Climate Change and its Influence on Design Flood Estimation

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ABSTRACT

Design flood estimation remains a problem for many professionals involved in the management of rural and urban catchments. Advice is required regarding design flood characteristics for many design problems including 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 environmental flow problems. This advice is complicated further by the increasing requirement to consider the impact of changing climatic states on design floods. Presented herein is a discussion of the design flood problem for both current and future climate states.

**Keywords:**Floods, Climate Change, Design

1. INTRODUCTION

Design flood estimation remains a problem for many engineering hydrologists. 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 – typically, it is the peak flow rate of the flood hydrograph that is the desired design flood hydrograph characteristic;
* Flood level – similar to the peak flood flow rate, it is the peak flood level during the flood hydrograph that is a common design flood hydrograph characteristic;
* Flood rate of rise – this flood characteristic is a design concern when planning for evacuation, for example, is undertaken. In these circumstances, the time that exit pathways are available is the major concern, so the design flood problem becomes one of estimating the time when the exit pathways are not available;
* Flood volume – this design flood characteristic becomes a concern when the design flood volume is a major factor in the design problem. This situation occurs when storage of a significant portion of a flood hydrograph is used as part of a flood management system; or
* System failure – the usual design flood problem is located at a single point. There are numerous design problems, however, where the issue becomes one of multiple points within a system. Typical examples of these problems include urban drainage systems where the individual components of the system are not statistically independent (a common assumption) and transportation routes with multiple cross drainage structures of one or more river systems.

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 historical 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*”. Current developments for management of urban water systems inclusive of WSUD, SUDS, LID and their many variants require consideration of flood volumes and flood levels in addition to this historical focus. Hence, for urban environments, these flood characteristics can be inserted into the statement of Robinson (1987) in lieu of flows without loss of generality and without changing the range of potential values.

In discussing the type of flood characteristic that is being considered for a design problem, it is worth noting that the desired flood characteristic(s) to be used for the design must be interpreted from a statistical viewpoint. This contrasts with analysis of the flood characteristics from a historical event where a deterministic viewpoint is appropriate.

A second aspect in estimating design flood characteristics is the need to consider both the hazard arising from the magnitude of the design flood characteristic and the likelihood of that hazard occurring or being exceeded. In other words, there is a need to consider the relationship between the magnitude and the likelihood of a design flood characteristic. An example of this relationship is shown in Figure 1. From a design flood perspective, therefore, it is the analysis of data leading to the relationship shown in Figure 1 that is fundamental to the estimation of the quantile for the desired flood characteristic.



**Figure 1**. Relationship between flood magnitude and flood probability

There are many approaches for the estimation of design flood characteristics for current climate regimes with the appropriateness dependent on the problem. Most of these approaches can be framed as an exercise in data mining since the available data is analysed to develop the desired relationship between the hazard arising from the magnitude of the flood characteristic and the likelihood of that hazard occurring; note that the available data includes the data collected during field monitoring and that generated by catchment modelling.

The purpose of this paper is to provide an overview of alternative approaches for generation of the information necessary for estimation of a design flood quantile. Also included will be a discussion of the associated assumptions for these alternative approaches. Furthermore, the implications of non-stationary climatic conditions on the estimation of flood quantiles are explored.

1. APPROACHES FOR ESTIMATION OF CURRENT CLIMATE DESIGN FLOOD QUANTILES

As discussed by Ball et al. (2011), alternative approaches for estimation of the design flood quantile are shown in Figure 2. As shown in that figure, there are two alternative situations when design flood characteristics are required; these are:

* Sufficient and suitable historical information is available; and
* Sufficient and suitable historical information is not available.

When sufficient and suitable historical information is not available, a common approach is to use catchment modelling to generate the necessary data. It should be noted that in many of these circumstances, the catchment model is being used to generate the data that would have been recorded if the catchment were monitored.

1. AT-SITE FLOOD FREQUENCY ANALYSIS

As shown in Figure 2, where sufficient historical information is available, estimation of the desired flood parameter can be undertaken using at-site flood frequency analysis methods (see, for example, Jin and Stedinger 1989, and Kuczera 1999). When these methods are applied, the desired design flood quantile is obtained from an analysis of the statistical pattern of the recorded data.

Most FFA techniques are based on the calibration of a statistical model to the recorded historical data; in this context, the calibration consists of determining the generic values of the distribution parameters that result in development of a relationship between flood magnitude and exceedance probability that replicates historical data. As part of this calibration process, the reliability of historical data needs consideration to ensure that robust predictions are attainable; this is achieved usually through estimation of the confidence limits for the statistical model.

An inherent assumption for application of FFA approaches is that the historical data is stationary. In other words, the statistical characteristics of the historical data remain constant with time. A number of studies (see, for example, Kiem and Franks, 2004) have shown that this assumption is not valid over short time frames due to climatic cycles such as the Interdecadal Pacific Oscillation (IPO) but may be approximately valid over long time periods. In this context, a long time period is one where data is available for at least one full climatic cycle (and preferably more).

The appropriateness of estimating design floods under future climate regimes using FFA techniques, therefore, needs to consider both the availability of data and the applicability of the assumption of stationarity. As historically recorded data cannot be available for future climate regimes, the expected lack of stationarity in the data does not preclude application of FFA approaches; it is the absence of the historical data that precludes application of FFA techniques for prediction of design flood quantiles under future climate regimes.



**Figure 2.** Alternative Design Flood Approaches

1. REGIONAL FLOOD FREQUENCY ESTIMATION

Regional Flood Frequency Estimation methods (RFFE) are a category of data-driven design flood quantile estimation techniques based on regression; in other words, recorded data and estimated flood quantiles are analysed to enable prediction of design flood quantiles at locations remote from gauged catchments. As a result, RFFE methods are applicable only in regions where the catchment and climatic conditions are similar to those used for development of the regression relationships. This applicability has implications on the use of RFFE methods to estimate design flood quantiles with future climate regimes.

All RFFE techniques are based on the results of an FFA at monitored locations. Hence, the reliability of an RFFE method is constrained by the reliability of the FFA at monitored locations. Once the FFA information is available, development of an RFFE technique consists of two principal steps:

* Formation of regions or the formation of regions comprising catchments with similar flood response. Historically, these regions have been assumed to be based on geographic proximity, but this is not an essential assumption; and
* Development of regional estimation models through the development of regression equations, or models, to predict design flood quantiles.

In developing an RFFE, formation of regions can be based on proximity in geographic or catchment attribute space. The regions are based on the explicit assumption of ‘regional homogeneity’. The decision on what constitutes a homogeneous region for the purposes of regional flood estimation depends on the methods used, more specifically on the extent to which differences in flood characteristics can be expressed through parameters in the regionalisation method. Further details are given by Rahman et al. (2011).

In developing an RFFE technique suitable for application in Australia, Haddad et al. (2011) discusses the predictor variables found to be significant in predicting design flood quantiles for existing catchment and climate conditions. While there are numerous ways of categorising the main predictor variables, for the discussion herein, the main predictor variables will be categorised as being either rainfall related or catchment related. For application in Australia, the main predictor variables have been found to be:

* Rainfall related predictor variables - the design rainfall intensity for a duration representative of the catchment response time; and
* Catchment related predictor variables – catchment area and a factor representing catchment shape.

The basis of the regression undertaken by Haddad et al. (2011) was a generalised least squares technique which can be expressed as

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where  is the prediction, k are the regression coefficients, Xik are the predictor variables, i and i are the random and residual model error respectively. In the interpretation of this equation, it should be noted that the predictor variable coefficients represent the relative contributions of the predictor variables to the estimated design quantile.

The use of RFFE methods developed for current climate regimes to estimate design flood quantiles for future climate regimes is based on the assumption that projected changes in the catchment and climate conditions can be reflected by changes in the selected predictor variables. For example, Haddad et al. (2011) found that rainfall intensity was a useful predictor variable while the major catchment related predictor variable was the catchment area. If these two predictor variables are used to estimate design flood quantiles for future climate regimes, then it is only the rainfall intensity that will need adjustment as the catchment related predictor variables would be expected to remain consistent.

However, adjustment of the rainfall intensity requires either a capacity to predict the change in the representative duration of the catchment response time, or the assumption that the representative duration of the catchment response time remains unchanged for future climates. While changes in catchment response time will reflect individual catchment characteristics, there is benefit in considering how estimates of catchment response time are obtained.

If the Probabilistic Rational Method (Pilgrim and McDermott, 1982) is used as an example of techniques for estimating the response time, then the representative time is given by

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where tc is the representative response time and A is the catchment area. While it is interesting that the only predictor variable is the catchment area (A), how this equation was developed is of greater interest for this discussion. As described by Pilgrim and McDermott (1982), this equation was developed by regression of recorded storm and flood events. In other words, it was developed for current catchment conditions generated under existing climatic conditions.

There are two regression coefficients in this equation. Embedded in their values are the physical factors influencing the catchment response time. For example, the drainage channel shape, density and slope will be incorporated in these values in some manner. It is possible that these catchment factors will change with the climate. Hence, the suitability of the two regression coefficients for future climatic conditions is unknown. A consequence is that estimation of representative catchment response times using regression relationships of is unknown.

1. CATCHMENT MODELLING

In general, the philosophical basis of catchment modelling is the generation of data that would have been recorded by a streamflow gauging station if a streamflow gauging station were present at the location of the predictions. This is consistent with a deterministic interpretation of catchment modelling. Characteristics of the catchment and rainfall used for generation of the data maybe the historical or the potential future characteristics of either the rainfall or catchment or both the rainfall and catchment.

When used with this philosophical underpinning, the catchment modelling system consists of a system of models of varying complexity. These models include those representing processes influencing the generation and propagation of floods; an example, of these process models is the routing model used to represent the propagation of flow through the catchment storage. In addition to these models of catchment processes, the system includes those models needed for representation of, for example, the rainfall characteristics in space and time across the catchment. When considered in this manner, it is convenient to categorise the models in the system into conceptual components; Ball (1992) presents a detailed discussion of this categorisation. These conceptual components are:

* Generation - This component is concerned primarily with the estimation of the input data such as the spatial and temporal characteristics of the rainfall, and the parameters necessary for operation of the catchment modelling system;
* Collection - This component of the system is concerned primarily with the accurate prediction of the flow at a point where the flow enters the drainage network, i.e. the hydrologic component of the system;
* Transport - This component of the system is concerned primarily with the routing of flows through the drainage system, i.e. the hydraulic component of the system; and
* Disposal - This component of the system is concerned with models describing how the flow is discharged into the receiving waters.

Due to the number of alternative problems encountered where design flood information is needed, different approaches for the application of catchment modelling systems for design flood estimation have been developed; these approaches range from single storm burst analyses to multi-storm burst analyses. Included in the multi-storm burst approaches are continuous simulation and Monte-Carlo approaches; both approaches have the aim of including variability in the factors influencing flood generation and propagation. Historically, applications of techniques considering a single burst have been the more popular. The alternative approaches, however, are gaining in popularity as computing capacity increases.

The philosophical basis of a catchment modelling approach provides an additional complexity. Application of a catchment modelling system with a single burst approach commonly is associated with the assumption that the statistical properties of the rainfall are transferred to the predicted flows; in other words, the x% flood event is generated by the x% rainfall. In Australian Rainfall and Runoff (ARR) (Ball et al., 2016), this assumption is referred to as AEP Neutrality.

Where the single burst technique has been implemented with an assumption that the frequency of the rainfall is transformed to the frequency of the resultant flood characteristic, it can be argued that the method as applied is an RFFE technique where the catchment model is a complex regression relationship. This question becomes more relevant when implementation of the approach requires values of the parameters to be selected on the basis that the transformation of rainfall frequency to flood frequency is ensured. An example of this approach is provided by Hill et al. (1998) who developed a method of estimating loss model parameters that will result in the frequency of the rainfall being transferred to the frequency of the design flood flow. Implicit in the adoption of this approach is the assumption that AEP neutral parameter values for all significant parameters are available from studies analogous to Hill et al. (1998).

As shown in Figure 3, application of an AEP Neutral approach can be considered a probabilistic approach. The alternative is a deterministic approach (also shown in Figure 3) where the catchment model is used to analyse the catchment response to a rainfall event. In these situations, the probability of the resultant flood characteristics is unknown. Analysis of historical storms is a deterministic approach.

When either of the other two alternative techniques, namely a Monte Carlo or a Continuous Simulation technique, are applied for generation of the data, it is necessary to undertake a statistical analysis of the generated data to develop an estimate of the design flood quantile. This statistical analysis is required as the aim of either technique is the generation of data that could have been recorded if a gauge was present and the catchment conditions reflected in the model parameters occurred. Hence, application of a catchment simulation approach using these techniques reflects a different conceptual basis to that necessary for a single burst approach with AEP neutrality.



**Figure 3.** Alternative Conceptual Bases for Catchment Modelling

Also shown in Figure 3 are examples of the rainfall and catchment factors that influence the conversion of rainfall during a storm event into a flood event. A fundamental question that needs to be addressed, however, is what combination of catchment and rainfall factors is necessary to achieve the desired AEP Neutrality; it is worth noting that a full analysis requires a joint probability analysis to obtain the desired flood statistic. In many cases, the techniques used to ensure AEP neutrality are based on parameter calibration aimed at ensuring AEP Neutrality. As these calibration approaches are focused on parameter values that ensure the transformation of statistical characteristics rather than parameter values that ensure the relevant process is replicated, there is a need to investigate whether these calibration approaches are consistent with the philosophical basis of the catchment model. Furthermore, there is an argument that adoption of the AEP Neutral calibration approach results in a complex regression model.

If the alternative approach, namely a deterministic approach, for implementation of a catchment model is adopted, then calibration and validation of the modelling system parameters and structure prior to use for estimation of the design flood characteristics is required. During the process, the primary aim is the selection of parameter values that ensure the modelling system adequately replicates the catchment response; in other words, the primary aim is determination of generic values for the many parameters in the modelling system.

Fundamental to a discussion of calibration and validation is the concept that all predictions obtained from systems of models for prediction of catchment response to either individual storm events or sequences of storm events will contain residuals, or differences between the predicted and recorded values. As shown in Figure 4, these residuals arise from multiple sources during the modelling process. following Kuczera et al. (2006), the sources can be categorised as:

* Process errors;
* Model Errors comprising
  + Structural errors;
  + Parameter errors; and
* Data errors.

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**Figure 4.**  Comparison of Actual and Model Catchments

Process errors arise from the difference between the conceptual process incorporated in the modelling system and the actual process within the catchment; in other words, the process errors arise from the need for representation of physical processes in a mathematical formulation. The magnitudes of these errors are influenced directly by the degree of simplification within the modelling system. For example, use of one-dimensional and two-dimensional river models result in differing simplifications and different errors. It is worth noting, however, that additional complexity in the process model may not result in a reduction in residuals due to the increased number of parameters necessary for definition of the more complex model.

Structural errors are the result of the manner in which the various process models are combined to provide the catchment modelling system. In many situations, alternative structures are available. For example, shown in Figure 5 are two alternative conceptual loss model structures for incorporation of rainfall losses in a catchment modelling system. Consideration of this example illustrates the linkage between conceptualisation of processes in the catchment modelling system and the existence of structural errors. Hence, the distinction between a process model and a structural error is diffuse and, in many cases, difficult to quantify. This difficulty is shown also through consideration of Umakhanthan and Ball (2005) who investigated the influence of the model used to estimate the spatial and temporal distribution of rainfall across the catchment.

The third form of errors are the parameter errors. For discussion of parameter errors, there are two alternative cases that need consideration. The first of these cases is where monitored data is available for estimation of the parameter values using data from the catchment. The second case occurs where there is insufficient data available for estimation of parameter values using data from the catchment and hence estimation of parameter values is based on regional relationships and other inference models. An example of the use of inference models for estimation of parameter values was presented by Choi and Ball (2002) who investigated the use of land-use classifications for prediction of the imperviousness of subcatchments.

In both cases, parameter errors arise from differences between the true value of the parameter and that used in the simulation. Residuals arising from errors of this type have been the focus of significant historical research with a significant volume of this research focussed on the problem of obtaining optimal or near optimal values for the modelling system parameters. Arising from this research has been the concept of equifinality (see Beven and Binley, 1992) which can be paraphrased as there are multiple sets of parameter values that will result in similar system performance.



**Figure 5**. Alternative Loss Conceptual Models (after Ball et al. 2011)



**Figure 6.** Conceptual Width of Subcatchment 103

The concept of equifinality becomes increasingly relevant as the catchment modelling system becomes more distributed. As urban catchments are especially heterogenetic, the issue of equifinality is very important for modelling of urban catchments. This is illustrated in Figure 6 where the Sum of Squared Error (SSE) for alternative values for the conceptual width of a single subcatchment are shown; 10,000 alternative combinations of parameter values were considered. As shown in this figure, similar values of the SSE can be obtained over a wide range of values. Consideration of this figure also illustrates the need to consider sets of parameter values rather than the value of a single parameter. The same value of the conceptual width parameter can result in different values of the SSE; these multiple SSE values are the result of alternative values for the other parameters.

The last form of error are the data errors. While there are many types of data errors, the characteristic of these errors is that they represent the difference between the true value of the monitored data and the value recorded in the database. An example of errors of this type are those errors arising from the need to extrapolate the rating table for a gauging station above the highest gauging to enable transformation of the recorded level to an equivalent flow. Note that, in addition to the extrapolation error, a measurement error associated with the recording of the level also occurs; these measurement errors are discussed by Ball et al. (2016).

Application of catchment models with a deterministic approach for flood estimation requires different techniques to those used with the probabilistic approach. Whereas the single event technique is used with the probabilistic approach, use of Monte-Carlo or Continuous Simulation approaches usually are used when a deterministic approach is applied. Shown in Figure 7 are predicted peak flow magnitudes obtained from:

* FFA of continuous simulations over a ten year period using two alternative parameter sets. These two parameter sets were those that resulted in the best reproductions of the peak flow for alternative events;
* FFA analysis using recorded data over a ten year period; and
* FFA analysis over the complete 40 year monitored period.

**Figure 7.** Simulated FFA for Powells Creek, Australia

As shown in Figure 7, the presence of errors in the modelling system result in predictions based on model generated data differing from those predictions based on monitored data. Nonetheless, there is reasonable correspondence in predictions based model and monitored data. This correspondence demonstrates the utility of a deterministic approach for prediction of design flood statistics. However, there is a need to ensure the rainfall data used in the simulation is representative of the long-term rainfall; differences between predictions based on ten years and 40 years of data illustrate the importance of the period used as the sample. For the example presented herein, the statistical characteristics predicted using the data generated by the catchment model using 10 years replicate the statistics obtained from the 10 years of monitored data but not the statistics obtained from 40 years of monitored data.

The prediction of flood statistics with potential future climate states using catchment models can be obtained with either the probabilistic or deterministic approaches. However, the inherent assumptions in the application of the alternative approaches will influence the interpretation of the predictions obtained.

Application of the probabilistic approach, AEP Neutral approach, requires knowledge of the future statistics from FFA analysis of monitored data for development of the parameter values that will result in the frequency transfer. This monitored data will not be available until the future climate states occur and, hence, the availability of AEP Neutral parameter values will not be available until this time. It is possible to use parameter values from the current climate conditions. However, this approach requires the assumption that the joint probability does not change with climate; given the interaction between the rainfall and catchment characteristics, the robustness of this assumption is very suspect. Hence, the reliability of predictions using the probabilistic approach have a high degree of uncertainty.

When the deterministic approach to catchment modelling is used, the reliable prediction of flood statistics requires the prediction of long-term rainfall for future potential climate conditions. While the availability of these long-term future rainfall statistics remains an issue, there is an additional inherent assumption that warrants discussion; this assumption is related to the parameters representing how the catchment responds to storm events. When the parameter values are assumed to be consistent with those used for simulation of the current catchment, there is an implicit assumption that the catchment response is not a function of the climate; this assumption is not consistent with geomorphic knowledge. Hence, there is a need to modify the values of the parameters related to catchment response from those suitable for the current climate state and current catchment conditions to future climate states and catchment conditions.

1. CONCLUSIONS

Design flood estimation remains a problem of interest to many catchment managers. This problem is amplified by the need to consider potential future climate states. In addition, the design flood problem is complicated by the need to consider alternative flood characteristics; the flood characteristic of interest will depend on the nature of the problem under consideration.

The estimation methodology is varied and dependent of the availability of suitable data. In general, the methodologies for estimation of current flood statistics can be considered as:

* Flood Frequency Analysis;
* Regional Flood Frequency Estimation; and
* Catchment Modelling.

Use of techniques from each of these categories for estimation of design flood characteristics has been discussed with an emphasis on the inherent assumptions necessary for their application to potential future climate states. A summary of these discussions is:

* Flood Frequency Analysis

Application of these techniques is based on the statistical analysis of data containing information about the rainfall events and the catchment response to those rainfall events. This approach assumes that data about the catchment response is available; a situation that is not possible for future climate states.

* Regional Flood Frequency Estimation

These techniques are those based on the use of regression models that are based on regional data for prediction of the desired flood characteristics. As these regression models are based on analysis of recorded data, these techniques have similar issues to FFA techniques for prediction of design flood statistics under future climate conditions; namely the lack of future data to enable the validity of the extrapolation of regression models for current climates to future climate states.

* Catchment Modelling

There are alternative approaches to catchment modelling; these approaches are a probabilistic approach and a deterministic approach. When the probabilistic approach is adopted, there is a need to calibrate the parameter values to ensure the frequency transfer. For future climate states, this is not achievable as the data about the future catchment response is not available.

For the other alternative, the deterministic interpretation, there is a need for long-term stationary rainfall data to ensure adequate sampling of potential storm events and a need for knowledge of how parameters related to catchment response vary with climatic conditions.

In summary, therefore, there is uncertainty associated with the prediction of future design flood statistics; this uncertainty is greater that the uncertainty associated with the estimation of design flood statistics for current climate conditions. Furthermore, there is a need for research into how catchment response to storm events is influenced by changes in long-term climate conditions and how these changes can be reflected in the parameters used to model catchment response.

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