A DESIGN VARIABLE METHOD FOR ESTIMATING FLOOD RISK IN AUSTRALIAN ESTUARINE CATCHMENTS

Michael Leonard[1], Seth Westra[1]

[1] School of Civil, Environmental and Mining Engineering, University of Adelaide, Adelaide

Abstract

A method is outlined for estimating flood risk due to the combination of catchment and coastal processes. The method allows for combinations of extreme storm tide and extreme rainfall/streamflow events to be evaluated in a statistically rigorous framework that is less exhaustive than methods of continuous simulation. To facilitate the method, a map of dependence along the Australian coastline has been developed, along with general guidance for the Australian design community.

Introduction

Approximately 85% of Australians live within 50 km of the coastline. Close to the coastline there are many estuarine reaches of rivers that have the possibility of flooding due to coastal processes, catchment processes, or a combination of both. The problem of determining risk when there are multiple processes is challenging, and it is further complicated by dependence between them (Svensson and Jones, 2002; 2004; Hawkes and Svensson, 2006; Zheng et al., 2013). The same storm system that brings rainfall to a catchment may simultaneously cause anomalously higher water levels in a coastal region (i.e. storm surge) and thereby exacerbate flooding.

Hazards that depend on multiple interacting variables are referred to as ‘compound events’ (Leonard et al., 2014) and require joint probability approaches for estimation of flood risk. Joint probability events involve an extreme impact that is determined by the coincidence of many factors rather than the traditional approach with a sole variable (e.g. extreme rainfall in one location) defining the hazard. It is not uncommon that when a hazard has occurred that was not explicitly designed for, it is often referred to as “unforeseen”, “unusual”, “rare” or “freak”. However, a more truthful interpretation is that the events were likely foreseeable, but that our design methods did not adequately take into account the possibility of coincidences. The propensity of humans to misunderstand coinciding events is famously encapsulated in the ‘birthday problem’ (Mollester, 2006), where there are many possible combinations of events leading to the same outcome (two people having the same birthday), yet a large portion are overlooked, causing the probability be estimated as less frequent than its true value. Flooding in estuarine regions can fall into this category, where the failure to account for the multiple processes leads to a misspecification of risk.

Traditional methods of estimating flood risk in estuarine regions have relied on one variable (typically rainfall) being designated as the primary driver of the flood, with heuristic adjustments made to conservatively allow for a second influence. For example, the 1% AEP water level at a location of interest might be constructed from the 1% AEP streamflow coinciding with a 10% AEP storm tide. While this approach has the benefit of simplicity, the method is not rigorous. It is open to the potential for poor outcomes due to the ad hoc selection of boundary AEPs and because the method does not account for dependence between the two processes.

Another technique for evaluating joint probability events is the method of continuous simulation. This involves the generation of long sequences of streamflow and tidal forcings (tens to hundreds of years) that are then used as boundary inputs for a hydraulic model. Importantly, the two timeseries are dependent, such that a model for the boundary forcing should be conditioned on weather states. The hydraulic model is simulated at the timestep of the input sequences so that the interaction of the random boundary events allows for all possible outcomes. The corresponding water levels are generated directly by the model. Where a 2D hydraulic model is used, this approach is not feasible, although steps can be taken to use a simpler 1D model for the long-term simulation followed by selected runs of a 2D model at the end. While the method of continuous simulation allows for a relatively simple flood frequency analysis of extreme water levels, generating those water levels is complicated and computationally exhaustive. It is inconvenient that this method is intended for extreme values, yet a large portion of the simulation time is devoted to reproducing non-extreme events.

This paper presents an alternative method for flood risk estimation of coastal and catchment processes referred to as the “design variable” method and has been developed for use by Australian Rainfall and Runoff. The method is focused on extreme events and is therefore more computationally feasible than continuous simulation, but retains a statistically rigorous method for calculating the risk of multiple events. The method is a static analysis method, which means that the coinciding streamflow and tidal level are specified as constant inputs to a hydraulic model (rather than being the emergent property of a time-dependent simulation). A general procedure has been developed for implementation of the method at any point along the Australian coastline and a basic software tool has also been provided (http://p18.arr.org.au/). The following sections outline the general implementation.

Method

The method presented in this paper is a bivariate method, meaning that only two forcing variables are accounted for. Conceptually, these variables relate to an upper and lower boundary of a hydraulic model. The upper boundary is the streamflow and the lower boundary is the storm tide (the tidal level including astronomical tide and tidal anomaly due to storm surge). Rainfall is used interchangeably in this paper as a surrogate for the upper boundary as rainfall data is more abundant and is less contaminated by observation errors than streamflow. To implement the method several inputs are required: (i) probability estimates of extreme storm tides, (ii) probability estimates of extreme streamflow levels, (iii) the dependence of extreme values and (iv) water levels at the location of interest from a hydraulic model, corresponding to specified combinations of inputs.

One benefit of the method is that by having the storm tide and rainfall processes in the model it is possible to account for changes in either of these marginal distributions. Thus for example, it is possible to model the impact of sea level rise or changes in streamflow due to climate change. Such an approach depends on the assumption that there are no changes to the dependence between the two processes, i.e. that this is a second-order effect. While the ability to accommodate climate change scenarios is a key advantage of the method, this aspect is not elaborated on further in the paper.

The general procedure for implementing the design variable method is outlined in Figure 1. The first step involves a pre-screening analysis, with the intention that not every design should require a detailed analysis of joint probability events. If it is necessary to proceed with the design variable method, there are three subsequent steps. The second step requires the selection of a dependence parameter; the third step requires a hydraulic model to be run for multiple inputs for determining the hydraulic response to climate forcings and; the final step requires integration of these elements for evaluating the exceedance probability. The steps are explained in more detail in the following sections.

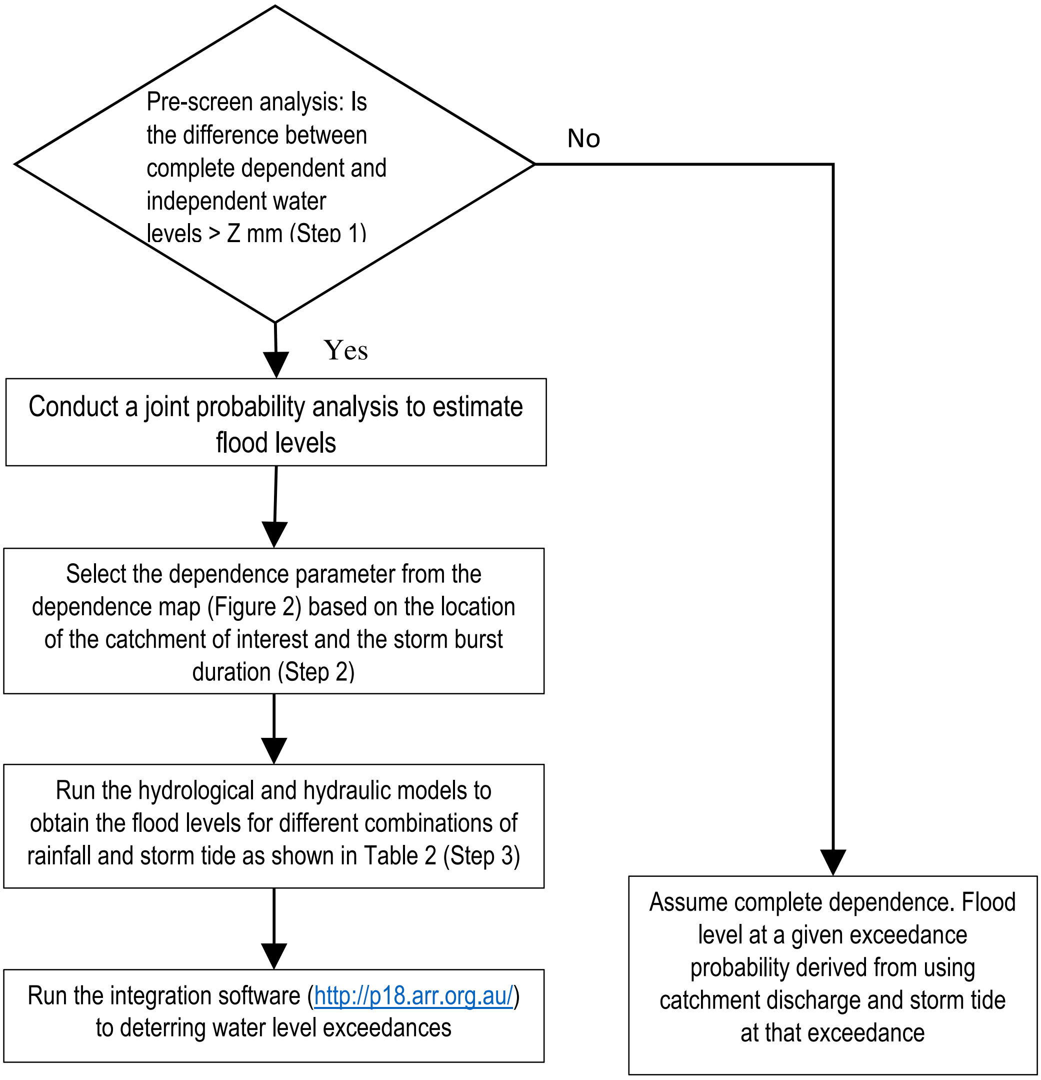

Figure 1: Australian Rainfall and Runoff guidance for the design variable method. The initial value of *Z* is determined by the user based on a tolerable magnitude of error in the flood estimation (adapted from Figure 6.5.11 of Australian Rainfall and Runoff).

Step 1 Pre-screen analysis

Accounting for joint dependence involves a significant amount of additional computation compared to simpler heuristic methods. A pre-screening analysis has therefore been recommended to determine if the additional computation is worthwhile for the problem being considered. For example, a design with lower consequence of failure such as a car park may not warrant the expense of the analysis involved in the method. The more conservative assumption of complete dependence will lead to a much simpler evaluation and overall cheaper outcome. The pre-screening analysis therefore requires a tolerance 'Z' to be specified by the end-user (e.g. *Z*=50 mm), then the two extreme cases of complete dependence and compete independence are calculated for comparison. The rationale is that the joint dependence is bounded by these two cases, and if there is little difference between them (i.e. within *Z* mm) then there is little value in the more complicated analysis.

An example is shown in Table 1 for how to proceed with the pre-screen analysis. The example assumes three AEPs of interest (20%, 2% and 1%), although the general procedure is the same if there was only one AEP of interest. For these cases the hydrological and hydrodynamic models must be run for 9 instances to determine the water levels corresponding to certain combinations shaded in the table. The cases in red (along the diagonal) assume complete dependence, whereas the cases in blue and grey are the respective cases of storm tide and rainfall being extreme with the other boundary specified at a low value. If the values for the complete dependence case are significantly higher (i.e. > *Z* mm) than either of the values where only one process is extreme, then this demonstrates a significant influence of joint probability and subsequent steps should be followed. If they are not, then the pre-screen analysis suggests that the complete-dependence values be used for all subsequent analysis.

Table 1: Flood levels of different combinations of rainfall and storm tide in terms of AEP (years) with a particular storm burst duration. Only the highlighted cells need to be determined.

		Rainfall events in AEPs			
		No rainfall	20%	2%	1%
Storm tide events in AEPs	Lower boundary				
	20%				
	2%				
	1%				

Step 2 Dependence parameter selection

To model dependence in the joint extremes of storm tide and rainfall a large study has been undertaken along the Australian coastline. There are a number of methods available for representing extremal dependence but for this method a basic one-parameter model has been selected (the threshold excess logistic model (Tawn 1988)). The model is shown in Equation (1), with *x* and *y* representing rainfall and storm surge respectively.

$$G(x, y) = \exp\{-(x^{-1/\alpha} + y^{-1/\alpha})^{\alpha}\} \quad 0 < \alpha \leq 1, x > u_x, y > u_y \tag{1}$$

where u_x and u_y are the threshold values for the two margins. The observations *(x,y)* with both components above their corresponding threshold values are defined as joint extreme events. The parameter α is used as a measure of the dependence strength, with α = 0 representing complete dependence and α = 1 representing independence. In Equation (1) a transformation of the *x* and *y* variables is required (not shown) for correct implementation, the details of which can be found in Zheng *et al.* (2014) along with a fitting procedure.

An analysis of dependence was conducted along the Australian coastline using 49 tidal gauges with hourly records. The storm tide was decomposed into the deterministic component (astronomical tide) and the random component (referred to here as the 'storm surge'). The storm surge is used for the dependence analysis because it is the component of the tidal signal that is influenced by the weather. The storm surge timeseries were paired with rainfall data from approximately 5000 gauges from across Australia having a minimum of 20 years record (Zheng *et al.*, 2013). Seventy subdaily rainfall stations were also used to analyse the influence of storm burst durations and lags (timing of peaks).

The outcome of the dependence analysis is presented in Figure 1, showing estimates of the dependence parameter for all regions of Australia.

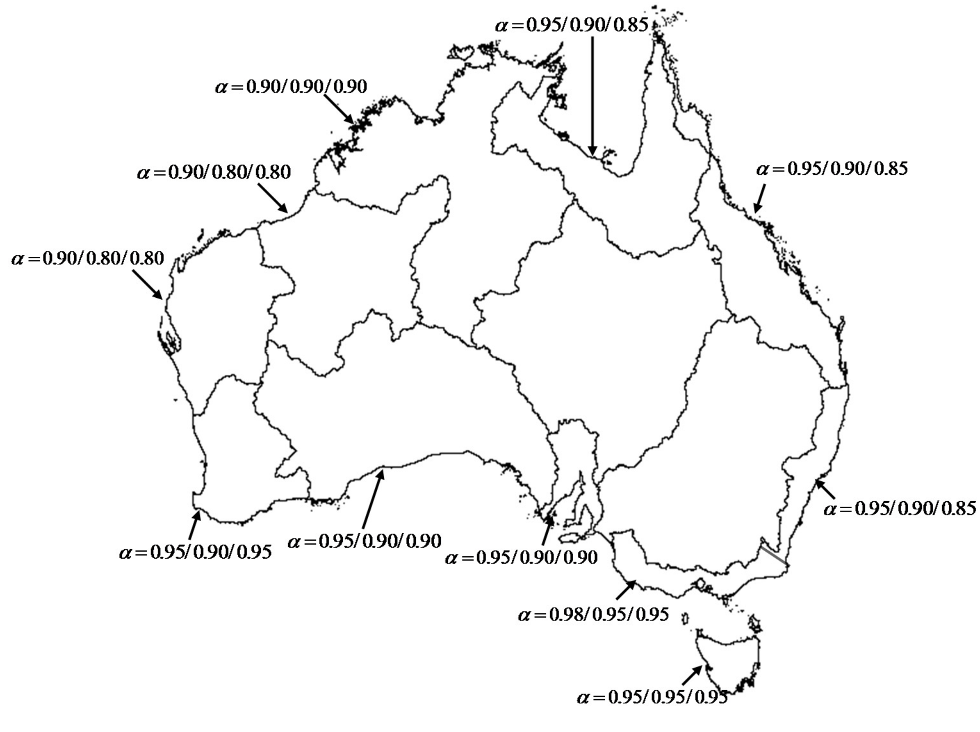

Figure 2 Dependence map for the basins of the Australian coastline. The three values of the dependence parameter (α) separated by the slash represent the dependence strength for storm burst durations shorter than 12 hours, between 12 hours and 48 hour, and greater than 48 hours, respectively. Values closer to 1 represent weaker dependence, values closer to 0 represent stronger dependence. Adapted from Figure 6.5.13, Australian Rainfall & Runoff (2016).

Based on extensive analysis it was decided that parameter estimates could not be provided at increments greater than 0.05 and that parameter values could only be provided for broad ranges of storm-burst duration. The three categories of storm burst duration were chosen as 0-12 hours, 12-48 hours and 48-168 hours. The coarse resolution is a reflection of the relatively small number of tidal gauges with respect to the length of Australian coastline as well as limitations at the sub-daily scale of restricted record length. Some basic features of Figure 1 are that the western Australian coastline has strongest dependence while the southern coastline has the weakest dependence. Also note from Figure 1 that the dependence increases with longer storm burst durations. An analysis of the time lags between the storm surge and rainfall revealed that the peak in storm surge occurred prior to the rainfall peak (and further allowing for time of concentration in a catchment) which suggests that it was not important to allow for the influence of time lags in Figure 1.

Step 3 Flood level modelling

This step involves the generation of a hydraulic response table. The reason for this requirement is that the table acts as a proxy lookup table which is quicker to evaluate than the hydraulic model (and especially for 2D models). Generating the table can require a significant amount of computation, but once obtained, the calculation of exceedance probabilities for the design variable method is straight forward.

Table 2 provides an example where there are 7 cases for the rainfall and storm tide respectively, leading to 49 overall runs that would be required form the hydraulic model. The number of rows and columns in the table and their increment is at the discretion of the modeller, but it is important to have a wide range of values from the case of a low boundary value through to very rare events. If, for example, the 1% AEP water level was of design interest, then it might plausibly arise from a 0.05% rainfall occurring on a low tide. In other words, it is not feasible to estimate a 1% water level by restricting the hydraulic response table to only consider 1% marginal events.

Table 2: Flood levels of different combinations of rainfall and storm tide in terms of AEP with a particular storm burst duration.

		Rainfall events in AEPs						
		No rainfall	20%	10%	2%	1%	0.2%	0.05%
Storm tide events in AEPs	Lower boundary							
	20%							
	10%							
	2%							
	1%							
	0.2%							
	0.05%							

Step 4 Flood exceedance calculation

The calculation of flood exceedances uses a method of bivariate numerical integration. While it is possible to use a Monte Carlo method to sample from the joint distribution, this method is less computationally efficient than other numerical methods. The procedure uses the information in the hydraulic response table (Table 2) along with a dependence parameter to indicate the degree of coupling between the extreme values of the margins. The procedure is conceptually straightforward, but difficult to implement practically, therefore an interface has been provided (http://p18.arr.org.au/) to perform this task.

Application of method to Nambucca case study

The Nambucca River catchment is located in New South Wales. Modelled flood levels for combinations of boundary conditions were available from a Tuflow 1D-2D hydraulic model covering a catchment area of 1315 km^2 (WMA, 2013). The model was calibrated to peak flood levels (1890-2011) and large historical events (1972, 1977, 2009). Figure 3 shows ten locations where a joint probability analysis was conducted, covering the upstream, downstream and midstream regions of the tidally influenced zone of the Nambucca River. The method is demonstrated for Macksville, which is centrally located in Figure 3 where the Pacific Highway crosses the river.

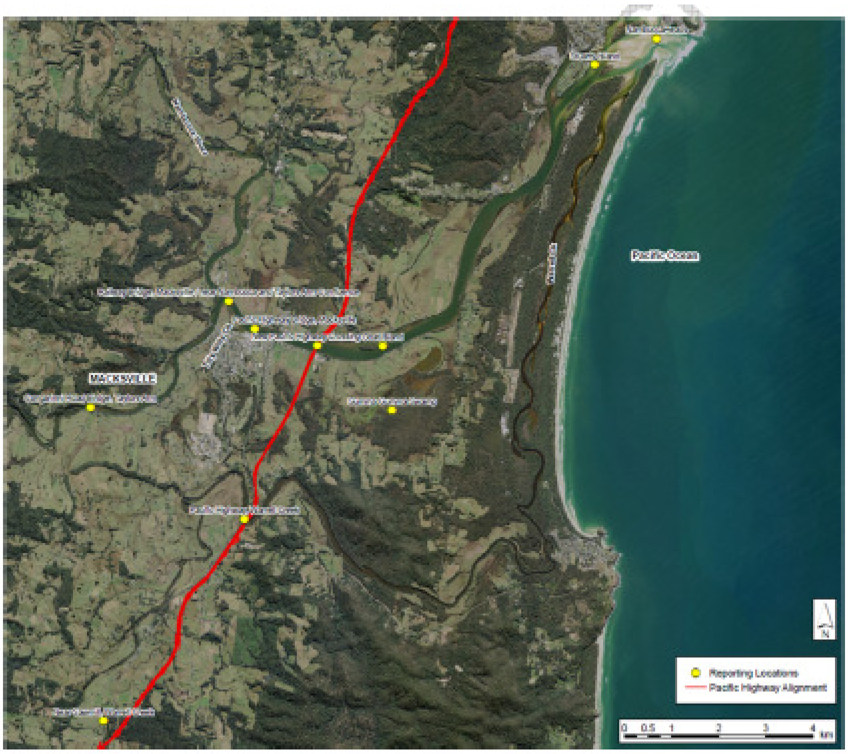

Figure 3 Ten different locations considered in Nambucca River catchment (dots)

Step 1. Preliminary analysis

A pre-screen analysis is shown in Table 3 for three pairs of AEPs at the Macksville site. At 9.5% AEP the difference in water levels is 0.21 m between the completely dependent case and the highest outcome of the marginal cases (rainfall event causing 2.26 m). For the 2% AEP the difference is 0.12 m and for the 1% AEP it is 0.12 m. Comparing these numbers, it is clear that joint probability is more influential for frequent events. If a tolerance of $Z = 0.1$ m was required for the design, a joint probability analysis should be undertaken to obtain more accurate estimates of the water level for each AEP.

Table 3 Pre-screen analysis pairs for Macksville

		Rainfall events in AEPs			
		No rainfall	9.5%	2%	1%
Storm tide events in AEPs	Lower boundary		2.26	3.32	3.68
	9.5%	1.45	2.47		
	2%	1.52		3.46	
	1%	1.55			3.80

Step 2. Dependence parameter selection

The Nambucca River catchment has a critical duration that lies between 36 and 48 hours. For this reason $\alpha = 0.90$, was obtained from Figure 1 to model the dependence between extreme rainfall and storm tide.

Step 3. Flood level modelling

Table 4 shows flood levels at Macksville for various combinations of critical-duration rainfall and storm tides in terms of AEP. The values are taken from 144 separate output maps of a TUFLOW model covering the region (WMA, 2013), and corresponding to the various combinations of 12 storm tide return-levels and 12 rainfall event return-levels respectively. The marginal probabilities range from 63%AEP to 0.05%AEP for both the rainfall and storm tide. The additional case of 100%AEP represents the lower boundary tide and 'no rainfall' cases respectively.

Table 4. Flood levels for various combinations of rainfall and tide levels at Macksville (Pacific Highway Bridge) in the Nambucca River catchment

		Tide levels (AEPs)											
		100%	**63.1%**	**39.3%**	**18.1%**	**9.5%**	**4.9%**	**2%**	**1%**	**0.5%**	**0.2%**	**0.1%**	**0.05%**
Rainfall levels (AEPs)	**100%**	0.60	1.35	1.38	1.42	1.45	1.48	1.52	1.55	1.58	1.62	1.65	1.68
	63.1%	*1.29*	*1.70*	*1.73*	*1.75*	*1.77*	*1.80*	*1.82*	*1.84*	*1.87*	*1.90*	*1.92*	*1.94*
	39.3%	*1.61*	*1.92*	*1.94*	*1.96*	*1.98*	*2.00*	*2.02*	*2.04*	*2.06*	*2.08*	*2.10*	*2.12*
	18.1%	*1.83*	*2.08*	*2.09*	*2.11*	*2.12*	*2.14*	*2.16*	*2.18*	*2.19*	*2.21*	*2.23*	*2.25*
	9.5%	*2.26*	*2.43*	*2.44*	*2.46*	*2.47*	*2.49*	*2.51*	*2.52*	*2.54*	*2.56*	*2.58*	*2.59*
	4.9%	*2.82*	*2.96*	*2.96*	*2.98*	*2.98*	*2.99*	*3.00*	*3.01*	*3.02*	*3.04*	*3.05*	*3.06*
	2%	*3.32*	*3.42*	*3.42*	*3.43*	*3.44*	*3.45*	*3.46*	*3.46*	*3.47*	*3.48*	*3.49*	*3.50*
	1%	*3.68*	*3.76*	*3.76*	*3.77*	*3.78*	*3.78*	*3.79*	*3.80*	*3.81*	*3.82*	*3.82*	*3.83*
	0.5%	*4.20*	*4.27*	*4.27*	*4.28*	*4.28*	*4.29*	*4.29*	*4.30*	*4.30*	*4.31*	*4.32*	*4.32*
	0.2%	*4.95*	*4.99*	*4.99*	*4.99*	*5.00*	*5.00*	*5.00*	*5.01*	*5.01*	*5.02*	*5.02*	*5.03*
	0.1%	*5.48*	*5.51*	*5.51*	*5.51*	*5.52*	*5.52*	*5.52*	*5.52*	*5.53*	*5.53*	*5.53*	*5.53*
	0.05%	*5.91*	*5.93*	*5.93*	*5.93*	*5.93*	*5.94*	*5.94*	*5.94*	*5.94*	*5.95*	*5.95*	*5.95*

Step 4. Flood exceedance calculation

The information in Table 4 along with the parameter $\alpha = 0.90$ were uploaded to the software for calculating the design variable method. Output from the software is shown in Figure 4, which is the water levels at Macksville (Pacific Highway Bridge) along with the calculated exceedance probabilities from the design variable method. The black line is the best estimate of the water level based on $\alpha = 0.90$ and two additional cases of complete dependence ($\alpha = 0$) and complete independence ($\alpha = 1$) are provided for context. The figure shows a small section in grey, the ‘extrapolation effect’ which is not large, but suggests that some of the larger events had a high degree of extrapolation outside the domain of the flood response in Table 4. However, this is not a significant issue since there is only a small difference between the complete dependence (red dotted line) and complete independence (blue dotted line) cases. The small difference between the two bounding cases of dependence suggests that that one of the flood-producing mechanisms dominates the estimates of flood levels. Further investigation of Table 4 shows the dominant mechanism to be the extreme rainfall because at less frequent AEPs there is a larger variation with changes in rainfall than with changes in tide.

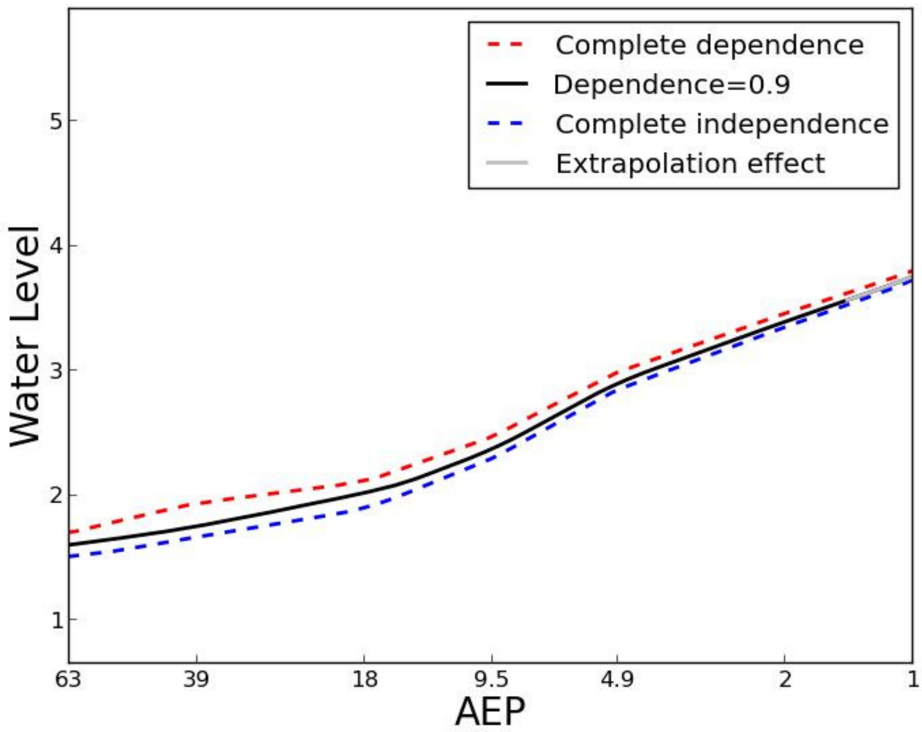

Figure 4 Water levels at Macksville (Pacific Highway Bridge) in the Nambucca river catchment, against the annual exceedance probability (AEP). The dependence parameters with 0 (red dot line) and 1 (blue dot line) represent complete dependence and independence, respectively.

Figure 5 shows a longitudinal profile of water levels along the Nambucca River for the 10% AEP and 1% AEP cases. These profiles are constructed from the results of separate analyses at each cross section location. The figure shows that the influence of joint probability is more significant for more frequent events (10% AEP) than for less frequent events (1% AEP), which is indicated by the lines for complete dependence and complete independence being separated further from each other. Future extensions to the method will allow for 2D maps to be constructed directly from inputs of 2D hydraulic surfaces rather than relying on the construction of longitudinal profiles at a collection of sites.

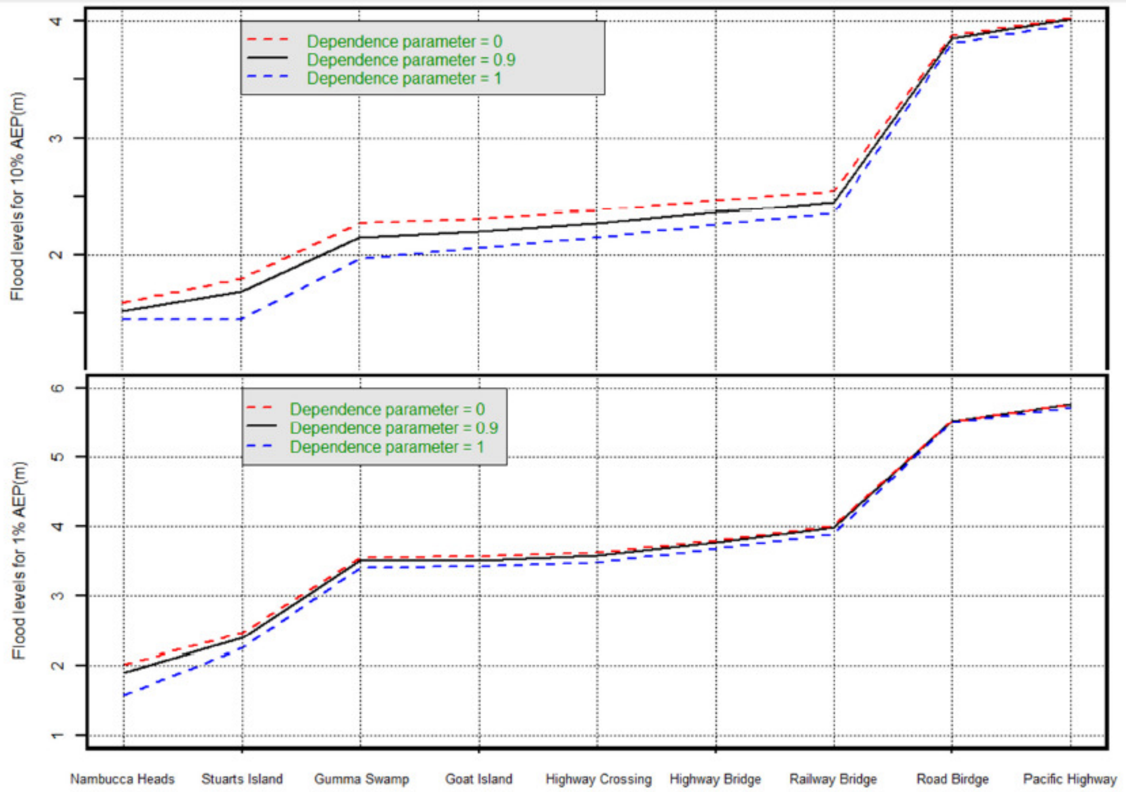

Figure 5 Flood levels at nine different locations in the Nambucca River catchment for AEPs=10% and 1%. The dependence parameters with 0 (red dot line) and 1 (blue dot line) represent the complete dependence and independence respectively.

Summary

There are many locations along the Australian coastline where flooding can occur due to the combination of extreme storm tides in combination with extreme streamflows. Part of the challenge in designing for these cases is that there is dependence between the extremes due to the role of common meteorological forcings. The design variable method has been demonstrated in this paper as capable of estimating flood risk where there is dependence in extremes.

The design variable method employs a relatively simple technique for linking extreme value analyses of storm tide and streamflow/rainfall, requiring only one parameter as input (which can be obtained from Figure 1). All remaining tasks involve standard analyses conducted by practitioners, including univariate analyses of extremes (to determine storm tide probabilities and rainfall/streamflow probabilities), hydrologic modelling to convert extreme rainfall to extreme streamflow and hydraulic modelling to determine water levels from pairs of extreme streamflow and extreme storm tide. The method allows for a pre-screening step in the event that a conservative assumption offers a simpler and cheaper outcome. Ultimately, the method offers a means for estimating flood risk in coastal regions with greater statistical rigour than existing heuristic approaches but without the computational and modelling complexity of continuous simulation.

Acknowledgements

This project was made possible by funding from the Federal Government through Geoscience Australia as part of the revision of Australian Rainfall and Runoff by Engineers Australia. This project has been the result of a significant amount of in kind hours provided by Engineers Australia Members. We are grateful to WMA Water who provided guidance on the Macksville case study.

References

Hawkes, P. J., and C. Svensson (2006), *Joint Probability: Dependence Mapping and Best Practice*. R&D Technical Report FD2308/TR1*Rep.*, DEFRA.

Leonard, M., Westra, S., Phatak, A., Lambert, M., van den Hurk, B., McInnes, K., ... & Stafford-Smith, M. (2014). A compound event framework for understanding extreme impacts. *Wiley Interdisciplinary Reviews: Climate Change*, *5*(1), 113-128.

Mosteller, F. (2006). Understanding the birthday problem. In *Selected Papers of Frederick Mosteller* (pp. 349-353). Springer New York.

Svensson, C., and D. A. Jones (2002*), Dependence between extreme sea surge, river flow and precipitation in east Britain,* International Journal of Climatology, *22*, 1149-1168.

Svensson, C., and D. A. Jones (2004), *Dependence between sea surge, river flow and precipitation in south and west Britain,* Hydrological Earth Systems Science, *8*(5), 973-992.

Tawn, J. (1988), Bivariate extreme value theory: Models and Estimation, Biometrika, 75(3), 397-415.

Westra, S, Leonard M and Zheng F, Australian Rainfall and Runoff, Book VI, Interaction of Coastal and Riverine Flooding-Draft, Engineers Australia, May 2016, downloaded 16 May 2016

WMA Water (2013), *Hydraulic modelling report - Nambucca River and Warrell Creek Report.*

Zheng, F., S. Westra, and S. A. Sisson (2013), *The dependence between extreme rainfall and storm surge in the coastal zone,* Journal of Hydrology *505*, 172-187.

Zheng, F., Westra, S., Leonard, M., & Sisson, S. A. (2014). Modeling dependence between extreme rainfall and storm surge to estimate coastal flooding risk. *Water Resources Research*, *50*(3), 2050-2071.

Zheng, F., Leonard, M., & Westra, S. (2015). Efficient joint probability analysis of flood risk. *Journal of Hydroinformatics*, *17*(4), 584-597.