Comparison between Design Event and Joint Probability Hydrological Modelling

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Abstract

The Design Event Approach (DEA) is a well-established method amongst practitioners, whilst the Joint Probability Approach (JPA) is still in developmental stages. An initial assessment indicates that as yet, there are no clear industry standards for applying the JPA to hydrological modelling. Further, there are currently two main schools of thought in its application. They are named TPT (Total Probability Theorem) and CRC-CH (Cooperative Research Centre – Catchment Hydrology) JPA methodologies in this paper. This study briefly describes the technical differences between the abovementioned approaches, applying both approaches to eight catchments of the Gold Coast and comparing their results with DEA estimates. The selected catchments cover a wide range of hydrological and physiographical features and therefore highlight the differences between these methodologies more sharply. The contribution of this study to the body of knowledge is to provide more insight into the JPA methodologies and to generate a better understanding of their differences with the DEA methodology.

Introduction

The Design Event Approach (DEA) is a rainfall based design peak flow and hydrograph estimation methodology. The methodology is currently recommended in Australian Rainfall and Runoff (ARR) (I.E. Aust., 1987, 1998) and is used widely by practitioners. The DEA uses one probabilistic input that is the rainfall depth for a given Average Recurrence Interval (ARI) and duration. All other inputs, such as loss parameters, temporal and spatial pattern assignment are assumed fixed. In estimating peak design flows for a specified location and ARI, design rainfalls for a number of durations are routed through a rainfall-runoff model. The duration which yields the largest peak flow rate is deemed the critical duration and its associated peak flow rate and hydrograph are used for subsequent hydrological and hydraulic analyses. The main shortcoming of this methodology is that (i) it is assumed that the design peak flow for a specified ARI is associated with a design critical duration rainfall event of the same ARI with fixed hydrologic inputs and (ii) the hydrologic inputs are fixed and assumed to be probability neutral. Limitations of this methodology are explained in detail in Weinmann et al (2002) and Kuczera et al (2006).

The Joint Probability Approach (JPA), also known loosely as Monte Carlo simulation, is designed to address these shortcomings. The fundamental principle of JPA is that a design flood can be generated by a variety of combinations of hydrological inputs. The approach necessarily considers the probabilistic nature of all the flood-producing inputs and their likely joint probabilities. Values for flood producing inputs are generated randomly from the full range of their probability distributions. Numerous combinations of these values are then used to formulate inputs to a rainfall runoff model whose outputs (design flows, volumes etc) are subsequently analysed using standard frequency analysis. The process is known as Monte Carlo simulation.

A literature review shows that there are currently two main schools of thought in the application of JPA; i.e. the Total Probability Theorem Approach (TPT) developed by Nathan, Weinmann and Kuczera (Laurenson et al, 2005) and the Corporate Research Centre for Catchment Hydrology (CRC-CH) approach developed by Rahman et al, 2002a. Both methodologies have been tested in different situations. Rahman and Weinmann (2002) used CRC-CH JPA in small catchments (83 to 130 km^2) in north Australia. Rahman et al (2005) used CRC-CH (using the URBS software platform) for a medium size catchment (441 km^2) on the Gold Coast and compared JPA flood estimates with those of the DEA. Charalambous et al (2005) used the CRC-CH JPA (using URBS software platform) to assess the performance of JPA in a large catchment (1000 km^2) in north Queensland.

Hill et al (2009) used the TPT approach (using RORB software platform) to assess the impact of water level behind the Hinze Dam wall on the Nerang River flooding. This study covered upstream sections of the Nerang River catchment down to Clearview (downstream of the Hinze Dam). The JPA in this study sampled temporal patterns, initial losses and the drawdown in Hinze Dam. Sih et al (2012a) continued this work by extending the joint probability framework to include sampling historical storm spatial patterns. This study showed that consideration of probability of spatial distribution of rainfall for the Nerang Catchment did not result in any meaningful change in peak design flow estimates. A comparison between JPA and DEA results showed that the differences were modest for the Nerang River catchment. However, any differences are likely to be masked by the presence of a large reservoir in the catchment i.e. Hinze Dam. This study also investigated the impact of filtering temporal patterns. Sih et al (2012 b, c) extended this study further to the full Nerang River catchment (491 km^2) through taking into consideration tidal and floodplain storage influences in the downstream reaches. The study also considered the influence of major tributaries of the Nerang River, i.e. Worongary and Mudgeeraba on overall flooding behaviour of the catchment.

A gradual migration from DEA to JPA appears to be inevitable. The Queensland Floods Commission of Inquiry Recommendation 2.2 (to apply JPA to the Brisbane River catchment) is likely to expedite this migration process. The body of knowledge in JPA including definitive techniques and appropriate ranges of applicability need to be strengthened to ensure a successful migration, otherwise inappropriate use could result in analyses that are likely to be inferior to the current DEA.

This study extends the existing body of knowledge further by making a comparison between the TPT and CRC-CH JPA methodologies for eight diverse Gold Coast catchments. These design flow estimates are then compared with those of the DEA. Where significant differences occur this paper identifies some of the reasons for these differences, though more work needs to be done.

The URBS software platform (Carroll, 2012) was used to apply the TPT and CRC-CH JPA methodologies as well as the standard DEA methodology. The TPT methodology is a recent addition to the URBS modelling capabilities and is based on the methodology as incorporated in the RORB runoff routing model (Laurenson et al, 2005).

Study Area

Figure 1 shows the extent of the study area. The Gold Coast is located in the southeast corner of Queensland, Australia (153.4098^{0}E, 28.0175^{0}S). The city area comprises of eight major catchments, namely Currumbin (52 km^2) , Tallebudgera (98 km^2), Nerang (491 km^2), Loders (10 km^2), Biggera (21 km^2), Coomera (441 km^2), Logan-Albert (3878 km^2) and Pimpama (125 km^2). These catchments drain runoff from the major rivers and creeks across the Gold Coast into the Pacific Ocean. The catchment characteristics change from very low density mountainous to highly urbanised flood plain and coastal areas.

Due to inadequacy of ARR rainfall maps for high rainfall gradient areas such as the Gold Coast, a new rainfall map for the Gold Coast (namely AWE) was developed in 2000, superseding previous rainfall maps (such as ARR 1987 and 1976).

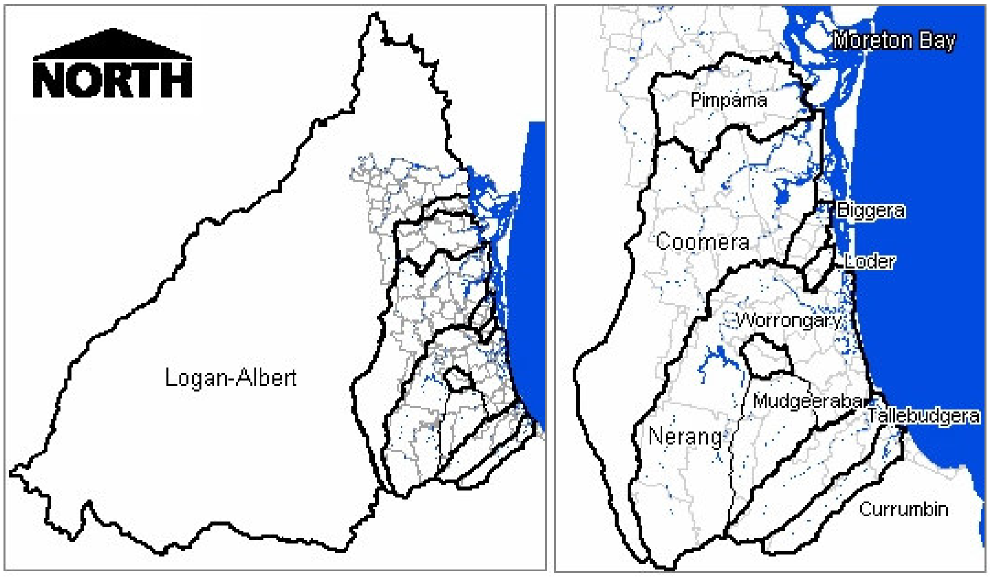

Figure 1 Study area

JPA methodologies

Over the past few years, the joint probability approach (JPA) has been under development (often referred to as Monte Carlo simulation which is an essential component of the joint probability approach). Currently there are two Monte Carlo techniques available; the Total Probability Theorem (TPT) methodology as developed by Nathan, Weinmann and Kuczera (Laurenson et al, 2005) and secondly the CRC-CH approach as developed by Rahman et al. (2001, 2002a). The former builds on the current critical storm duration approach whereas the latter generates design storms of variable storm duration. The CRC-CH methodology is more difficult to apply as it requires event based IFD tables which are generally derived from raw pluviograph data, whereas the TPT methodology uses burst IFD tables as issued by the BoM or, as for the Gold Coast, those developed by AWE.

The steps taken in the CRC-CH methodology in the URBS software platform can be summarized as follows:

- Storm core duration is selected from an exponential/gamma probability distribution (fitted to the available pluviographs of the area)
- A conditional distribution in the form of Intensity-frequency duration (IFD) curves is established.
- Temporal patterns are randomly selected based on the multiplicative cascade model (Rahman et al, 2001) and parameterized according to Carroll (2004). These patterns were filtered for the TPT analysis to ensure that the generated patterns did not result in inconsistent within-storm bursts.
- A beta distribution is assumed for the initial loss whose parameters were sourced from Ilahee (2001) and from the historical calibration events.
- Thousands of combinations of the design inputs are generated and routed through the runoff routing model, followed by conventional FFA (Flood Frequency Analysis) of the simulated flood peaks.

To assist with the DEA and JPA comparative exercise, specifically the use of the CRC-CH approach, a relationship was developed between complete storm IFD tables and burst IFD tables for the Gold Coast Region (Carroll 2012, unpublished). This was done by obtaining raw pluviograph data from the BoM to derive complete event IFD tables and comparing these tables to their burst table equivalents. The relationship between the tables was assumed to be:

$$I_e = p \times D^q \times T^r \times I_b$$

Where p, q and r are constants, D is the Duration (hours), *T* is the ARI in years, *I* is the intensity. *b*=burst, *e* = event.

For the Gold Coast area it was found that $p = 0.1 \times I_2 D_{24} - 0.25$, $q = 0.6 \times (1 - p)$ and $r = -0.025$. The mean duration was found to be approximated by $0.9 \times I_2 D_{24}^{1.56}$ where $I_2 D_{24}$ is the 2-year 24-hour burst intensity.

It was assumed for both approaches that for catchments containing dams initial levels are set to full supply level. Continuous losses and spatial rainfall patterns were assumed to be constant.

The steps in the TPT approach can be summarized as follows:

- Choose a range of durations around the critical storm duration (from DEA)
- Generate 1000 rainfall bursts through stratified sampling of the rainfall frequency curve for each duration.
- Randomly select a temporal pattern from the database of temporal patterns obtained from pluviographs of the area
- Apply loss parameters (random initial loss, fixed continuous loss)
- Determine ARIs for nominated peak flows based on TPT analysis

The most important difference between the TPA and CRC-CH methodologies is the latter's inclusion of variable storm duration. For the CRC-CH methodology, the storm duration is generated through random selection from the probability distribution of storm durations. For the TPT methodology storm durations are set and the critical duration identified as per the DEA.

Results

Figures 2 to 9 show a comparison between DEA, TPT and the CRC-CH.

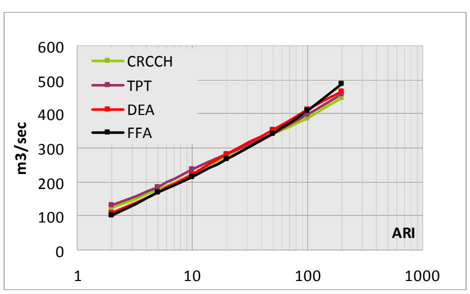

Figure 2 – Peak Flow at a location in the Currumbin Catchment

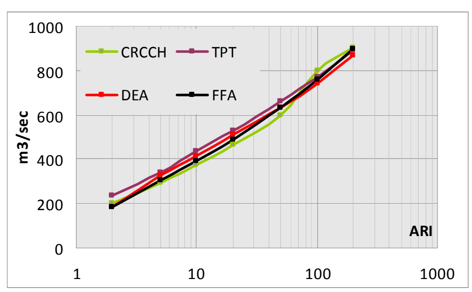

Figure 3 – Peak Flow at a location in the Tallebudgera Catchment

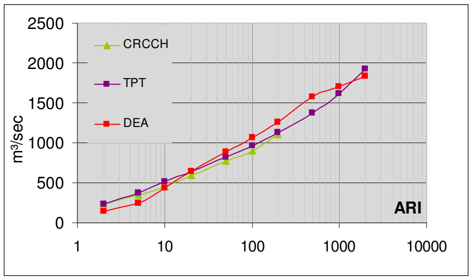

Figure 4 – Peak Flow at a Location in the Nerang Catchment

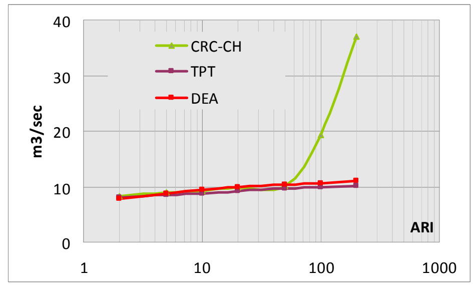

Figure 5 – Peak Flow at a Location in the Biggera Catchment

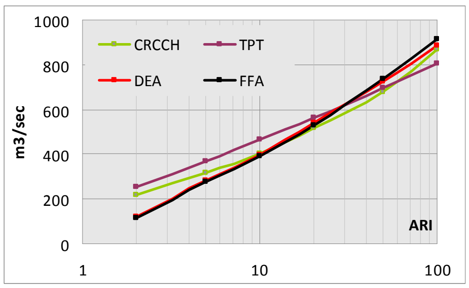

Figure 6 – Peak Flow at a Location in the Coomera Catchment

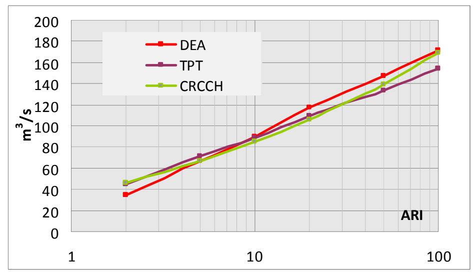

Figure 7 – Peak Flow at a Location in the Pimpama Catchment

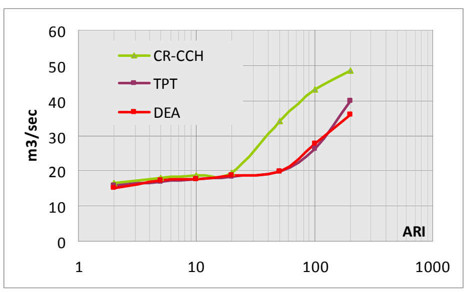

Figure 8 – Peak Flow at a Location in the Loders Creek Catchment

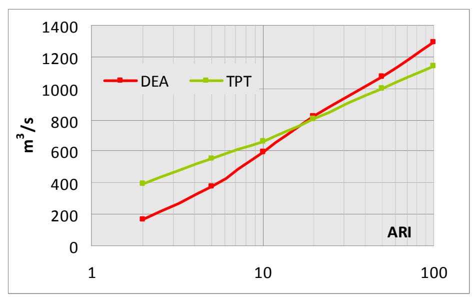

Figure 9 – Peak Flow at a Location in the Logan Catchment

Significance of Application of JPA

The JPA is a theoretically superior methodology to the DEA. However, the difference between DEA and JPA estimates appears to be within the uncertainties associated with design flood estimation. Mirfenderesk et al (2011) details a number of these uncertainties in the context of design flood estimation for the Gold Coast. In the conduct of this comparative analysis it was found that the main challenge is still poor quality/insufficient hydrological data sets upon which we base our design flood estimates. For example, anomalous design rainfall estimates were identified and are likely due to data paucity and subsequent interpolation in high rainfall gradient areas. One such area required a 25% increase in design rainfall estimates as current estimates were found to be significantly lower than those for downstream coastal areas.

Anomalies were also found in the DEA methodology itself. Figure 10 highlights one such issue that may arise for design estimates for ARIs greater than 100 years. The reasons for these anomalies are two-fold; (a) in some cases merging of the CRC-Forge and the AWE IFD tables resulted in lesser intensities with increasing ARI for the same duration and (b) the abrupt change from the AWE temporal pattern for design events up to and including 100-year rainfall events to the use of the GSDM/GTSMR pattern for events greater than 100 years ARI.

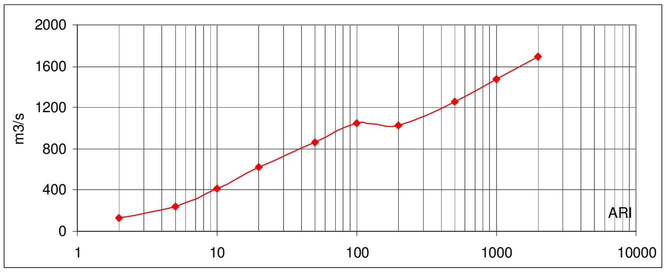

Figure 10: DEA Anomalies for events > Q100: Nerang River

Discussion

The use of Monte Carlo techniques yielded excellent results for the Tallebudgera, Currumbin and Nerang catchments and good results for Loders, Biggera and Coomera. Results for the Logan catchment were average and it was found that application of the CRC-CH technique would require additional background work for it to be used with confidence for this catchment. Overall, the Monte Carlo approach supported the DEA results.

It should be noted that both methodologies suffer from limitations. The TPT methodology has been developed for large to extreme floods and its application here for the more frequent ARI's is questionable. The CRC-CH methodology while often applied in the derivation of design flow estimates up to and including large floods is not robust in the estimation of rare and extreme floods when compared to the TPT approach. Other limitations are:

- the assumption that the loss distribution applied is consistent across the entire frequency range – generally higher losses are experienced with the more frequent ARI events, as is often required when reconciling DEA estimates with flood frequency estimates,
- convective storms are typically front loaded whereas frontal storms are end loaded which is not accounted for, - sampling historical patterns would address this,
- storm patterns are likely to be less variable with increasing ARI, and
- how El Nino/La Nina cycles impact antecedent conditions.

It is obvious that further research work is required to apply these technologies over the entire frequency spectrum, but as applied, it is likely there will be over-estimation of peak flows for the more frequent design events.

Overall, it was found that the TPT methodology provided a closer fit to the DEA results (as expected as both assume the critical duration assumption) whereas the CRC-CH approach generally underestimated the DEA results. The CRC-CH methodology was not suitable for the Logan catchment as it was found the adopted Burst to Complete Event IFD table conversion process was not applicable for areas on the western side of the dividing range.

Conclusion

It is concluded that the JPA supports the DEA estimates for catchments within Gold Coast and therefore the DEA results can be confidently used as input to the Gold Coast catchment's hydraulic models.

There are two modelling approaches available, namely the Design Event Approach (DEA) and the Joint Probability Approach (JPA). The former approach is well established amongst practitioners whilst the latter is still in developmental stages. As yet there are no clear industry standards for applying the JPA to hydrological modelling. Further, there are currently two main schools of thought in its application, the TPT and CRC-CH JPA methodologies. The TPT methodology is more aligned to the current DEA but not a full JPA approach. The advantage of the TPT methodology is that it builds on the existing DEA and is more robust for the rarer and extreme events and therefore, will be more readily taken up by the industry's practitioners. The CRC-CH methodology is conceptually superior but more difficult in its application. Both methodologies are (theoretically) a considerable advance over the current DEA; however, their range of applicability needs to be better understood.

Due to theoretical supremacy of JPA to DEA, a migration to JPA is inevitable. Such migration needs to happen with care. The JPA is a more complicated approach than DEA and its application requires more technical and in-depth hydrological modelling knowledge. It is also not a replacement for sound engineering judgement, which is required irrespective of which approach is used. In the absence of adequate capacity building and training, this methodology can be used incorrectly by practitioners, posing a risk to flood risk management practice.

The JPA because of its numerical intensity and inherent sophistication may give a false sense of confidence to practitioners about the accuracy of their work. The JPA, as for all modelling approaches, follows the maxim: "garbage-in-garbage out". A comparison between the three methodologies, i.e. DEA, TPT and CRC-CH JPA, shows that the differences in results for the Gold Coast area are modest and most likely within the uncertainties associated with hydrological data-set upon which we build our models.

It is concluded that improvements in design flood estimation will require both better hydrologic data sets and more defensible flood estimation methodologies such as the JPA.

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