble Event	Monte Carlo Event	Continuous Simulation
Hydrologic Inputs	Design rainfalls (ie rainfall depth for given burst duration and annual exceedance probability)			Observed (or synthetic) time series of rainfall and evaporation
Hydrologic variability	Fixed patterns of rainfall and other inputs	Ensemble of *N* temporal patterns	Ensemble (or distribution) of temporal patterns, losses, and other factors.	As represented in the time series of inputs – if not in time series then not represented
Model	Event-based model based on routing rainfall excess through catchment storage (see Book 5 for details of technique)			Model of catchment processes influencing runoff generation
Framework	Single simulation for each combination of rainfall depth and AEP	*N* simulations for each combination of rainfall depth and AEP (N≈10)	Stochastic sampling of input distributions using continuous or stratified domain (potentially thousands of simulations)	Continuous simulation at time step for *N* years
Flood AEP	Assumed same as input rainfall		Statistical analysis of joint probabilities (eg frequency analysis of maxima or Total Probability Theorem)	Computed from frequency analysis of *N* annual maxima
Flood magnitude	Single estimate derived from each set of inputs	Single average (or median) of *N* simulations		
ARR guidance	Book 4, Sect 3.2.2	Book 4, Sect 3.2.3	Book 4, Sect 3.2.4	Book 4, Sect 3.3

Event-based approaches are based on the transformation of rainfall depths of given duration and annual exceedance probability ("design rainfalls") into flood hydrographs by routing rainfall excess through catchment storage. Such models can include the allowance of additional pre- and post-burst rainfalls to represent complete storms, and can separately consider baseflow contribution from prior rainfall events to represent total hydrographs. The defining feature of such models is that they are focused on the simulation of an individual flood event and that antecedent conditions need to be specified in some explicit fashion. Design event methods can be applied in a deterministic fashion (termed here "*simple event*" methods), where key inputs are fixed at values that minimise the bias in the transformation of rainfall into runoff. Alternatively, stochastic techniques can be used to explicitly resolve the joint probabilities of key hydrologic interactions. The *ensemble event* method represents a modest increase in computational requirements over the traditional deterministic design event approach. Rather than adopting typical fixed values of inputs in the hope of achieving probability-neutrality, selected inputs are selected from an ensemble of inputs and the simulation results are based on the central tendency of the outputs (ie the average or the median, as judged appropriate for the degree of non-linearity involved; Sih et al, 2008; Ling et al, 2015). This can be done in a variety of ways, but most simply this is applied to temporal patterns as they typically have the largest influence (after rainfall depth) on the timing and magnitude of hydrograph response. To this end, a representative sample of, say, ten temporal patterns is selected from recorded data in a meteorologically homogeneous region, and the hydrographs obtained by simulating flood response from a given combination of rainfall depth and duration are analysed to provide a centrally tended estimate (either the arithmetic mean or the median) of the peak flow associated with the AEP of the input rainfall. A representative hydrograph from the ensemble can be scaled to match the derived peak for design purposes.

The basis of the *Monte Carlo event* method is a recognition that flood maxima can result from a variety of combinations of flood producing factors, rather than from a single combination as is assumed with the deterministic approaches. For example, the same peak flood could result from a large, front-loaded storm on a dry basin, or a moderate, more uniformly distributed storm on a saturated basin. Such approaches attempt to mimic the joint variability of the hydrologic factors of most importance, thereby providing a more realistic representation of the flood generation processes. The method is easily adapted to focus on only those aspects that are most relevant to the problem. To this end, it is possible to adopt single fixed values for factors that have only a small influence on runoff production, and full distributions (or data ensembles) for other more important inputs, such as losses, and temporal patterns, or any influential factor (such as initial reservoir level) that may impact on the outcome. The approach involves undertaking numerous simulations where the stochastic factors are sampled in accordance with the variation observed in nature. Most simply, the simulations can be undertaken for specific storm durations (applying the critical rainfall duration concept) and the exceedance probability of the desired flood characteristic may be computed using the Total Probability Theorem (Nathan et al, 2003).

With continuous simulation approaches, a conceptual model of the catchment is used to convert input time series of rainfall and evaporation into an output time series of streamflow; the flood events of interest are then extracted from the simulated streamflow record and analysed by conventional frequency analysis. The models used to transform the input rainfall into streamflow tend to be rather more complex than those commonly used in the design event or stochastic approaches. The main reason for this complexity is the ability of the models to account for changes in state variables (eg soil moisture and other catchment stores) during the simulation period. While these models have been used for the past 40 years for the prediction of continuous flow sequences, their dominant purpose has been for estimation of flow sequences for either yield analysis or for environmental considerations (Chiew, 2010). That said, their use has been extended to the estimation of design floods (Cameron et al, 2000; Boughton and Droop, 2003; Blazkova, & Beven, 2009).

4. ADVANTAGES AND LIMITATIONS

The methods described above have their differing strengths and weaknesses, and this means that each method is suited to a particular range of data availability and design contexts. While the broad differences in the applicability of the different methods are discussed below, it should be recognised that there is considerable overlap in the ranges of applicability between rainfall-based and flood data based procedures. The degree to which different procedures should applied to provide multiple sources of evidence for design decisions is dependent on context, but it is strongly advisable to use all available data and a range of methods for high value designs with large consequences of failure. The comparison of different methods yields insights about errors or assumptions that might otherwise be missed, and the process of reconciling the different assessments provides valuable information that aids adoption of a final “best estimate”.

4.1. Flood Data Based Procedures

The prime advantage of flood frequency analyses is that they provide a direct estimate of flood exceedance probabilities based on gauged data. Peak flood records represent the integrated response of a catchment to storm events and thus are not subject to the potential for bias that can affect rainfall-based procedures. Furthermore, flood frequency analyses are quick to apply compared to rainfall-based procedures and have the ability to provide estimates of uncertainty, most easily those associated with the size of sample and gauging errors. These represent very considerable advantages, and thus it is not surprising that flood frequency analysis is an important tool for the practicing flood hydrologist.

However, there are some practical disadvantages with the technique. The available peak flood records may not be representative of the conditions relevant to the problem of interest: changing land-use, urbanisation, upstream regulation, and non-stationary climate are all factors that may confound efforts to characterise flood risk. The length of available record may also limit the utility of the flood estimates for the rarer quantiles of interest. Peak flow records are obtained from the conversion of stage data and there may be considerable uncertainty about the reliability of the rating curve when extrapolated to the largest recorded events. In addition, gauges may be relocated, survey datums altered, and channel conditions may change, and hence different rating curves are applicable to different periods of historical data. There is also uncertainty associated with the choice of probability model which is not reflected in the width of derived confidence limits: the true probability distribution is unknown and it may be that different models may fit the observed data equally well, yet diverge markedly when used to estimate quantiles beyond the period of record.

Perhaps the most obvious limitation of flood frequency analysis is that relies upon the availability of recorded flood data. This is a particular limitation in urban drainage design as there are so few gauged records of any utility in developed catchments. But the availability of representative records is also often a limitation in rural catchments, either because of changed upstream conditions or because the site of interest may be remote from the closest gauging station.

For this reason, considerable effort has been expended on the development of a regional flood model that can be used to estimate flood quantiles in ungauged catchments (Rahman et al, 2015). The prime advantage of this technique is that it provides estimates of flood risk (with uncertainty) using readily available information at ungauged sites; the estimates can also be combined with at-site analyses to help improve the accuracy of the estimated flood exceedance probabilities. The prime disadvantage of the technique is that the estimates are only applicable to the range of catchment characteristics used in development of the model, and this largely excludes urbanised catchments and those influenced by upstream impoundments (or other source of major modification). For such catchments it will be necessary to consider the use of rainfall-based methods, as described below.

4.2. Rainfall Based Procedures

A key advantage of rainfall based approaches is that they provide the means to derive flood hydrographs. The derivation of a full hydrograph rather than a single attribute (such as flood peak) allows the design loading condition to be assessed in terms of both peak and volume, which is of prime importance when considering the mitigating influence of flood storage. Of arguably greater importance is the ability of rainfall based approaches to take advantage of the extensive availability of rainfall data. This is a very important advantage as rainfall characteristics vary across space in a more predictable and generally more uniform fashion than floods. This feature, along with the greater length and density of rainfall gauging, allows the derivation of probabilistic estimates of rainfalls that are much rarer and more easily transposed than flood characteristics.

However, these significant advantages are offset by the need to transform rainfalls into floods using some kind of design event transfer function or simulation model. Common examples of the former include the Rational Method and Curve Number method of the US Soil Conservation Service; while such methods provide an attractive means of simplifying the complexity involved in generation of flood peaks, their use in the new edition of ARR has been replaced by the more defensible implementation of the Regional Flood Model (Book 3, Section 3). The focus of the new ARR guidance on rainfall-based methods is thus on the use of event-based and continuous simulation approaches. While these models provide a conceptually more attractive means to derive flood hydrographs arising from storm rainfalls, they present the very real potential for introducing probability bias in the transformation. That is, the methods are well suited to the simulation of flood hydrographs, but great care is required when assigning exceedance probabilities to the resulting flood characteristic.

The continuous simulation approach has the major advantage that it implicitly allows for the correlations between the flood producing factors over different time scales. This can be a great advantage in some systems (such as a cascade of storages or some complex urban environments) where the volume of flood runoff is the key determinant of flood risk. However, its major drawback for flood estimation is that considerable modelling effort is required to reproduce the flood characteristics of interest; the structure of continuous simulation models is geared towards reproduction of the complete streamflow regime, and not on the reproduction of annual maxima. This has implications for model structure, as well as for how the model is parameterised and calibrated to suit the different flood conditions of interest. The vast majority of the information used to inform model parameterisation is not relevant to flood events other than to ensure that the right antecedent conditions prevail before onset of the storm. Under extreme conditions, many state variables inherent to the model structure might be bounded, and the process descriptions relevant to such states may be poorly formulated and yield outcomes that are not consistent with physical reasoning; while this is the case for flood event models, the more complex structure generally used with continuous simulation models may confound attempts to detect such behaviour. In addition, if the length of historic (sub-daily) rainfalls is not long enough to allow estimation of the exceedance probabilities of interest, it will be necessary to use stochastic rainfall generation techniques (or some down-scaling technique) to produce synthetic sequences of sufficient length. Lastly, given the interdependence between model parameters and the difficulty of parameter identification, it can be difficult to transpose such models to ungauged catchments.

Simple event based approaches, ie those involving the deterministic application of models based on linear and non-linear routing, have a long history of application in Australia. However, considerable care needs to be taken when selecting “typical” values of the key inputs to avoid the introduction of bias in the transformation of design rainfalls into floods. Ensemble event approaches have the potential to mitigate this bias, but these are only likely to be defensible for those problems influenced by a single dominant factor in addition to rainfall. Monte Carlo event techniques can be used to derive expected probability quantiles of selected flood characteristics arising from the joint interaction of many factors. Monte Carlo approaches represents the most rigorous means of removing bias in the transformation of design rainfalls into floods, but the defensibility of these estimates rests upon the representativeness of the inputs and the correct treatment of correlations which may be present.. The degree of modelling sophistication adopted should be commensurate with the complexity of the system being considered, and the choice between Simple Event, Ensemble Event, and Monte Carlo approaches can be informed by evaluating the sensitivity of model outcomes to the key factors of most importance.

5. RELATIVE APPLICABILITY OF DIFFERENT APPROACHES

The broad nature of applicability of the different methods is illustrated in Figure 2. This figure is not intended to be prescriptive, but rather it is intended to illustrate the relative ability of the different methods to provide unbiased estimates of flood characteristics in the given AEP range.

Flood frequency analyses are most relevant to the estimation of peak flows for Very Frequent to Rare floods. Flood frequency analysis methods can also be applied to other flood characteristics (e.g. flood volume over given duration) but this involves additional assumptions. Peak-Over-Threshold analysis is most relevant to the estimation of flood exceedances that occur several times a year, up to floods more frequent than around 10% AEP. For rarer events the use of an annual maximum series is preferred, and with good quality information at-site frequency analyses are suited to the estimation of Rare floods with AEPs as infrequent as 2% to 1%. The use of regional flood data provides valuable information that can be used to help parameterise the shape of the flood distribution, and thus where feasible it is desirable to use at-site/regional flood frequency methods. The use of regional information can support the estimation of flood risks beyond 1% AEP and can greatly increase the confidence of estimates obtained using information at a single site.

The RFFE model provides estimates of peak flows for Frequent to Rare floods for sites where there is no streamflow data. While its primary purpose is for the estimation of flood quantiles, the resulting estimates can also be used to develop scaling functions to support the transposition of results obtained from rainfall-based procedures to ungauged sites. This is the same concept as the simple quantile regression approach discussed above, but as it is based on a more rigorous statistical procedure and is more suited to transposition of results where factors other than merely area are important. The RFFE method is quick to apply and provides a formal assessment of uncertainty, and thus is well suited to provide independent estimates for comparison with other approaches.

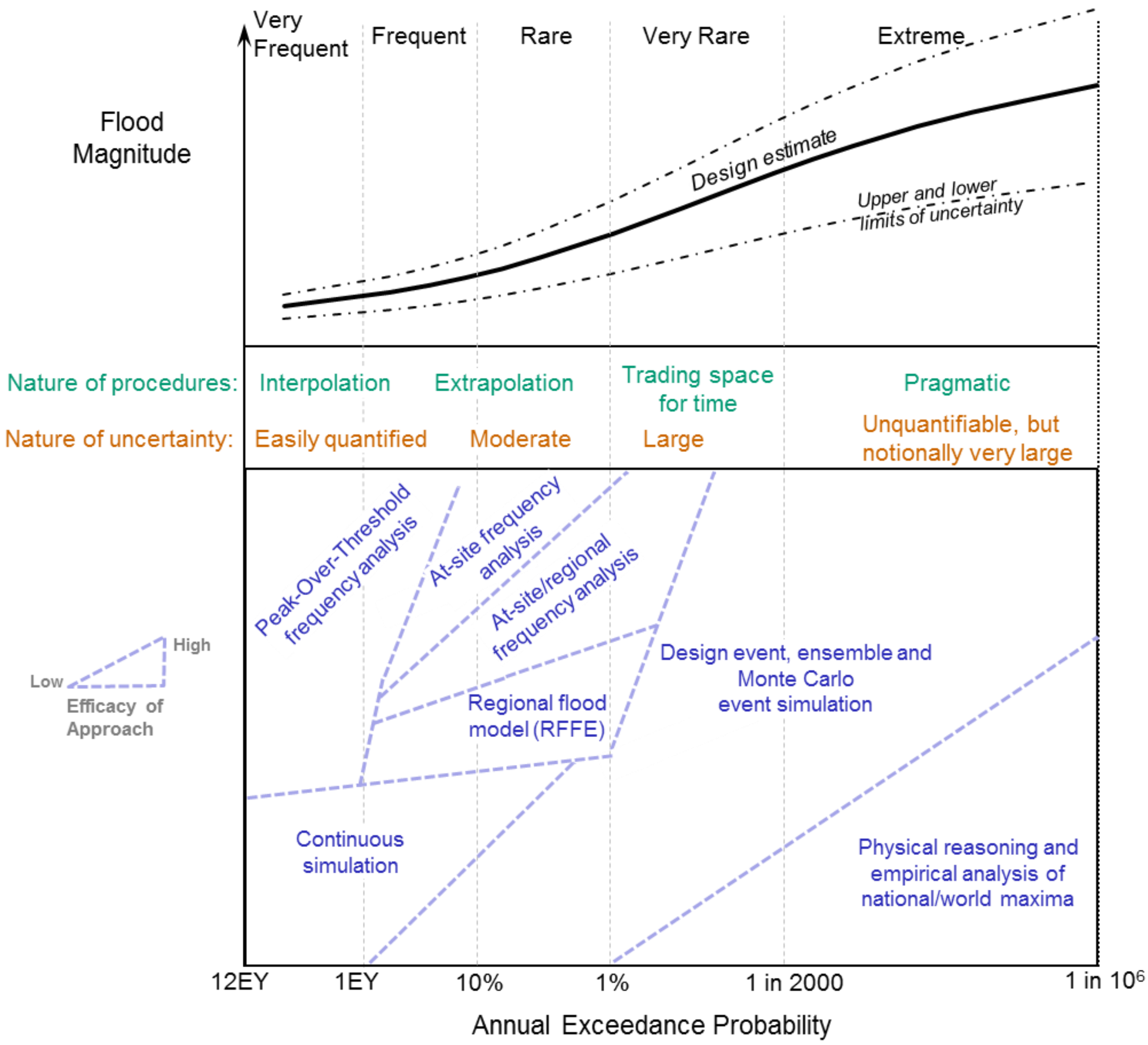

Figure 2 Illustration of notional efficacy of different approaches for the estimation of design floods.

Figure 2 also illustrates the areas of design application most suited to rainfall-based procedures. These are applicable over a wider range of AEPs than techniques based directly on the analysis of flow data as it is easier to extrapolate rainfall behaviour across space and time than it is for flow data. But while these methods can capitalise on our ability to extrapolate rainfall data to rarer AEPs and infill spatial gaps in observations more readily than flows, their use introduces the need to model the transformation of rainfalls into floods.

Continuous simulation procedures are well suited to the analysis of complex systems which are dependent on the sequencing of flood volumes as the method implicitly accounts for the joint probabilities involved. Application of these methods require more specialist skill than event-based procedures; for example, it is important that the probabilistic behaviour of the input rainfall series relevant to the catchment (either historic or synthetic) is consistent with design rainfall information, and that the model structure yields flood hydrographs that are consistent with available evidence. Transposition of model parameters to ungauged sites presents significant technical difficulties which would require specialist expertise to resolve. Given these challenges it is presently recommended that the main benefit of continuous simulation approaches is for the extension of flow records at gauged sites with short periods of record, where system performance is critically dependent on the sequencing of flow volumes; if flow data are not available, then it may be appropriate to consider their application to small scale urban environments where runoff processes can be inferred from an analysis of effective impervious areas.

The event-based methods considered in these guidelines generally involve a similar suite of storage-routing methods. There are some conceptual differences in the way that these models are formulated, but in general these differences are minor compared to the constraints imposed by the available data. Australian practice has generally not favoured the use of unitgraph-based methods combined with node-link routing models; in principle such models are equally defensible as storage-routing methods, and the strongest reason to prefer the latter is the desire for consistency when used to estimate Extreme floods that are well beyond the observed record, and also for the local experience with regionalisation of model parameters.

Perhaps the greatest choice to be made with event-based models is the adopted simulation environment. For systems that are sensitive or contain elements (such as storages) that are sensitive to differences in temporal patterns, there is little justification to use simple event methods: the additional computational burden imposed by ensemble event models is modest, and the resulting estimates are much more likely to satisfy the assumption of probability-neutrality. However, this additional effort may not be warranted in those urban systems which are dominated by hydraulic controls, and in such cases the most appropriate modelling approach is likely to be a hydraulic modelling system with flow inputs provided in a deterministic manner. Monte Carlo event schemes provide a rigorous solution to the joint probabilities involved, and the solution scheme ensures expected probability quantiles that are probability-neutral, at least for the given set of ensemble inputs and distributions used to characterise hydrologic variability. For those catchments or systems where flood outputs are strongly dependent on the joint likelihood of multiple factors, it is necessary to adopt a Monte Carlo event approach.

The greatest uncertainties in terms of both flood magnitude and exceedance probabilities are associated with the estimation of Extreme floods beyond an AEP of 1 in 2000. There is very little data to support probabilistic estimates of floods in this range, and it is prudent to compare such estimates with empirical analysis of maxima based from national (eg Nathan et al, 1994) or even global (Herschy, 2003) data sets.

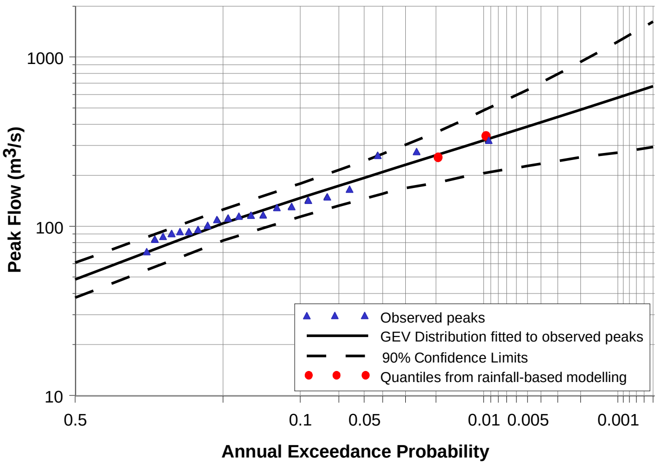

Figure 3 Illustration of reconciliation of rainfall-based estimates with flood frequency quantiles.

It needs to be recognised that the ranges of applicability of the different methods illustrated in Figure 2 are somewhat notional, and that there is considerable overlap in their ranges of applicability. It is thus strongly advisable to apply more than one method to any given design situation. The comparison of different methods yields insights about errors or assumptions that might otherwise be missed, and the process of reconciling the different assessments provides valuable information that aids adoption of a final "best estimate" (Figure 3). The adoption of a single best estimate is ideally achieved by weighting estimates obtained from different methods by their uncertainty. In practice, however, the information required to do this is limited. Estimates of uncertainty can be derived for flood frequency analyses and regional flood estimates, as described in Kuczera and Franks (2015) and Rahman et al. (2015), though generally additional uncertainties are required in the scaling and/or transposition to the design site of interest. At present there are no established methods suited for general use by practitioners that can be used to quantify uncertainty in rainfall-based methods, though a range of approaches are certainly available (eg Blazkova and Beven, 2009; Mittiga et al, 2007; Yu et al, 2014).

6. CONCLUSIONS

This paper presents the proposed ARR recommendations covering the selection and application of methods available to the flood practitioner. The methods discussed are divided into two broad classes of procedures based on: (i) the direct analysis of observed flood and related data and (ii) the use of simulation models to transform rainfall into flood maxima. The strengths and limitations of the different methods and how they vary in their suitability to different types of data and design contexts are also discussed. While the basis of the proposed flood frequency analyses should broadly familiar to practitioners familiar with ARR87, the new edition of ARR focuses on how best to achieve "probability-neutrality" when using rainfall-based techniques. A number of more computationally intensive procedures are introduced (such as ensemble event, Monte Carlo event, and continuous simulation approaches) to help ensure that the method used to transform rainfalls into design floods is undertaken in a fashion that minimises bias in the resulting exceedance probabilities. In addition, the new edition presents a new regional flood model which provides the means to estimate the magnitude of peak flows for AEPs ranging between 50% to 1%, with uncertainty bounds.

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