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Submission details

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Submission type	I am making a personal submission
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1.2 Preparation	See attached

and planning

Supporting documents or images

Attach files	• 1927103.pdf • 1887870.pdf • Flood review submission J Stuart.pdf

Atmospheric Rivers, Cyclones and Extreme Flood Estimation: Predicting the location of the next great flood.

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Background

In May 2016, Stuart et al[1] submitted to the Flood Management Association (FMA) that investigated a number of issues in hydrological design methods and in their application to rare and extreme floods in Australia related to the use of the Generalised Tropical Storm Method – Revised[2] (GTSMR).

Key conclusions from the 2016 paper were:

- The use of the Annual Exceedance Probability (AEP) of the Probable Maximum Precipitation (PMP) as an anchor for probability is a methodology that constitutes interim advice and has documented drawbacks. It is this advice that is input into dam upgrade programs.
- The use of the Average Variability Method (AVM) for rainfall temporal pattern creation produces results which appear to be in contrast to patterns associated with many observed events with which our dams need to cope. The stated aim of selecting the AVM is to preserve AEP neutrality between rainfall and floods.
- Utilising data with three hour time steps re-distributes more intense rainfalls over longer time frames.
- The apparent application of the GTSMR method without regard to notified uncertainty was identified in 15 studies in Queensland and New South Wales.
- Variation in model calibration parameters and in assumptions on rating curve extension can have a major effect on modelled design levels when these have been calibrated to more frequent floods.
- Implications for dam owners are related to initial conditions in reservoirs. For instance a high peak, low volume flood occurring when the dam is already spilling is likely to be in contrast to assumptions used in design.
- Some observed events globally compare favourably with PMF design flows in Australia.

It is no surprise that there is variability between a design flood event AEP and an observed event AEP. The issue is one of acceptable variability. The 2016 paper indicated that it is feasible for some of our dams to see levels that challenge their design criteria. As outflows from dams approach their nominal design standards (i.e. extreme flood events) communities, dam owners and emergency responders may find the situation well beyond their experience or preparation. Design standards are based on the application of a single design event storm. The validity of this method is an assumption in itself. In tropical areas, where sizeable floods can be generated from smaller areas of the catchment, it may be more appropriate to look at what is feasible given the nature of the catchment and potential meteorological set up.

This paper explores several physical elements that may result in a significantly different flood level from that expected based on rare and extreme deign flood methods using similar rainfall depths. The elements are;

- Reasons why rainfall temporal patterns that are skewed towards the end of events might be more likely during some tropical events;
- A review of a past events with regard to the implications of the work of Seo et al (2012) related to storm movement resulting in enhanced flood peaks;
- Catchment geometry and how design methods may not identify high risk locations;
- Other factors such as catchment breakouts and vegetation.

Finally, the issue of atmospheric moisture is investigated with regard to rare and extreme flood risk, an area of growing research in the United States.

This paper should ideally be read in conjunction with the previous 2016 paper[1].

Meteorology

Stuart et al. (2016) identified that temporal patterns that are skewed towards the end of the storm (end weighted) are of particular risk to dam owners and in some catchments (depending on size, shape and terrain). In rare to extreme flood events, dams may already be spilling or catchments already in flood prior to the onset of the most intense rain. The AVM generally leads to a temporal pattern where duration and rain content are broadly equal (centre weighted). However, there appears good meteorological reasons as to why tail weighted temporal patterns are to be anticipated during tropical rain systems such as cyclones.

Figure 1 Tropical Cyclone Marcia, February 2015 (Bureau of Meteorology)

Tropical cyclones spin clockwise. As they approach the Queensland coast the heaviest rain is generally around the core and on the southern side of the core associated with the onshore flow[3]. Figure 1 shows Tropical Cyclone Marcia (TC Marcia). During TC Marcia, rain bands arrived well south of the system providing significant rainfall and ensuring minimal catchment losses and filling or spilling storages prior to the rainfall associated with the core. As a result, rainfall temporal patterns generated during this event were significantly end weighted[1]. Key to this effect was the movement in a north – south direction. The question arises, how many cyclones approach the coast in this direction with the potential to deliver ‘end weighted’ temporal patterns? To attempt to answer this question, the Bureau of Meteorology (BoM) Tropical Cyclone (TC) database was examined using Geographical Information Systems (GIS) and the following methodology;

- Develop cyclone tracks from the BoM dataset and filter out cyclones that did not originate from the Coral Sea; and
- Determine the cyclone/coast interception angle for each region along the Queensland Coral Sea Coast. The Queensland coast was simplified to avoid any local effects associated with the coastline. All cyclones with a bearing of 0 to 120 degrees were excluded as no coastal crossing is possible within this range. (This is a potential limitation as rain can affect the coast without crossing but the number of cyclones that run parallel to the coast without crossing has been assessed as small in terms of the broad picture being assessed)

The cyclone heading after crossing is clearly important for any study of greater detail; however this investigation was one of establishing angle of crossing.

127 cyclones were identified that crossed the Queensland coast from 1906 to 2016. (See Table 1). Of these, 42 (33%) have crossed with a bearing between 140 and 220 degrees (broadly from a northerly direction). The numbers approaching from this direction increase markedly as the crossing point moves south in Queensland. For instance, 59% of the coastal crossings in Central Queensland have approached the coast from a broadly northerly heading. The headings were related to the storm, not the shape of the coast.

Information in Table 1 indicates that the risk of north-south crossings varies according to latitude and consequently that the risk of cyclones delivering temporal patterns that are end weighted may also vary. Not every cyclone moving north-south will deliver such temporal patterns, of course.

Bearing of crossing (degrees)	Number		FNQ	NQ	CQ	SEQ
120-140	3			3		
140-160	1			1		
160-180	7	33%		4	3	
180-200	12		1	3	4	4
200-220	22		8	9	3	2
220-240	20		5	9	3	3
240-260	33		19	11	2	1
260-280	22		18	2	2	
280-300	5		3	2		
300-320	2			1		1
Total	**127**		**54**	**45**	**17**	**11**
Total northerly approach			**9**	**17**	**10**	**6**
% northerly approach			**17%**	**38%**	**59%**	**54%**

Table 1: Queensland Coastal Crossing Cyclones (1906 -2016) with angle of crossing

Further work is required to investigate the effect to which weather troughs also have the ability to create such temporal patterns. There is good reason to believe that this is the case. The hypothesis to be investigated is that as a trough moves east, the instability caused by changing air masses leads to greater instability and the generation of potentially more convective intense rainfall at the end of the event.

Storm Direction and Lessons from Charleville in 1990

Another characteristic of both troughs and cyclones is that they can move and deliver a spatial rainfall pattern that is significantly different from single design storms.

Seo et al (2012)[4] identified the possibility of enhanced flood peaks caused by storm movement aligned with the direction of the broader catchment stream network. The BoM report into the 1990 Western Queensland floods[5] indicates just such an occurrence happened in the Warrego catchment. The Warrego catchment (65000km^2)

drains from the Central Highlands in Queensland to the south. It descends rapidly through steep terrain to Charleville. The 1990 rainfall led to a fast developing, record flood peak that led to evacuation of 25000 people, very high velocities and all but three buildings not flooded. Such an occurrence is of interest to dam owners, insurance companies and emergency planners in Australia with the point of investigating what may be possible in a catchment under different meteorological events.

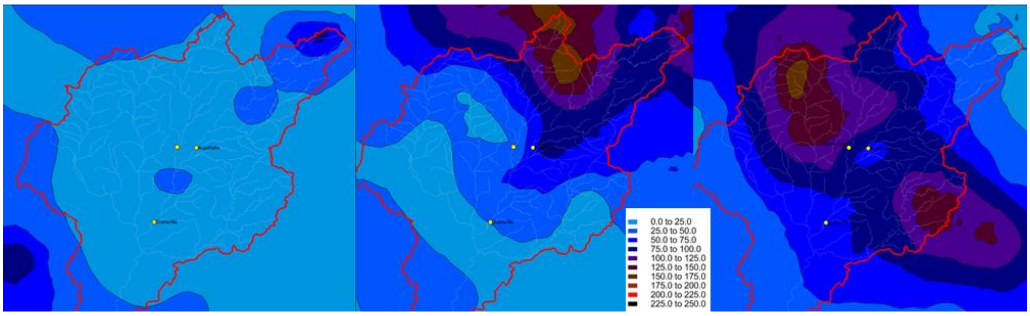

Figure 2: Daily rainfalls across the Warrego catchment for the 18th, 19th and 20th April 1990

Figure 2 demonstrates the conclusion of the BoM report[5] using daily rainfall grids provided by BoM. The rainfall clearly moves progressively downstream as each day passes. The ability of a weather system to move and enhance a developing flood peak is another identifiable reason why observed floods may challenge those modelled on design assumptions.

Similar types of weather systems were the cause of both the 1997 and 2012 Warrego floods. In the 1997 instance, the trough moved upstream away from the flood peak as shown in Figure 3.

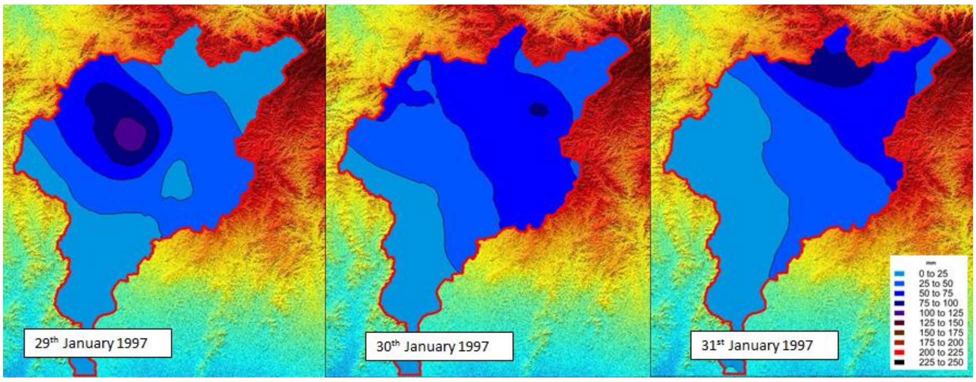

Figure 3: Daily rainfall in the Warrego catchment from 29th January to 3rd February 1997.

In 2012, flood levels at Charleville reached just above 1997 level to reach a peak that is presently 2nd on record. The 2012 trough didn't move from the upper catchment. A key demonstration of the importance of temporal and spatial distribution in this case was the lack of daily rainfalls that exceeded 100mm. There were none in the upstream catchment on any event day[6] in contrast with previous events. Rainfall depths were less in 2012 than 1997 but the flood peak was over 0.25 metres higher.

Hydrologic Modelling

The Upper Burdekin catchment in Queensland is around 36000km^2 to Sellheim (see Figure 4**).** To test the potential for a moving storm to generate flood peaks larger that design floods, URBS modelling was undertaken. Four rainfall stations were selected as shown in Figure 4, broadly equidistant from one another and located along the main channel.

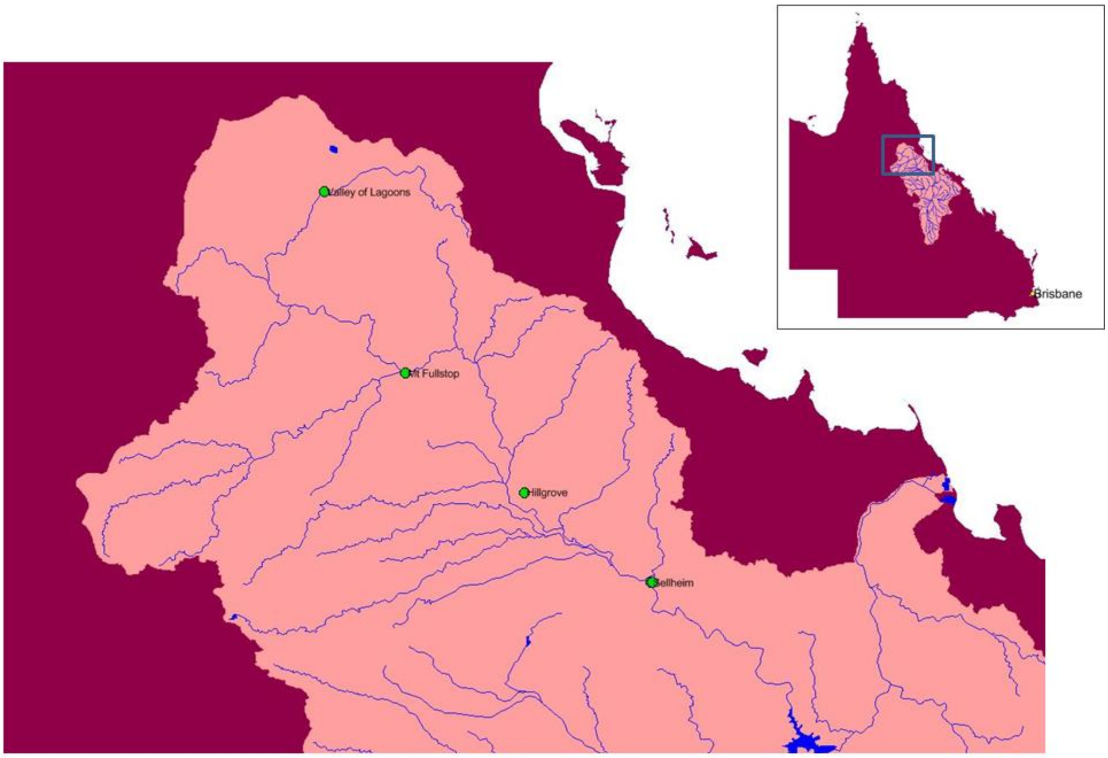

Figure 4: Upper Burdekin catchment showing four rainfall station locations

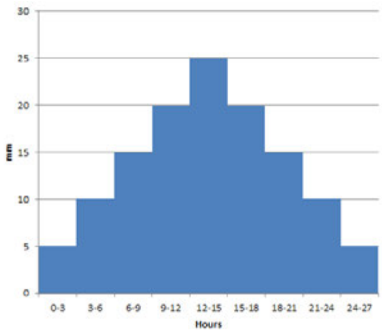

Figure 5: Temporal pattern used

A rainfall amount of 125mm was selected and a basic rainfall temporal pattern created as shown in Figure 5. To establish a base case, this depth and pattern was then simulated across the catchment using a calibrated URBS model. This formed the base case, a broad equivalent to a design case. No reduction factors were used as this exercise was one of relative comparison.

The rainfall was then distributed amongst the four stations with increasing time gaps between the start of the rainfall. For instance, the rainfall remained the same at the Valley of Lagoons. At Mt Fullstop, the rainfall started 3 hours later for the first case, with the rainfall commencing 3 hrs after rainfall at Mt Fullstop at the Hillgrove site and so forth. Rainfall temporal patterns were created with rainfall start gaps from 3 to 24 hours and sub-catchment rainfall files created accordingly based on the location of the nearest location. Results are shown below in Figure 6.

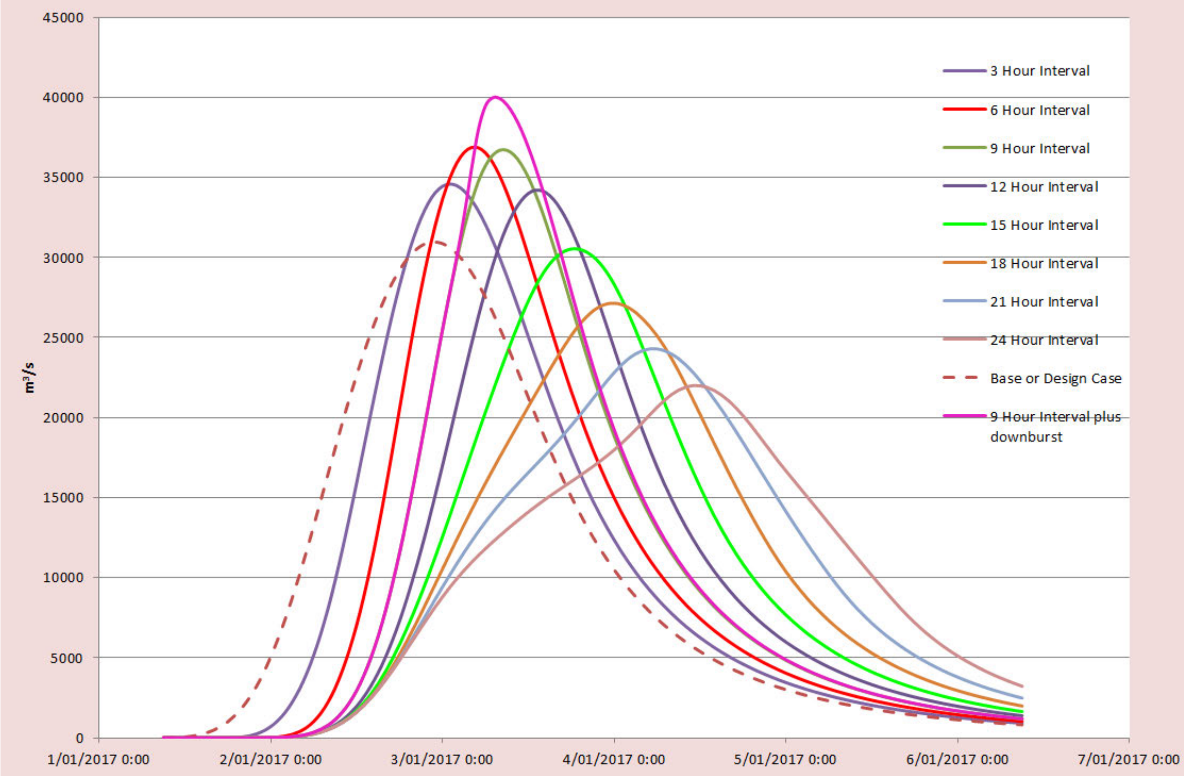

Figure 6: Modelling Results showing flows to Sellheim

The base case, or design case equivalent, with a single depth distributed across the catchment with no time variation is shown as the dashed line in Figure 6. The peak flow was approximately 31000m3/s. Delaying the commencement of the rainfall by 6 hours between each site in a downstream direction resulted in an increase of peak flow of approximately 37000m^3/s, an increase of 19%. Such an increase would have significantly greater flood impacts. At Burdekin Falls Dam, the flood volume would arrive with greater speed than the design flood.

For interest, a burst of 200mm in 3 hours over a small 150km^2 catchment was added in to the scenario with 9 hour gaps between the start of rainfall as the hypothetical storm moved down the catchment, falling on a sub-catchment as the peak was close to its outlet resulting in an increase of the peak flow to 40000m^3/s.

The results show that storm movement can be a key characteristic of rainfall, particularly relevant to fast moving systems such as cyclones and one that has the ability to significantly challenge community perceptions of flood risk achieved from design hydrology.

A moving storm and a record flood?

Plate 1: Burdekin River Flood Heights at Macrossan Bridge near Sellheim. 1946 (top) is the record.

Researching the 1946 record flood shown on the flood record at Macrossan Bridge (**Error! Reference source not found.**) near Charters Towers has revealed that an un-named cyclone moved down the catchment just offshore likely caused the flood. This would have allowed heavy rainfall to travel down the catchment, potentially at a similar rate as the flood peak. Relatively slow moving, it would likely have started to impact the catchment late on March 1st 1946 and continued for the following 36 hours. The path of the cyclone is shown in Figure 7. It would be risky to draw a firm conclusion that the movement of this storm enhanced the peak flow but there are good reasons to think that this may well have been the case given the average 36-48 hour time to peak for the Upper Burdekin to Sellheim[7].

The 1946 storm is not one considered for use in current design methods for Burdekin Falls Dam.

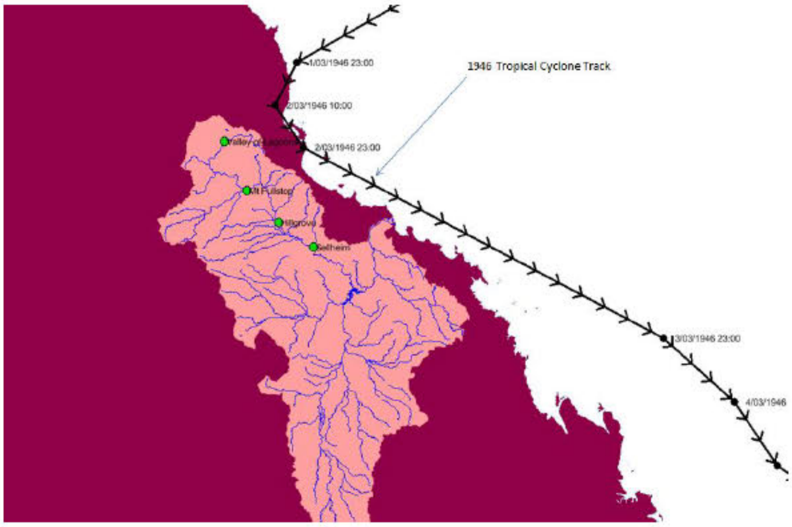

Figure 7: 1946 (un-named) Tropical Cyclone path and the Burdekin catchment

Risk Map for dynamic storms systems

Using the information obtained from the earlier investigation into cyclone tracks and information on how troughs have behaved in Central Queensland, it is possible to identify catchments based on angle of the main drainage course and assign the possibility of a peak enhanced by storm movement and where much larger floods than current estimation methods would indicate may, one day, occur. Figure 8 is an example of what might be achieved in this regard.

The challenge is to tie this together with existing methods of flood estimation through spatial distribution of rainfall, something which is challenging when considering probability. The probability we need, that of a moving storm in a certain direction is not something that is readily available. It does underline the importance of risk assessments that are fit for the purpose for which design hydrology is being conducted.

Catchments that could be affected as cyclones move north to south are shown within 250km of the coast and with a greater area than 3000km^2. This map is only a demonstration at this stage as it doesn't include all weather events nor information from storms from the Gulf of Carpentaria.

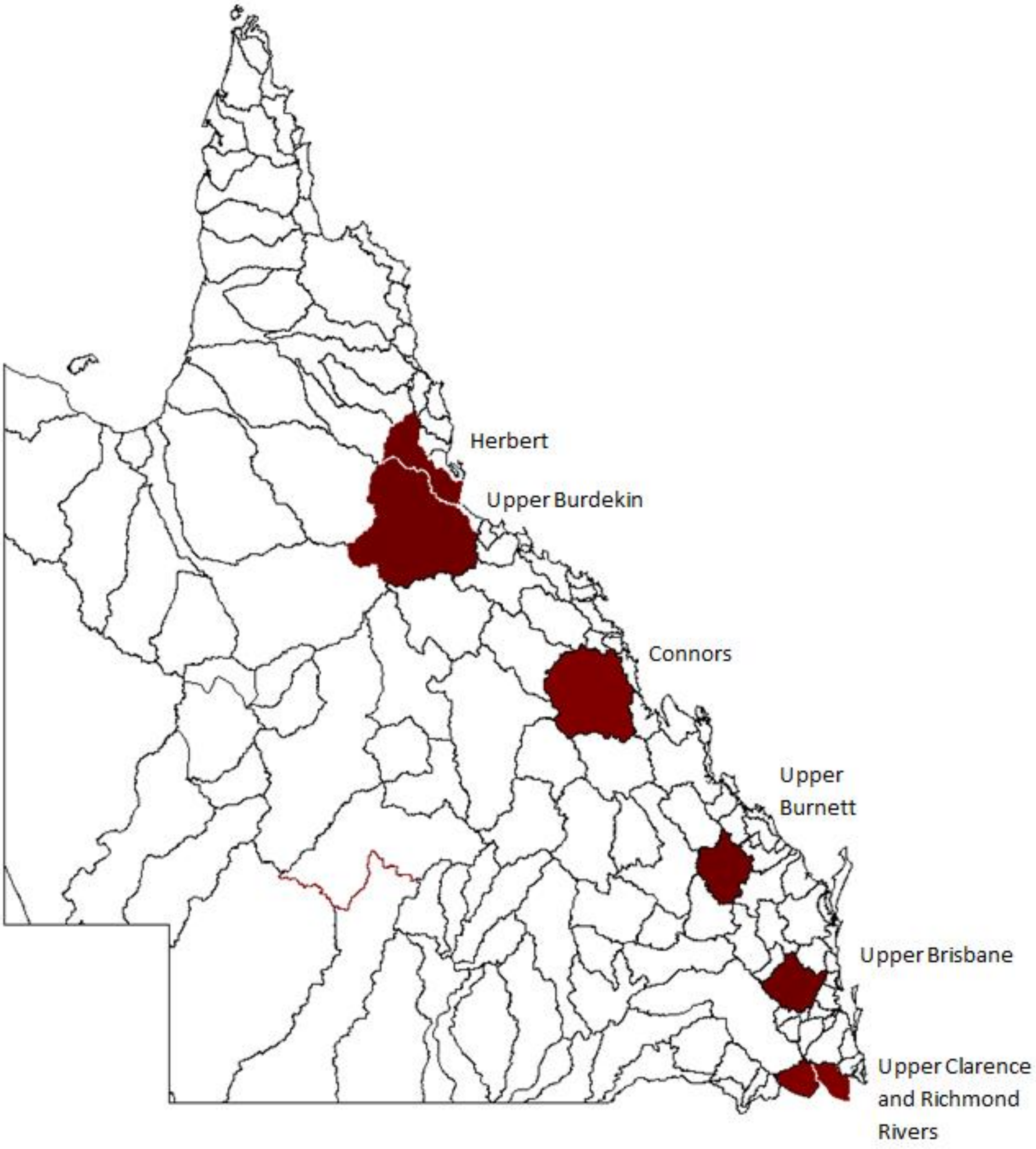

Figure 8: A demonstration risk map for catchments at risk from enhanced flood peaks associated with cyclones moving from north to south based on catchments within 250km of the coast greater than 3000Km2.

At Site Geometry

A third factor of concern with relevance to the implementation of the GTSMR[2] method is one of catchment geometry. This is illustrated graphically in Figure 9 which shows the storage above full supply levels at three Queensland dams. Dams 1 and 3 are broadly similar and indicate a significant amount of storage as lake levels increase. Dam 2 demonstrates quite a different relationship with 10000ML above full supply level during a flood event meaning a rise of three metres.

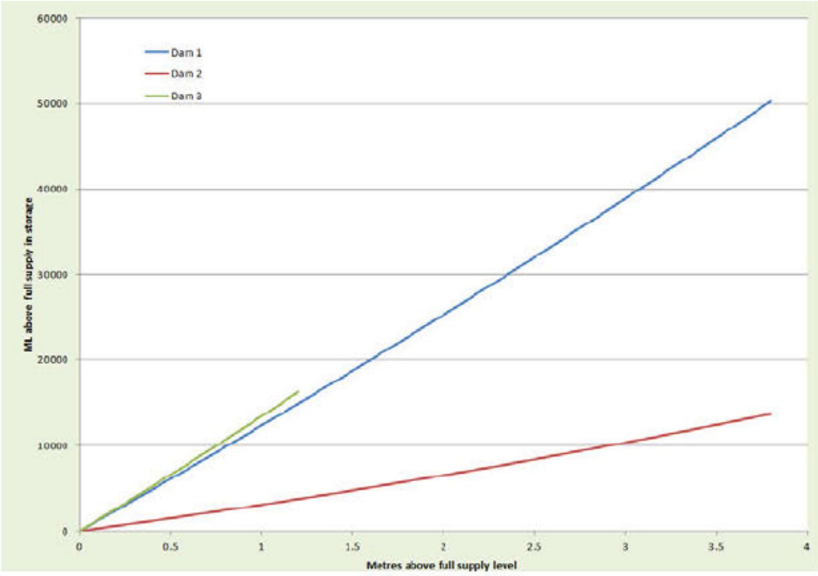

Figure 9: Storage above full supply for three Queensland dams

The relevance here is one of investigating sensitivity and impacts. It is for reasons such as this that the GTSMR methods recommend that the hydrologist should satisfy themselves that the temporal patterns used are appropriate. In the case of Dam 2, a high peak low volume flood would be a far from ideal scenario. Crucially this may or may not have been considered during design, depending on the temporal patterns used. The same effects can occur in catchments that are not dammed. Extreme flood risk methods need to consider what else may be relevant and such analyses as above can expose the potential risks and the need for greater investigation.

How big is a catchment?.. and at what time of the year?

Another factor of which hydrologists need to consider that can lead to surprises in flood risk is one of breakouts. Figure 10 shows four locations in Queensland that the authors are aware of where, at high flows, flood waters move across traditional flood catchment boundaries. These are the Warrego to Paroo, Burdekin to the Haughton, Pioneer to Sandy Creek, Moonie to the Balonne River and the Ross to the Bohle around Townsville. There are no doubt others, some of which we may not be aware. Figure 11 shows the hydrograph

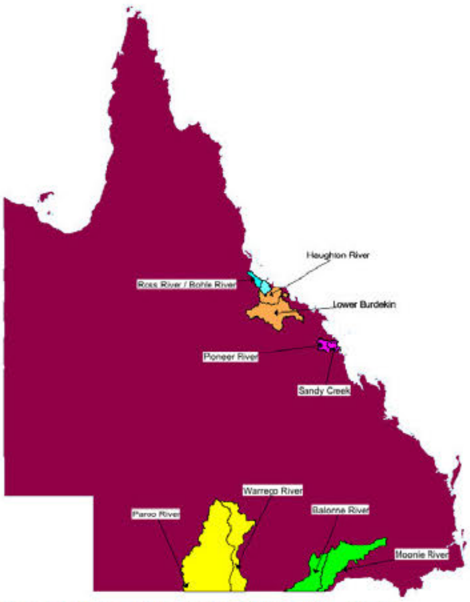

Figure 10: Some known Catchments where floodwaters can move to neighbouring catchments in Queensland (not an exhaustive list)

along the Paroo River at Eulo during the 2012 flood with catchment rainfall. The arrival of water from the Warrego is quite distinctive.

This effect may also be compounded by vegetation in some tropical areas that leads to significant variation in hydrologic and hydraulic response. For example, Sugar takes large volumes of storage from the floodplain once full grown. What comes with this is a very effective flow impediment when leaf debris is combined with the density of the plants. In cane areas, the effect of this just prior to harvest time is a completely different hydrologic and hydraulic response that may include floodwaters moving across small catchment boundaries

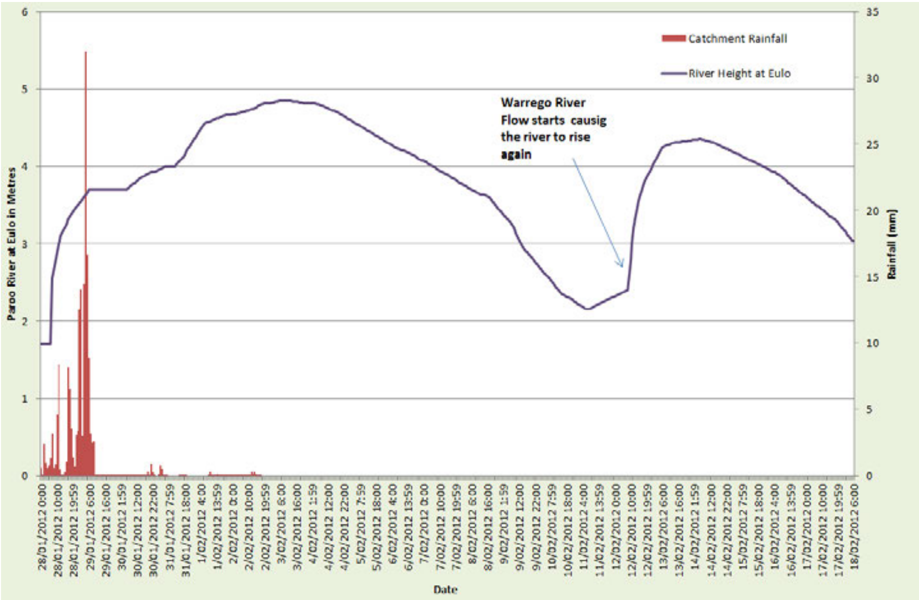

Figure 11: Warrego to Paroo breakout, early February 2012. (Source; Bureau of Meteorology)

Atmospheric Rivers and Atmospheric Moisture

The previous four characteristics related to storm direction, meteorology, varying catchment size and geometry are all predictable factors that can be reviewed to potentially assist in risk sensitivity analysis. In the course of the investigation, the subject of atmospheric moisture came to the fore a number of times.

- Major flooding in Colorado in 2013 was also attributed to much greater TPW than had previously been observed[9] and the same observation was made with regard to the record floods in Louisiana in 2016[10].
- Jordan Mcleod, a Research Associate with the Southeast Regional Climate Center at the University of North Carolina, noted the following prior to the South Carolina Floods of 2015 “Over the next day or so, we will essentially see the formation of what meteorologists refer to as an "atmospheric river”. While this one may not fit the standard criteria, it is basically serving the same purpose”[11] This introduced the concept of ‘AR-Like’ events for events that behave as such but don’t necessarily meet the criteria. The resulting floods led to the breach or collapse of 36 dams[12].
- The emergency at Oroville Dam in February 2017 occurred during an Atmospheric River. Whilst the failure of the spillway itself cannot be attributed to the size of the flood, a short sentence in the report from the California Water

Resources Dept. of “inflows to Lake Oroville reached 190435cf/s, significantly higher than forecast”[13] implies that perhaps dam decision makers were surprised by events.
- The June 2016 Tasmanian record floods had very high levels of TPW (see Figure 12).

In the United States, the importance of TPW has gained a lot of traction in recent years through research into Atmospheric Rivers and links to major flood events. This link is much more obvious in Pacific Coast America as in some locations, most[8] floods comes from Atmospheric Rivers.

An Atmospheric River is a narrow region of high water content in the lower atmosphere. Atmospheric Rivers criteria have been summarised by Ralph et al[8] as having a length of 2000km or greater, a width of up to 500km, wind speeds of greater than 12.5m/s in the lowest 2 km and integrated water vapour (IWV) of at least 20mm. IWV is broadly equivalent to Total Precipitable Moisture (TPW). IWV is measured in kg/m^2 and TPW is measured in mm or inches. TPW is depth of water in the atmosphere measured that, if the depth was able to fall to earth, would result in recorded rainfall.

TPW needs a weather system to react with and draw out the moisture as rain. In Australia, the link is not so clear due to our proximity to the tropics and variety of rainfall drivers in comparison to California. However, the 2016 Tasmania floods (see Figure 12**Error! Reference source not found.**) met the criteria outlined above in determining what constitutes an AR but the broader interest is in any event linked to tropical moisture – including AR-Like events.

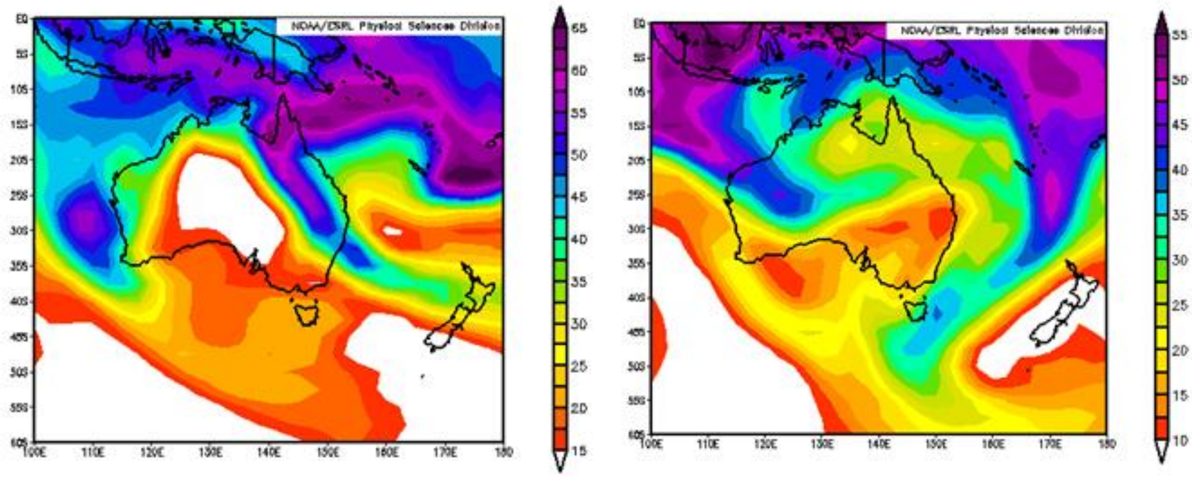

Figure 12: Atmospheric Rivers in Australia? 2012 (Maranoa and Warrego floods, left) and 2016 (Tasmania floods, right) (source: NOAA)

In Figure 13, flood peaks at Emerald, Queensland have been plotted against the average event TPW values sourced from the National Oceanic Atmospheric Administration (NOAA) reanalysis tool that includes TPW estimates from January 1948 to the present day. There’s not much to report from this investigation, except a finding that the record flood in 2010 resulted from TPW values not experienced in any other flood event since 1950.

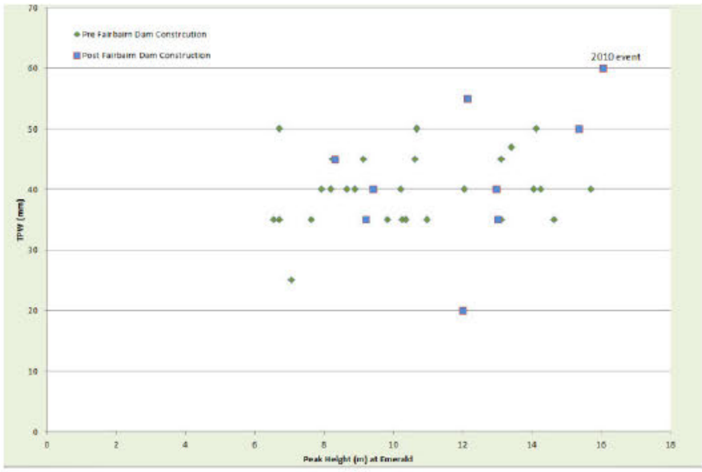

Figure 13: TPW content over the catchment for the main rain event and peak height at Emerald

The content of an AR or AR-like event can vary in much the same was as a conventional river indicating the duration of such events may last longer than the 144 hour maximum advised in design flood estimation. In Queensland, where travel times can be up to two weeks in catchments such as the Fitzroy, Warrego, Condamine and Balonne, this may be important for risk when assessing rare and extreme events.

An example of this is the 2012 Central Queensland event. According to the BoM, a surface trough was present for around 10 days and moved little, the trough provided a conduit for the northerly moist airflow[6]. This led to a record flood in Mitchell from a record reaching back to 1864. The longevity of the event ensured significant flows in catchments prior to an increase in rainfall volumes and intensities[7]. This adds weight to the need to consider the temporal and spatial implications in greater detail and look beyond the guidelines which are the starting point.

Lockyer in 2011 and Tasmania 1929

Atmospheric moisture is also of interest from a historical point of view. The Cascade Valley flood in 1929 led to the failure of the Breisis Dam and the deaths of 14 people[14]. From the Tasmanian Historical Society, we know that the direction of the moisture was from the north east and that an estimated 125mm fell within an hour and a half when the spillway was already overflowing. The same direction introduced tropical moisture to the island (see Figure 12) in June 2016 from an East Coast Low. Weekly rainfall totals for the 1929 event are shown in Figure 14 and compared with the 2016 flood event. It seems likely the 1929 flood was a similar set-up meteorologically.

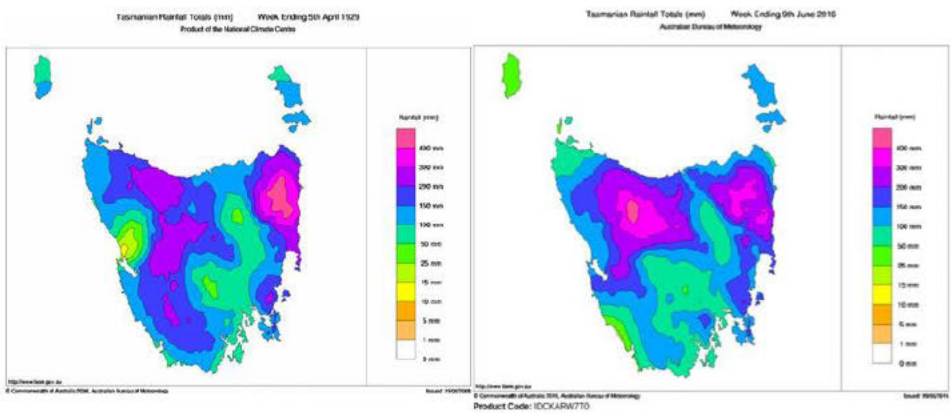

Figure 14: A comparison of the 1929 and 2016 weekly rainfall totals (Source, Bureau of Meteorology)

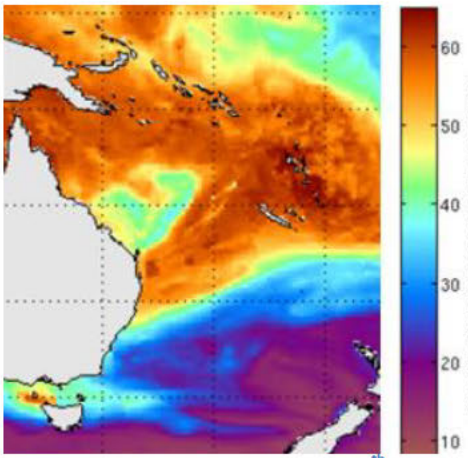

Figure 15: TPW data from January 10^{th} 2011 in the Coral Sea

The current Cascade Dam built on the site to replace the Breisis Dam is 3 metres higher and impounds around 3800ML. With a catchment area of $32km^2$, 125mm means a bulk volume of 4 million m^3 or 4000ML, approximately the same volume as the dam so it would seem unlikely that the failure of the dam itself was responsible for the downstream flood. Studying photographs of the event (see Plate 2), the resultant scour appears to compares favourably with some of the upstream catchments of the Lockyer Valley in Queensland where a catastrophic flood occurred in 2011 that led to the deaths of 21 people. Scientists estimate[15] that the velocities required for the erosion of Paradise Creek (a tributary of Lockyer Creek, see Plate 3) would have been of the order of 30-50 m/s resulting in a 4 metre lowering of the channel bed, 2 metres of that through bedrock. Figure 15 shows TPW on January 10^{th} 2011. Was this an AR-like event? It certainly appears worthy of additional research given the high values of TPW.

Plate 2: Lockyer Creek post 2011 flood (left (source, author) and Cascade River post 1929 flood (right ((source, tasmaniangothic.com)

Plate 3: Erosion in Paradise Creek, Lockyer Valley, January 2011 (Lockyer Valley Regional Council)

Significant though the rainfall rates observed in 1929 and 2011 are, they are not that uncommon, certainly at a point scale. The 2003 SEQ floods[16] and Cooroy floods in 2012[6] both had rainfalls well in excess of 100mm in an hour in several locations, yet damage seen during the Lockyer Valley event wasn't observed. So what was different?

Clearly, terrain and lead up conditions but does this explain velocities so great they can scour bedrock?

This leads to the question of what else might have occurred that made these events different. A possible answer is rainfall so intense it gets lost in our post event analysis generating massive volumes over small areas. According to the Bureau of Meteorology website, rainfall rates of 136mm in 8 minutes and 305mm in 42 minutes have been observed globally. Why should such rates not occur in tropical Australia? Is there a link to TPW? Such rainfall probably rarely gets recorded. Similar events will occur again. Whilst there is no way presently of taking in such rainfall into account when considering flood risk, it demonstrates the importance of considering what may be possible, particularly on small catchments and in upland areas and the importance of sensitivity analysis in flood risk assessment.

Conclusions

This paper has investigated potential physical reasons why observed flood events may cause flood levels that are significantly different from assessed rare and extreme design levels for similar rainfall totals.

Analysis of tropical cyclone movement indicates that the risk of a cyclone moving in a north-south direction increases as latitude decreases. The potential for such storms to produce end weighted rainfall temporal patterns was observed during TC Marcia in 2015. More research is needed to look at how the storms from the cyclone database moved prior to and after the coastal crossing and to assess other systems such as East Coast Lows (ECL) and ex-cyclones as well as troughs and also how often tail weighted temporal patterns eventuated at a catchment scale.

Cyclones may also travel at the same speed and direction as flood peaks, potentially enhancing them. A 19% increase in flood peak was has been modelled from such movement. Flood enhancement has been recorded by the BoM in 1990.

Site of interest geometry, effects from vegetation and high level cross catchment flows are all features that could also surprise communities with regard to their understanding of rare and extreme flood risk if not considered adequately.

Characteristics of moving atmospheric moisture related to extreme floods are an area that needs further research including existence of large volumes of rainfall within very short time frames that traditionally we haven’t considered.

“The validity of the assumption that an AVM pattern transforms the rainfall frequency to the flood frequency is unknown and untested” is a quote from Project 3 for the renewal of Australian Rainfall and Runoff (AR&R) 2016[17], the industry standard for frequent rainfalls. The lack of confidence by industry experts in hydrological design assumptions that are fundamental to results for communities, insurance, infrastructure and emergency planning, demonstrates the need for consideration of such matters by hydrologists. This effect is compounded by the use of guidelines as a method[1]. There are good reasons outlined in this paper and the 2016 paper[1] to suggest that in tropical Australia, the transformation of probability requires review.

The potential for storm movement to increase flood peak levels by 19% in the Burdekin catchment indicate a further design assumption that of the single design event storm may also need review for application in tropical Australia.

These current assumptions are being used to assess flood risk on dams yet to be upgraded to meet changes in the PMP estimates. These issues are present prior to any consideration of climate change impacts.

The next great flood will be characterized by one or all of the following; levees exceeding design criteria easily resulting in overtopping; dam owners considering downstream evacuations and a confused and angry public with flood records exceeded by large margins.

The probability we examine in Australia is the probability of the rainfall, not of the resulting flood. The use of an unknown and untested assumption at the core of engineering hydrology means Australia has a potentially huge legacy issue in relation to design flood risk. With respect to rare and extreme floods, is tropical Australia engaged in Russian roulette?

Where to?

Rainfall runoff methods are only a single part of flood estimation yet is generally the only method used in Australia. However, there are a number of things that can be considered to achieve a more realistic flood risk assessment.

Given that Queensland can generate very large floods from intense rain systems, it would seem appropriate to explore what has occurred globally as a starting point, most appropriately for emergency management and large and extreme event response.

Figure 16: Maximum observed flows for Australia and the world[18]Figure 16 illustrates the peak flows globally that have occurred by catchment area. Estimates of events in Australia show such discharges are possible.

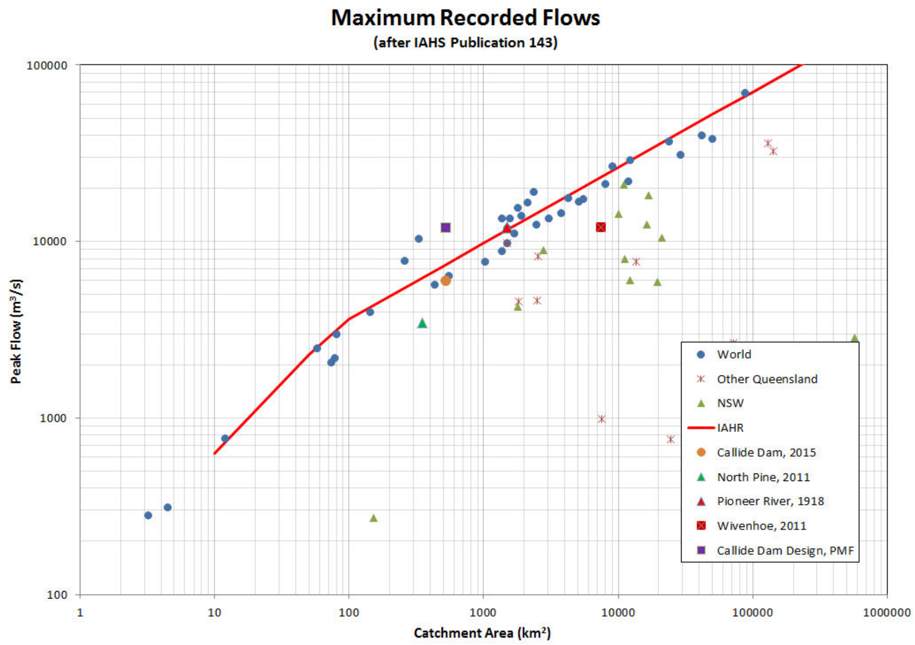

Figure 16: Maximum observed flows for Australia and the world[18]

Sediment analysis is another way to assist in reducing uncertainty around flood frequency estimates. This physical link can extend the current flood record back by thousands of years if catchment conditions are good. Combined with rating estimates and cross sectional analysis, it is possible to estimate magnitude also.

Currently available flood estimation techniques in Australia have left untapped a huge gold mine of hydrological data for flood risk assessment from ALERT stations. ALERT data is used for flood warning purposes and the number of stations continues to grow in Australia. Using this data, the potential exists to create a 'poor man's Monte Carlo' method. If we assess AEP neutrality based on AVM selected temporal patterns as invalid, observed temporal patterns from the subject catchment would be a good starting point to assess what the potential resulting flood for any given rain depth may be.

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18. International Association of Hydrological Sciences. *World catalogue of maximum observed flood events.* IAHS Publication 284; 2003.

1. I am a Fellow of Engineers Australia with 20 years' experience in flood management and modelling.

2. I am a former Regional Hydrology Manger at the Bureau of Meteorology in Queensland, a former representative on the Queensland Flood Warning Consultative Committee (2014-2022) and a former representative on the Commonwealth joint reference group on water information (2016-2022).

3. The submission relates to Terms of Reference item 1.2, planning.

4. As part of this submission, Attachment 1 is a paper written for the Flood Management Association in 2016 titled "100- or 10000-year flood, who knows? Implications for dam, floodplain and emergency management (FMA, 2016)" Link- https://www.floods.asn.au/client_images/1887870.pdf

5. Attachment 2 is a paper written for the 2017 Flood Management Association annual conference titled *Atmospheric Rivers, Cyclones and Extreme Flood Estimation: Predicting the location of the next great flood*. Link - https://www.floods.asn.au/client_images/1927103.pdf

6. In the context of the above papers, I would like to highlight two specific areas that may assist in preparing communities for future floods.

7. A) Design hydrology, or flood estimation is the use of statistical methods to ascertain flood frequency at defined locations.

8. Estimation of flood magnitude for a given frequency can vary significantly from that experienced.

9. Whilst some variability is expected, there is growing evidence that at some locations, frequency estimates using current Australian best practice can vary by an order of magnitude or more. e.g., what was thought to be 1:1000 flood level may actually be the 1:100-year flood level.

10. The Queensland Dam Safety Regulator noted this issue in his submission to the Queensland Flood Commission of Inquiry (2011) where flood levels between 1:5000 to 10000 in frequency were generated from 1:200-year rainfall.
http://www.floodcommission.qld.gov.au/__data/assets/file/0020/8516/Statement_of_Peter_Allen_with_attachments.pdf (Para 149)

11. The review should assess if design hydrology issues were evident in any locations or catchments.

12. B) Rating curves show the changing relationship between water height and discharge.

13. Rating curves in flood studies are a key component and are one of the most important inputs.

14. The variety of sources for rating information means they aren't all necessarily representative of the full range of flood heights required for consideration in flood studies.

15. A rating curve that doesn't cover the full range of flood heights requires extension to ensure the complete range of discharge and height relationship is available for any flood study.

16. Modelling software will generally extrapolate from the last point of the curve if no extension is completed.

17. Extrapolation can have a significant impact, on modelled flood levels, causing underestimation or overestimation dependent on the topography but is likely to impact larger flood events as this is the part extrapolated.

18. Underestimation produces modelled flood heights are lower those that are credible for a given frequency.

19. Overestimation produces modelled flood heights that are higher than those credible for a given frequency.

20. This relationship must be fully understood at all flood locations for a full range of modelled flood heights.

21. The review should assess if rating curve detail could be improved at the locations being considered.

100 OR 10000 YEAR FLOOD, WHO KNOWS?

IMPLICATIONS FOR DAM, FLOODPLAIN AND EMERGENCY MANAGEMENT.

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Background

Many community planning and community safety activities are based on hydrologic design methodologies. These include but are not limited to:

- Land use planning, which utilises design flood levels associated with annual exceedance probability (AEP), e.g. the community is protected from loss by excluding residential development in areas that are affected by a flood risk frequency of greater than say, 1%.
- The construction of flood risk protection works such as levees, also designed to withstand a certain flood frequency;
- Safety assessment of major dams, based on societal risk.
- Emergency planning and considering the level of immunity afforded to critical infrastructure, such as communication systems and evacuation routes.

The aim of the methodologies is AEP neutrality, that is, a rainfall event of a particular AEP produces a flood event of a similar AEP.

SunWater has undertaken research into a number of events where there has been a significant inconsistency between the AEP of the rainfall event and the apparent AEP of the associated flood. In two cases, design dam safety measures were close to automatic triggers. This inconsistency has significant implications for communities regarding their level of exposure to flood risk in that it may be far higher than is understood. The consequences of understated risk could lead, in the event, to greater damage, the failure of emergency plans and, most importantly, potential loss of life.

SunWater has identified that there are a number of possible deficiencies in design methodologies, and the understanding and application of those methods by practitioners.

This paper explores these possible deficiencies including:

- The appropriateness of assumptions and data sets used in the development of design methodologies and errors potentially introduced. This includes the limitations of historic storm events used to develop Probable Maximum Precipitation (PMP) estimations and their representation of intensity.
- The application of methodologies by practitioners in a prescriptive manner , without considering appropriate sensitivity analysis around issues such as the uncertainty of the AEP of the PMP;

Callide Dam Flood of Record

The trigger for the investigation on which this paper is based was the significant rainfall event in 2015 associated with Tropical Cyclone Marcia (TC Marcia) in the Callide Valley. TC Marcia passed over Callide and Kroombit Dam catchments (Figure 1) resulting in record floods in both.

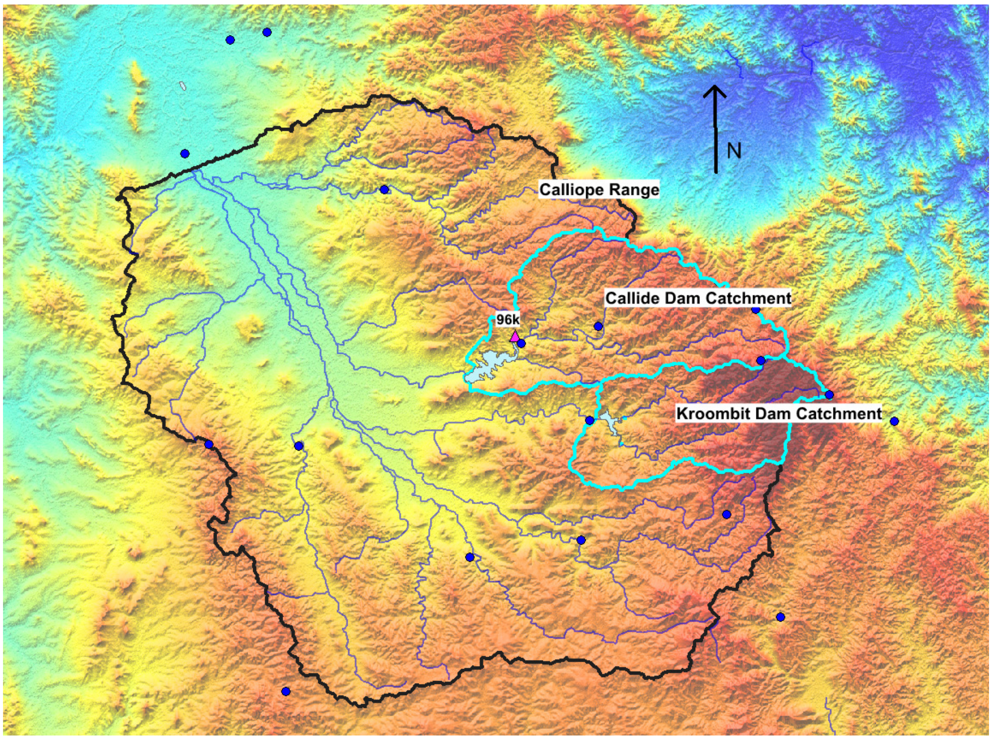

Figure 1 Callide and Kroombit Dams (Rain gauges in blue)

The critical design storm duration is assessed as 6 hours. The event lasted around 24 hours over the catchment although some point locations received rain for a total of 48 hours. Operational and post event modelling was complicated by the highest rating curve ordinate having been exceeded, in the event, by over 2 metres and the need to use relatively low storage parameters. The catchment rainfall temporal pattern is shown in Figure 2.

SunWater assessed the rainfall as having around a 1:200 – 1:500 Annual Exceedance Probability (AEP). An independent review reached the same conclusion[1]. An examination of the design hydrology report[2] showed the peak lake level had an AEP of the order of 1:4000. This inconsistency presents a significant problem. The 200-500 year rainfall resulted in lake levels that were 2 cm below automatic emergency structural preservation measures being triggered.

An investigation was initiated through the SunWater Portfolio Risk Assessment process in 2015 into this inconsistency and its implications. This is ongoing at the time of writing but has focused on researching other similar rainfall events, design rainfall methods and their implementation.

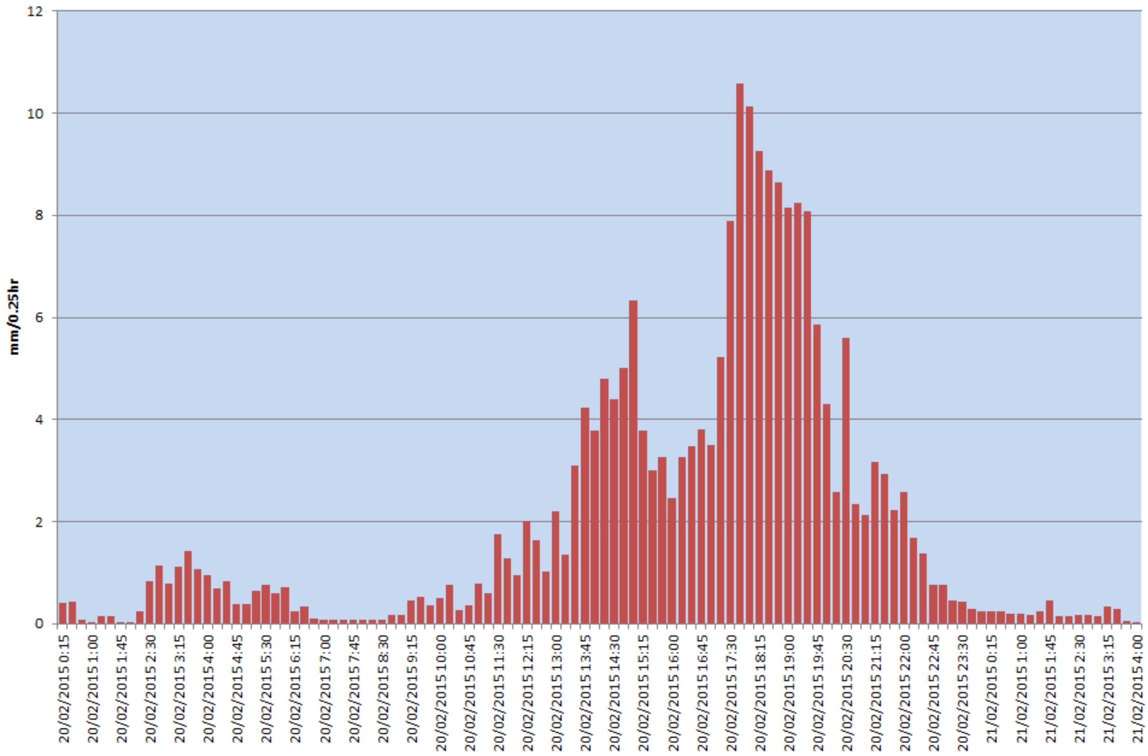

Figure 2 Callide Dam Catchment Rainfall Temporal Pattern

Other record dam flood events

The inconsistency between the probability of rainfall and consequential lake level was not unique to the TC Marcia event; it was also observed in the following two events.

North Pine Dam, Qld, 2011

North Pine Dam (north of Brisbane) experienced a similar event on 11th January 2011. Preliminary post event analysis in the operational report[3] estimated that the event was of the order of 1:9000 AEP in terms of lake level with an inconsistent rainfall estimation of 200 years AEP.

Four similarities with the Callide experience were obvious: the catchment area, the rainfall temporal pattern with an intense period towards the end of the event (see Figure 3), both dams having gates and like Callide, modelling led to underestimation of volume and peak flow despite the low nature of loss rates.

In 2011, The Queensland Director of Dam Safety wrote to the Queensland Flood Commission of Inquiry stating that there had been “an apparent miscalculation of the risk of large floods in the dam catchment”[4].

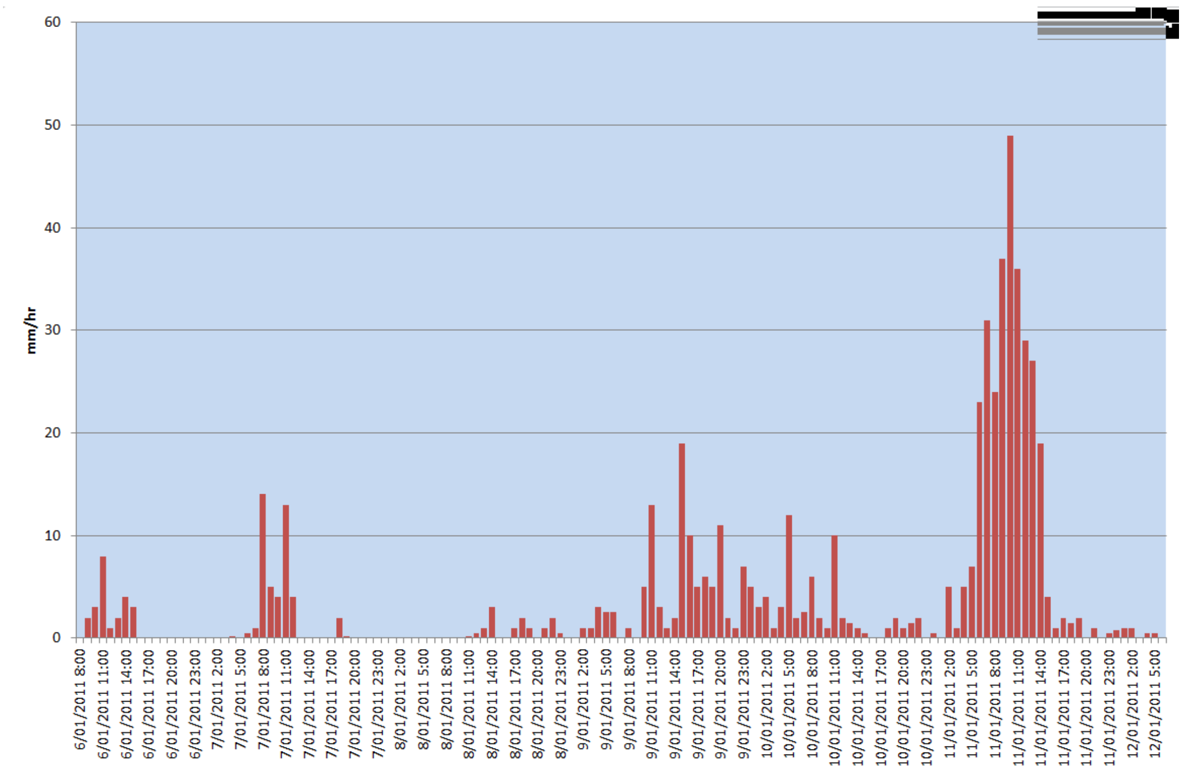

Figure 3 North Pine Dam catchment rainfall temporal pattern[3]

Wivenhoe, Qld 2011

Wivenhoe Dam (west of Brisbane) experienced a significant intense rain event on 11[th] January 2011. In contrast with Callide and North Pine, the event was relatively local to the dam but again, the most intense rain occurred after a period of rainfall in the catchment. The flood compartment of the dam had a significant volume already used. In a catchment of 7020km^2, the rainfall went largely unmeasured around the dam according to the SEQwater[5] report and was a major factor in the management of dam during the event.

The report describes 1:200 AEP catchment rain. Lake levels, in design terms, were close to the initiation of the emergency fuse plug, something, assigned an AEP of 1:6000. Radar echo shows the intense band moving south towards the dam (Figure 4), between 4am and 7am on the 11[th] January 2011. The type of convective rainfall stream shown is a significant feature in sub-tropical and tropical Australia.

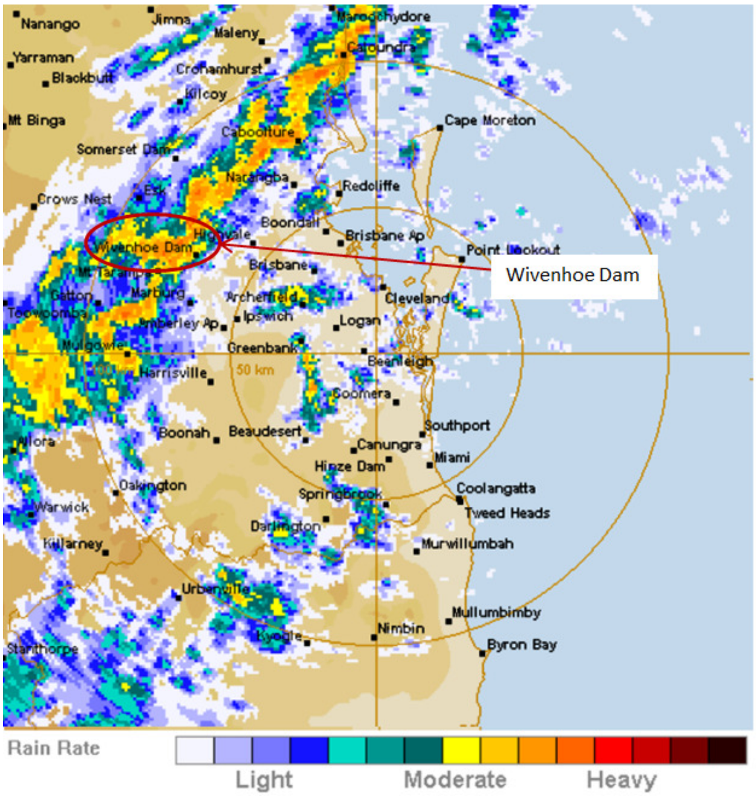

Figure 4 Wivenhoe Dam Rainfall, 6 a.m. 11th January 2011

Other flood events

Three additional events were researched in greater detail as distinct similarities with the above events were identified; the temporal pattern, record floods and reviews or judicial proceedings in all cases.

Briseis dam, Tasmania, 1929

The Briseis dam collapse remains only 1 of 2 dam failures causing fatalities in Australia. In his book[6] Brothers' home, John Beswick describes the rainfall temporal pattern "*Following unprecedented rainfall of 450mm in the previous 2 days, a deluge of 125mm in one and a half hours fell on the catchment area above the dam*" A jury put the cause of the disaster down to catastrophic rainfall.

Hunter Valley, NSW, 2015

In the Hunter Valley on 21st April 2015, very intense rainfall occurred. Around Dungog, catastrophic flooding resulted. At Tocal, the incremental minute rain data was captured by the Automatic Weather Station as shown in Figure 5. The peak intensity delivered 6.8mm of rain in 2 minutes (a rate of 204mm/hr) during a period when more than 52mm was delivered in 20 minutes. Significant damage was caused in the Tocal area as shown in Plate 1.

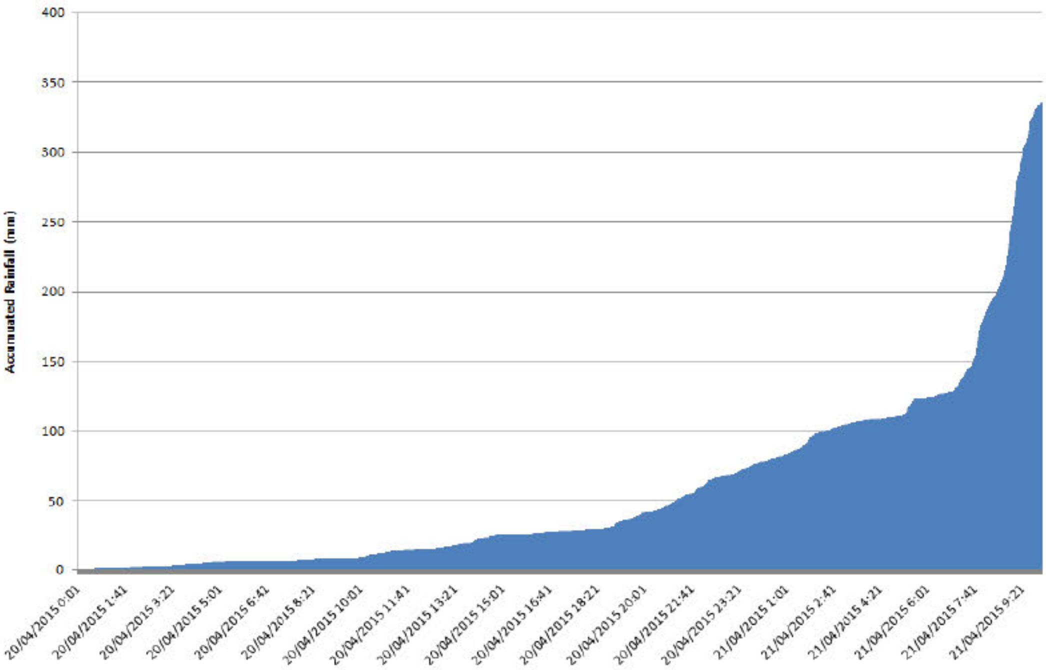

Figure 5: Tocal AWS accumulated one minute rainfall

Damage to the rail line near Tocal. PHOTO: Cameron Archer

Plate 1: Damage to infrastructure near Tocal, 21st April 2015

Deception Bay and Caboolture, Qld, 2015

On May 1st 2015, an east coast low led to intense rainfall around the Deception Bay and Caboolture areas just north of Brisbane. 350mm was recorded as a general event total in the immediate vicinity of the Hays Inlet catchment (80km^2) with 240mm in three hours[7]. The flooding along Hays Inlet was the subject of an independent review[7] concerning a major rail project under construction at the time.

In the Caboolture River catchment (355km^2), a catchment average total of 264mm in 36 hours was estimated using URBS modelling. The temporal pattern for the Caboolture catchment is shown in Figure 6. 87 mm was received prior to the increase of intensity above 5mm/hr. Peak intensity measured was 4mm in 1 minute (240mm/hr) at several locations.

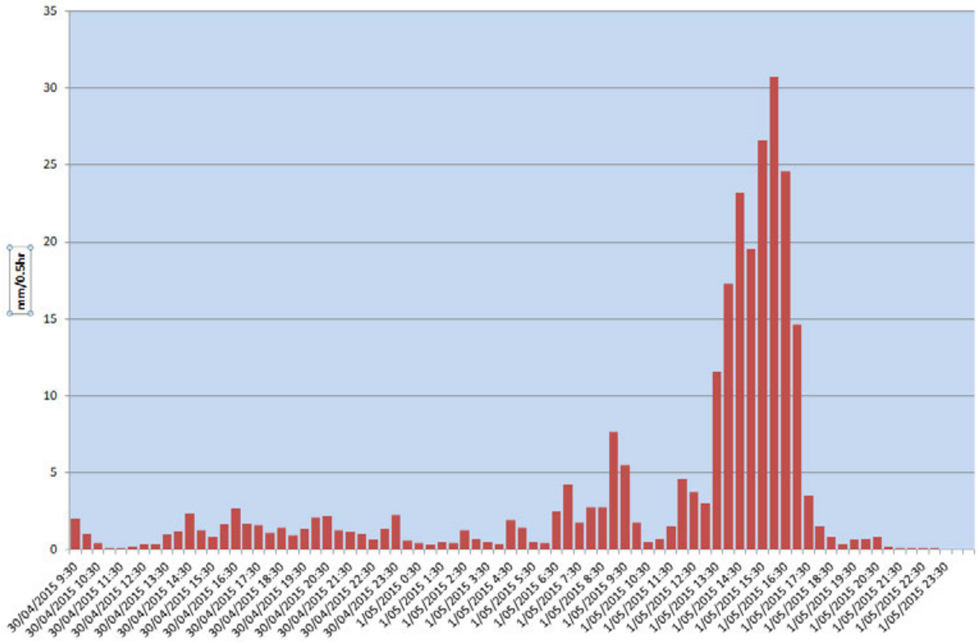

Figure 6: Caboolture River catchment temporal pattern, 2015 event

Similarities

A number of similarities are apparent from the above six events:

1. All catchment temporal patterns have a more intense period towards the end of the event when storages already had a significant volume above FSL or catchments were already wet.
2. Intense rainfall cells achieved levels at Callide, North Pine and Wivenhoe at which dam safety was becoming the overriding priority.
3. In two cases discussed, modelling predictions were unable to keep pace with the rate of rise. Adopted modelling parameters were different from those used in calibration events.
4. All events resulted in flooding of property,
5. Records floods at Callide and Wivenhoe are not the largest catchment floods known to have occurred prior to construction.
6. All events resulted in reviews or judicial proceedings

Based on these similarities, research for contributing factors was broadly grouped into three areas; Design rainfall methods including data inputs; application of those methods and lastly climate change.

Design rainfall methods and associated data inputs

Design methods used for the range of frequencies available to Engineers in Australia are summarised in Table 1. The focus for this study is in the range 2000 years to PMP as it is this range in which SunWater has a particular interest as a dam owner and operator.

<table>
<tr><th>Burst Duration (h)</th><th>Average Recurrance Interval (ARI)
2 to 100
years (Large)</th><th>ARI
200 to 2000
years (Rare)</th><th>ARI
2000 years to PMP (Extreme)</th><th>PMP (Extreme)</th></tr>
<tr><td>1</td><td rowspan="8">BoM (2013) design rainfalls
ARF
ARR Project 2 (2013)</td><td rowspan="7">CRC-Forge (2005)
ARF
ARR Project 2 (2013)</td><td rowspan="8">Interpolated using procedures Nathan & Weinmann,</td><td rowspan="2">Generalised Short Duration Method (GSDM) (2003)</td></tr>
<tr><td>6</td></tr>
<tr><td>24</td><td rowspan="5">Generalised Tropical Storm Method Revised (GSTMR) (2003)</td></tr>
<tr><td>48</td></tr>
<tr><td>72</td></tr>
<tr><td>96</td></tr>
<tr><td>120</td></tr>
<tr><td>168</td><td>Extrapolated CRC-Forge (2005)</td><td>Extrapolated GTSMR (2003)</td></tr>
</table>

Table 1: Design methods summary (modified from Aurecon8)

There will undoubtedly be discussion about whether it is appropriate to compare burst theoretical events with actual, observed events. This is the first issue. If we are unable to compare design methods for levees and dams with those through which they need to survive, this suggests, as an industry, we have a problem. Effectively, what's being inferred in such discussion is 'it's not designed for such a situation'. If it's not appropriate, how can we properly operate and manage our assets with storms that don't fit the design methods? There will always be variability in flows for any estimated probability. The issue is one of acceptable variability. Is a 9000 year design level from 200 year rainfall acceptable variability?

Informal conversations during the preparation of this paper have suggested that analysis should solely consider the most intense part. To discard the rain in the lead up period is, in the view of the writers, not credible.

The issue is summarised in Figure 7. At 355km^2, the Caboolture catchment fits into the GSDM[9] and theoretically requires comparison to a 1 - 6 hour storm. As the event was around 48 hours, this is not possible. Comparing the storm pattern with the GTSMR derived patterns for larger areas is not really appropriate but has been carried out to demonstrate the significant variability of actual storms against derived temporal patterns.

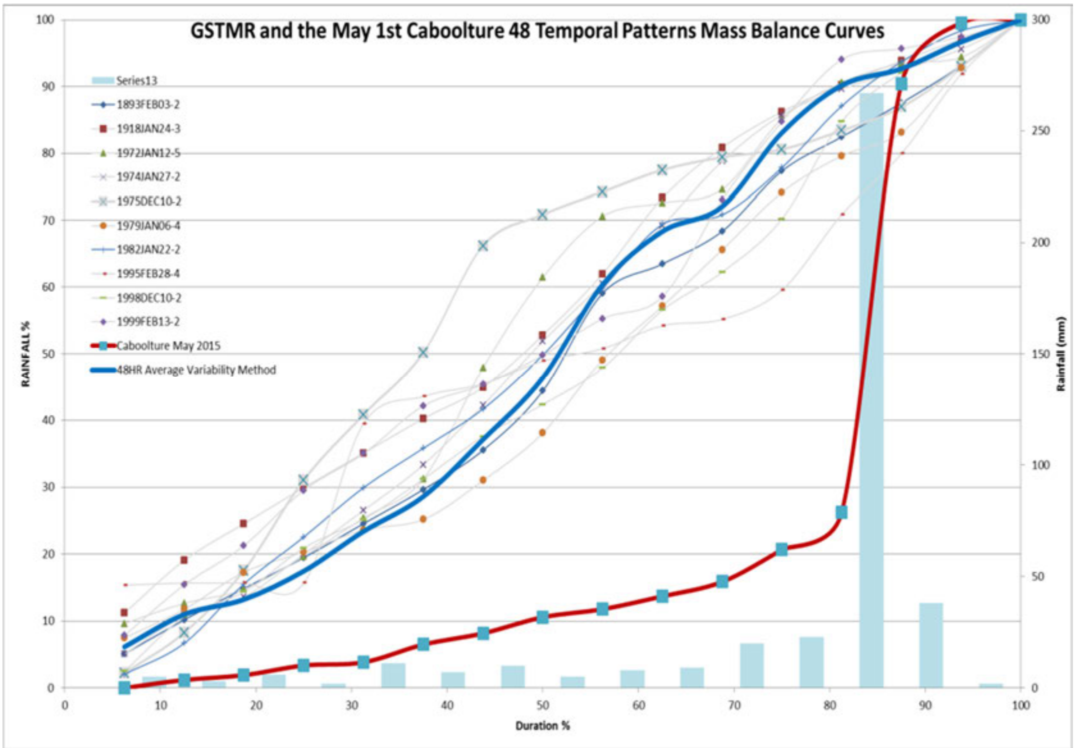

Figure 7: Caboolture storm 48 hour rainfall temporal pattern compared to GTSMR

The methodology behind the GTSMR for catchments greater than 1000km^2 is described in Hydrology Report Series number 8[10] (HRS8). A key feature is to "adopt an AEP-neutral approach where the objective is to derive a flood with an AEP equivalent to its causative design rainfall" In order to achieve this, the forerunner to the GTSMR used the Average Variability Method (AVM) which was subsequently adopted in the GTSMR. This results in temporal patterns for which %rainfall is broadly the same as the associated % of storm as shown in Figure 7. The method was constructed with dam owners in mind, so the observed inconsistencies suggest there may be issues with the approach. Adding to the complexity is that design rainfall from methods intended to estimate more frequent events achieved these extreme levels. AVM temporal patterns appear to be at markedly different to observed patterns. Extremes are not average. Appendix 1 shows 8 such patterns from Australian flood events and those from overseas.

In order to assess probability for floods between 2000 year ARI and the PMP events, it is necessary to interpolate between these two points. The AEP of the PMP is needed as a prerequisite, to develop an anchor point. The method for assigning an AEP to the PMP is based on catchment area and is outlined in Book VI of Australian Rainfall and Runoff[11] (Book six) which gives the following comment:

"Laurensen and Kuczera concluded that at present there is no conceptually sound, defensible basis upon which to make recommendations for design practice. Therefore, the recommendation below must be viewed as interim pending the outcomes of ongoing research"

Book six goes on to state that "*the recommended AEP values plus or minus two orders of magnitude of AEP should be regarded as the notional upper and lower limits for the true AEP's"* and that *"the recommended AEP values should be regarded as the best estimates of the AEP's"*

As such, this is likely to be a significant contributor to the observed inconsistencies as a small change in the AEP can alter the frequency of any flood with an AEP less frequent than 1 in 2000, as shown in Figure 8. The effects are summed up by Nathan et al[12]; *"Changes in the AEP of the PMP by an order of magnitude or more can markedly alter the estimated risk of infrastructure failure due to flood loading; in some cases differences of this magnitude may alter the decision on whether or not to undertake expensive upgrading works."* added to this is the operation of dams with such uncertainty. Local authorities are planning community safety with the same uncertainty.

Book six also suggests that the coast of Queensland is subject to significantly longer storm durations than exist elsewhere. On this basis, the lack of a specific zone (removed in the current revision) may mean dams in this area having underestimated PMP as methods group the Queensland coast with other areas.

In a final note on methods, GSDM links critical floods on small catchment areas with short duration rainfall. This assumption would appear invalid based on the events discussed earlier. The important information for dam owners is related to the rainfall over the catchment area not the storm duration.

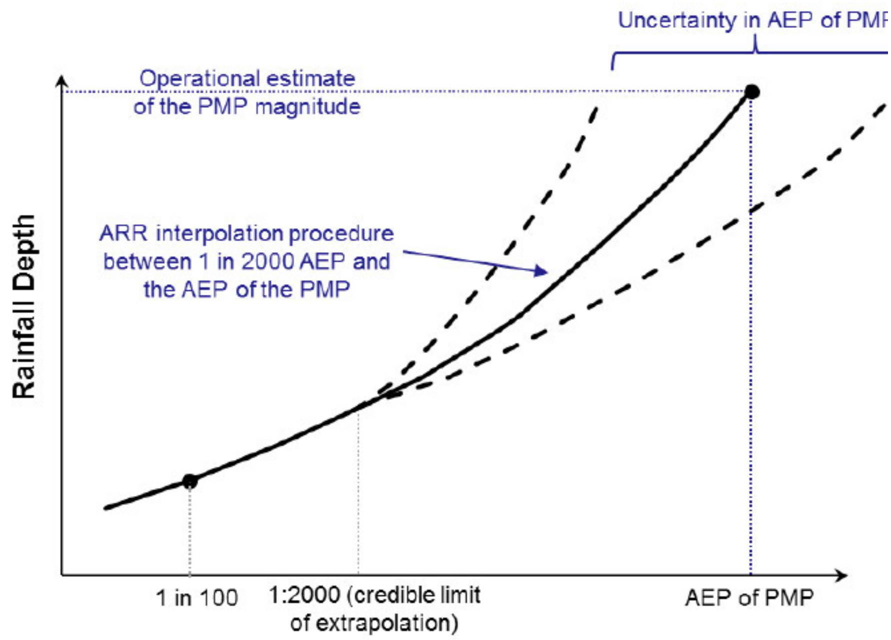

Figure 8: AEP of the PMP uncertainty (source Nathan13 et al, 2015)

Associated data inputs to design methods

GSDM contains data used from the United States and supplemented with data from five storms in NSW, Victoria and South Australia. The most severe of these, at Dapto in the Southern Highlands in 1984 delivered PMP estimates of 460mm over 6 hour for an area of 500km^2.

The lack of considered storms in Queensland presents a potential issue. 460mm over 6 hours in Queensland appears possible as a weather event. Records show 330mm was recorded at Clermont over 500km^2 in 6 hours[13]. The danger here is from the input data location making PMP in tropical areas being a possible event. Taking this a stage further, under current methods, this would then be assigned an unlikely probability based on catchment area. This is potentially a significant contributor to the observed inconsistencies on small catchments. In addition, the temporal pattern advice has been conceived from storms in Australia, none of which were from tropical events. Further investigation is ongoing.

HRS8 details depth data gathered from 122 storms from 92 rain events for use in the GTSMR. Storms were selected based on passing a threshold generated by the Intensity Frequency Duration curves from AR&R, 1987. Increments of area (e.g. 500km^2, 2000km^2) were allocated the 10 greatest storm depths in the data base and then an AVM temporal pattern was allocated from these 10 storms. In many locations only one station location was available to source three hourly temporal data, particularly for older storms in the database. Of the 122 storms considered, 37 have no temporal pattern at all, 19 have one temporal pattern, and 36 have one temporal pattern for areas less than 5000km^2.

The following comments can be made with regard to this method:

1. Smaller catchment areas are likely to be affected by a reduced availability of temporal pattern data compared with larger catchments as there is a greater chance any one of the storms used of only having one temporal pattern. Given the wide variety of temporal patterns evident throughout a catchment in any storm, this is unlikely to be representative. Table 2 below lists the top ten 24, 36 and 48 hour duration storms for 2500km^2 and 10000km^2 listed in Hydrology Report Series report number 9[14] along with the corresponding number of temporal patterns. The effect on the inconsistencies observed of potentially unrepresentative patterns being used is difficult to ascertain as we are unable to confirm how representative each temporal pattern is representative of a greater area.

2500 km^2					
24 hour top ten storms	number of stations used in 3 hrly temporal pattern	36 hour top ten storms	number of stations used in 3 hrly temporal pattern	48 hour to ten storms	stations used in 3 hrly temporal pattern
1893FEB03-1	1	1893FEB03-2	1	1893FEB03-2	1
1898APR03-2	1	1898APR03-2	1	1918JAN24-3	1
1954FEB21-1	1	1954FEB21-2	1	1963APR16-4	1
1955FEB25-2	1	1955FEB25-2	1	1972JAN12-5	1
1956JAN22-2	3	1963APR16-4	1	1974JAN09-3	2
1963APR16-4	1	1974JAN27-2	3	1974JAN27-2	3
1974JAN09-3	2	1974MAR13-4	5	1975DEC10-2	2
1974JAN27-2	3	1978JAN30-5	2	1979JAN06-4	2
1974MAR13-4	5	1982JAN22-2	2	1982JAN22-2	2
1989MAR14-1	2	1989MAR14-2	2	1995FEB28-4	2

10000km^2					
24 hour top ten storms	number of stations used in 3 hrly temporal pattern	36 hour top ten storms	number of stations used in 3 hrly temporal pattern	48 hour to ten storms	stations used in 3 hrly temporal pattern
1893FEB03-1	1	1893FEB03-2	1	1893FEB03-2	1
1898APR03-2	1	1898APR03-2	1	1918JAN25-5	1
1916DEC29-2	5	1954FEB21-2	2	1963APR16-4	1
1954FEB21-2	2	1955FEB25-2	1	1972JAN12-5	1
1955FEB25-2	1	1963APR16-4	1	1974JAN09-3	2
1956JAN22-2	4	1974JAN27-2	8	1974JAN27-2	8
1963APR16-4	1	1974MAR13-4	7	1975DEC10-2	5
1974MAR13-4	7	1982JAN22-2	6	1978JAN30-5	2
1976FEB09-2	1	1989MAR14-2	4	1982JAN22-2	6
1989MAR14-2	4	1995FEB28-4	2	1995FEB28-4	2

Table 2: 24, 36 and 48 hour top ten storms and associated number of temporal patterns used in associated AVM temporal pattern.

2. Three hourly time step temporal patterns used in GTSMR are likely to make design events less representative of real events because of a poor representation of intensity. To investigate this, peak intensity point rainfall rates were identified for two events, Tocal and Caboolture. The resulting average runoff during the period was calculated over three example areas. E.g., over 100km^2, 4mm in sixty seconds distributes 6667m^3/s. Each event was then assessed for average contribution over three hours assuming it were part of a GTSMR temporal pattern. The results are shown in Table 3 and demonstrate that intensity is not represented well by the GTSMR. In summary, this compares the reality with how GTSMR would represent such intensity. Such intense events provide challenges for dam owners and floodplain managers as they arrive with little warning and have little agreement with calculated design levels. This concurs with observed events and is identified as a cause of observed inconsistencies for areas of 1000km^2 or more.

Location	Date	mm	Minutes	Runoff (m^3/s) from 1Km^2	Runoff (m^3/s) from 10Km^2	Runoff (m^3/s) from 100Km^2
Tocal (AWS)	21/04/2015	6.8	2	56.6	567	5667
Caboolture (Short St)	1/05/2015	4	1	66.6	666	6667
Tocal (AWS)	N/A	6.8	180	0.62	6.8	62
Caboolture (Short St)	N/A	4	180	0.37	3.7	37

Table 3: Maximum intensity rainfall and resulting inflows if applied over 1, 10 and 100km2 – real time vs. three hourly.

3. Allocation of depth over area doesn't include any possibility of intense rain cells moving. Seo et al.[15] found that there was a significant change to peak flow and volume when events were associated with a moving storm, travelling at a slower rate than the travel time of the runoff. In summary, the movement of intense rainfall areas in a downstream direction of a catchment can produce extreme flood peaks. For dams such as Wivenhoe with a relatively linear, large surface area where travel time is very short, this may be an important consideration. It's easy to make a case that could link this with observed inconsistencies although more information would be required to assess the full impact in any of the cases discussed.

An assumption is included in HRS 8 that "the temporal variability seen in the largest events represents what would occur in a PMP" would seem appropriate. However, the temporal scale and effective use of point temporal patterns for many storms raise the question over whether it can be considered valid once applied to any catchment.

Method application

The following three factors were identified as having the potential to significantly alter modelled flood levels with regard to the application of design methods:

- The GTSMR guidebook[16] advises the following: *"Because of the uncertainties involved with deriving the design temporal patterns, especially at very small and very large areas and long durations (Walland et al., 2003) and in cases where* *the catchment or reservoir characteristics warrant special consideration, hydrologists should not discount temporal patterns other than the recommended single AVM design patterns."*

- The use of rating curves to calibrate events defines the timing and volume parameters that are used to model extreme events. During large events, many rating curves are already beyond the gauged limit or have related to looped ratings so may have significant uncertainty. To investigate the effect, a rating curve at a gauge used for model calibration was altered with 20% added to the final ordinate making 1200m^3/s instead of 1000m^3/s. The difference in estimated 10000 year lake levels between the calibrated models was 410mm.
- In a similar vain to the above, Book six suggests that the user should consider flood non linearity when calibrating model parameters as they can vary significantly with larger floods.

In order to ascertain any possible effects of the above on the observed inconsistencies, 15 studies have been analysed where 10000 year and Probable Maximum Flood (PMF) events had been modelled since 2005 for evidence that the above three factors had been considered. Studies were chosen at random from many organisations throughout NSW and Qld. In all 15 studies, no mention of any sensitivity analysis concerning temporal patterns, rating curves, or calibration parameter non linearity was found. This is no confirmation that such analysis wasn't considered although it would seem likely that such an investigation would have warranted mention in reports.

In a further observation, rainfall runoff appears to have become the sole method in the industry for estimating flood magnitude. The community and government are informed by these figures but it only details part of the story. As AEP neutrality doesn't appear to hold true for these methods, discharge and level frequency require estimation in addition, it is rainfall magnitude that is being used to benchmark flood events and therefore performance of structures and Engineers without consideration of all factors.

Climate Change

The impact of climate change is difficult to assess for any individual event, perhaps even more so in tropical areas. However, there are obvious links between more water in the atmosphere, more energy and therefore more extreme weather. The fifth assessment report[17] from the Intergovernmental Panel on Climate Change suggests medium confidence in increased extreme rainfall related to flood risk in Australia.

The ANCOLD guidelines[18] currently have no climate change guidance, nor do the Queensland Acceptable Flood Capacity guidelines[19]. The only comment that can be made is that what we have observed in some locations (see Figures 9) is what experts have warned in terms of more records broken and intense events.

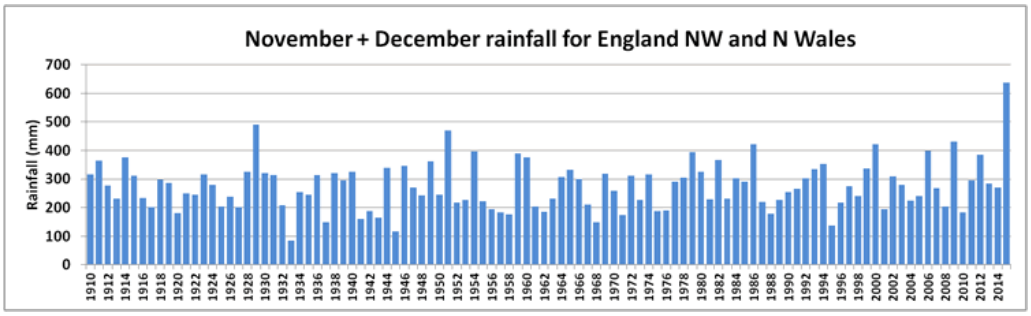

Figure 9: NW England and N Wales Rainfall totals 1910 to 2015. (source UK Met Office)

The need to discuss the impact of climate change, in the same way as modelling parameter sensitivity is an indication of the problem in itself. By nature of the PMP concept, climate change shouldn't require consideration. The potential use of feasible rainfall as a PMP in tropical areas when using GSDM and the lack of reasonable intensity representation when using GTSMR mean that it is possible climate change may have an effect on floods of less frequent than 1:2000.

Summary

The use of the PMP as an anchor point with an assigned probability that can vary by orders of magnitude could contribute significantly to variance observed.

The GSDM rainfall PMP depths may not be adequate in tropical areas due to the location of the storms used for input. In combination with assigning a very infrequent AEP based on catchment area and use as an anchor point for storm between 2000 and PMP, variation between resulting design levels and observed events could be expected on small catchments. Further work is needed.

The number of temporal patterns in many storms used in GTSMR was limited to a single station which may not be representative of a greater area. The effect on final results of this varying data set needs further work.

The observed inconsistencies are in contrast to the stated objective of the GTSMR to achieve AEP neutrality. In conjunction with this, intensity is poorly represented yet rain in tropical areas has the ability to deliver large volumes in a matter of minutes.

The application of guidelines in a recipe style approach without associated sensitivities has been demonstrated to have an ability contribute to the inconsistencies.

Implications for Emergency Management

The possibility of a flood level estimated to have a 1:10000 AEP (for example) having a much more frequent likelihood may be disastrous. A particular concern is related to the potential under-design of community safety structures. There are flood levees in

Queensland that use 100 year design levels for construction. Such events as observed could lead to levees being overtopped by orders of magnitude. Uncertainty around storm movement, depth and temporal variations along with calibration inputs need to be part of such designs to fully inform cost benefit decisions and emergency plans. More extreme lake levels can be expected from dams in eastern Australia with record gate discharges.

As an example, findings from a recent disaster exercise found a Council had received advice of 36 hours as a critical storm for a 1:100 event. The resulting levels, timings and velocities have been assumed as the worst case and used in disaster planning. The location, at the outlet of a small catchment may have as little as nine hours based on the type of event at Caboolture. Nine hours was deemed insufficient time to proceed with an effective evacuation by that Council. Advice provided based on the methods and their application means people are unlikely to be evacuated and may experience flood flows significantly higher than those planned for, with more damaging velocities. Existing GTSMR methods don't represent the intensity and therefore speed with which situations can develop in short periods in tropical areas.

Lessons can be drawn from the way such events behave at dam sites. Flat plains in valleys slow rapidly arriving discharge, effectively storing it, for a period. Applying methods that poorly represent intensity in these types of location may mean flood levels are underestimated to a greater degree than in catchments with a more average slope profile.

The final implication related to gauging station locations, now critical for emergency management. Many were installed for low flow monitoring. Reviewing the adequacy of monitoring infrastructure must be a priority.

Implications for Dam Operations and Asset Management

Events at North Pine Dam and at Callide Dam demonstrate the difficulty in operational modelling during large flood events once levels are above the flood of record. The runoff generated over small areas can be huge; modelling systems are generally not geared towards riverine flash flooding.

It is worthy to mention that all the rain events described ended in inquiries or judicial proceedings. It is no surprise that there are several gated structures involved. In such floods, gates open quickly to control the lake level resulting in rapid rises to record levels downstream.

To investigate the effects of different temporal patterns, 16 catchment temporal patterns were sourced from actual flood events around Queensland and simply replicated elsewhere. As catchment patterns, some implicit representation of spatial effects is present. The storms used are shown in Table 4.

The results for one of SunWater's dams with a small catchment are shown in Figure 10. Of greatest concern is the Clermont storm that results in a modelled metre of water overtopping an earth dam.

Catchment and event	Basin	Depth (mm)	Area (km^2)	Duration	Max (mm) in 1 hour	Source
Kroombit Ck to Dam, 2015	Fitzroy	228	338	18	56	SunWater
Boyne (Gladstone) to Awoonga Dam 2013	Boyne	728	2266	86	31	Bureau of Meteorology
Caboolture River to outlet 2015	Caboolture	296	355	38	57	Bureau of Meteorology
Cooya Creek to Cooyar 2011	Brisbane	346	258	86	42	Bureau of Meteorology
Don River to Bowen, 2008	Don	212	1038	42	39	Bureau of Meteorology
Enoggera Creek to Outlet, 2009	Brisbane	378	79	51	41	Bureau of Meteorology
Tocal area, 2015 (Hunter Valley)	Hunter	388	210	33	110	Bureau of Meteorology (climate)
Nogoa River to Raymond, 2008	Fitzroy	322	8374	231	16	SunWater
Ross River to dam, 2010	Ross	300	738	24	20	SunWater
Cattle Creek to Gargett, Mackay1958	Pioneer	820	340	48	58	BoM, flood data and 1958 rain analysis
Sandy Creek to Clermont 1916	Fitzroy	763	517	635	127	Qld Water supply Commission, 1970
Cameron Ck, Herbert 2009	Herbert	499	366	90	69	Bureau of Meteorology
Ross River to dam, 1998	Ross	762	738	46	28	SunWater
Ross River to dam, 2000	Ross	449	738	62	29	SunWater
Don (Rannes) River to Kingsborough, 2010	Fitzroy	310	747	94	33	Bureau of Meteorology
North Pine River to Dam, 2011	Pine	584	348	80	49	SEQwater report, 2011

Table 4: Storm data used for temporal pattern analysis

Next, design rainfall was investigated. As a recent event over a similar sized catchment, the Caboolture event temporal pattern was applied to rainfalls sourced from the existing design hydrology for the dam for 4 probabilities. Results estimate crest overtopping in any event larger than 1000 year rainfall (Figure 11). Methodologies have been mixed here using GSDM rainfall estimates over a 36 hour pattern but the object of the exercise was to demonstrate what may be possible. The current estimated probability of overtopping occurring is 108000 years. More sensitivity analysis is required by practitioners.

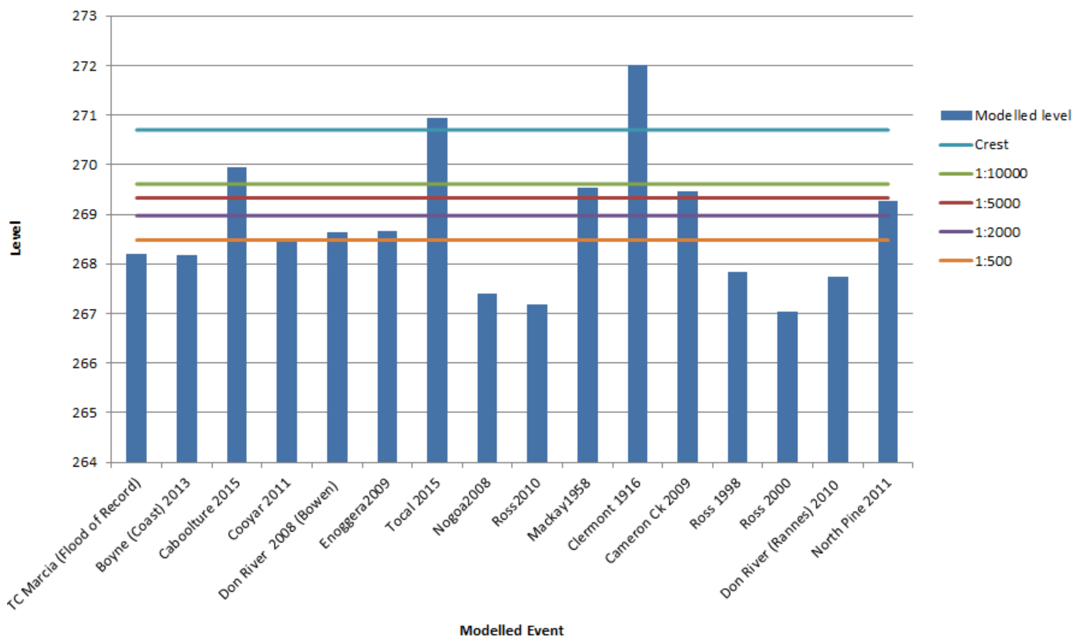

Figure 10: Modelled heights at a SunWater dam using observed storms

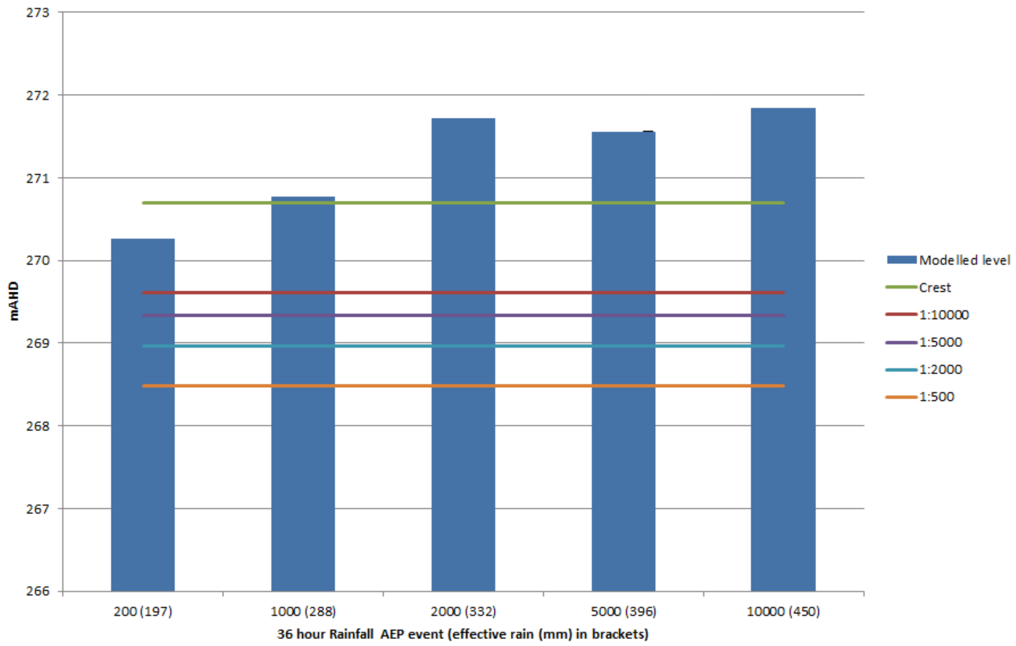

Figure 11: Modelled heights using design rainfall and observed temporal patterns

Implications for the dam safety programme centre on probability estimates. If these are uncertain by orders of magnitude, this has significant implications for any dam management programme. The probability is a key input to the societal risk reference guideline. As such, any change may well alter tolerability from acceptable to unacceptable with flow on implications for capital expenditure. Potential loss of life estimates are selected based on the design methods and their implementation, these are used to set monitoring frequency and categorise a dam.

Back ended temporal patterns mean sensitivity on antecedent reservoir levels is required. Assuming full supply level may not be appropriate in current methods.

Conclusions

There is strong evidence that the inconsistencies between design rainfall and observed lake level at Callide, North Pine, and Wivenhoe dams relate to design rainfall methods and their implementation. The use of the AEP of the PMP as an anchor for probability is a methodology that constitutes interim advice and has documented drawbacks. It is this advice that is input into dam upgrade programs. Simultaneously, and of greater concern, is the use of storm data unrelated to tropical areas, which raises the possibility of relatively frequent rainfall being given an implausible probability. This, in turn would affect interpolation of the AEP's between 2000 and PMP on small catchments. Further work is required.

In larger catchments, the use of the AVM for temporal pattern creation produces results/outcomes which appear to be in contrast to patterns associated with many actual extreme events with which our dams need to cope. The stated aim of selecting the AVM is to preserve AEP neutrality between rainfall and floods. Based on observed events, these methods require urgent review. Utilising such methods with three hour time steps, effectively re-distributes intense rainfalls over a longer time frame, resulting in a greater disparity than might be expected. Given the explosion of intensity data which has become available in recent years, three- hourly data used at the start of this millennium is no longer appropriate. Methods have in part become outdated by the digital/technological capacity to manage far finer time increments.

The apparent application of existing methods in 15 studies without regard to notified uncertainty is alarming. The uncertainty in model calibration parameters and in rating curves, in conjunction with significantly skewed temporal patterns together with potential inherent issues with design methods and inputs, all combine to generate a situation whereby such parameter and uncertainty consideration is imperative: it can make sizeable differences in modelled peak flood levels in storages. These same factors mean that consideration should be given to the effects of climate change.

It is worth noting that the plotting of these observed events is of an order comparable with the maxima observed on the planet (Figure 12) and that flows that would compare favourably with PMF design flows have been observed for comparably sized catchments elsewhere.

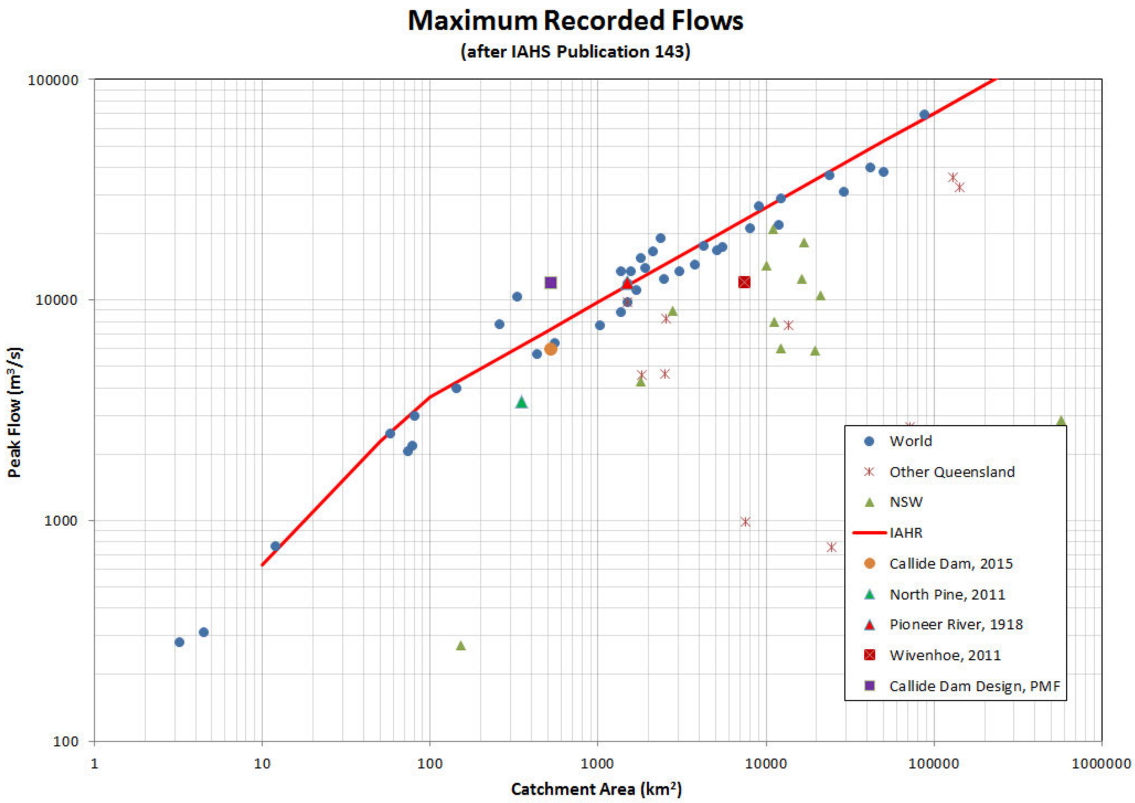

Figure 12[after20]: Maximum observed flows for Australia and the world and Callide Dam PMF

The implications for floodplain and emergency managers are potentially grave as structures may not have been designed to cope with such floods or planned for. Probabilities of 5000 year rainfall or less, for example, are understandably deemed unlikely, yet the resulting modelled flood has a significantly more frequent probability caused by the assumptions behind the methods and their implementation.

For dam owners and operators, the same applies. In design terms, uncertainty considered within the tolerable risk framework needs consideration along with a review of the adequacy of the methods. To this end, SunWater has initiated a catchment temporal pattern database to investigate how structures will cope under a range of conditions.

For anyone involved in floodplain management, it would seem prudent to prepare for much larger events. Given that operating rules are usually based on design floods, gated dams and smaller catchments are at greatest risk. The peak flows shown in Figure 12 would seem a reasonable place to begin preparation for future operations. The impacts of such disparities in densely populated suburbs will make world headlines. Flood estimation in tropical areas requires a unique method that is fit for purpose to ensure structures and communities have full knowledge of risk that utilises uncertainty of inputs.

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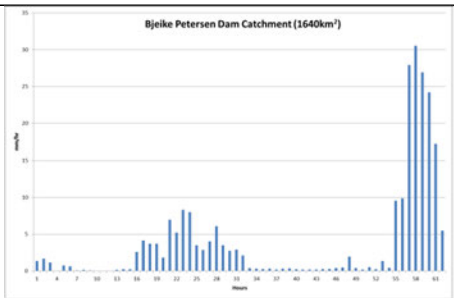
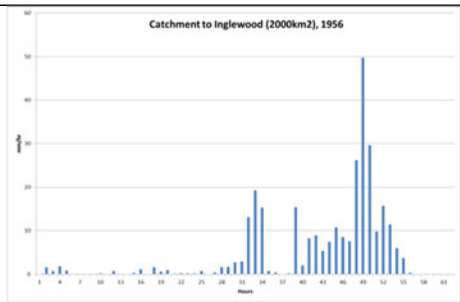
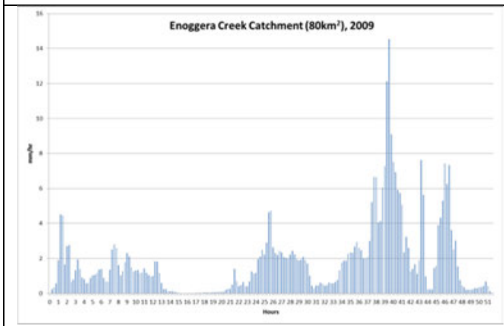
Appendix A: Catchment Temporal Patterns from eight significant flood events



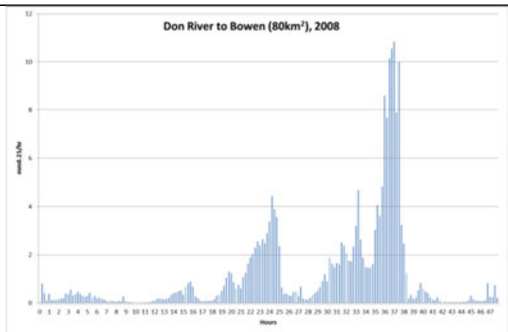
Bjelke Petersen Dam catchment, 2011. Record flood. The dam volume of 136000 ML could have filled from empty in 4 hours.



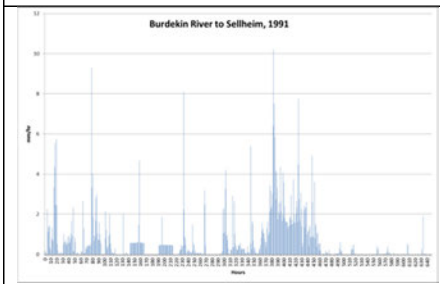
Catchment to Inglewood, 1956. Record flood, 3 metres higher than Engineers thought extreme.



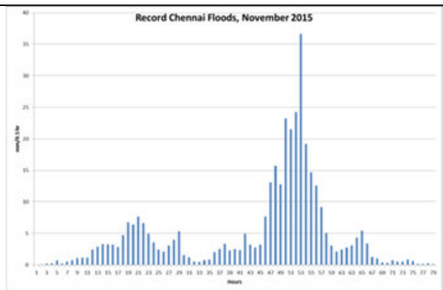
Enoggera Creek, 2009. 5th on record (many higher are backwater from Brisbane River)



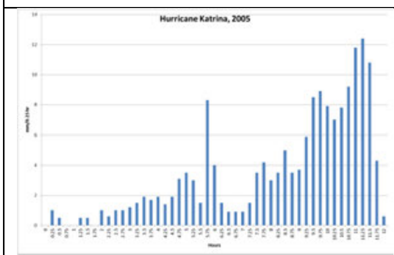
Don River, 2008. New Record at headwater locations, 4th on record at Bowen



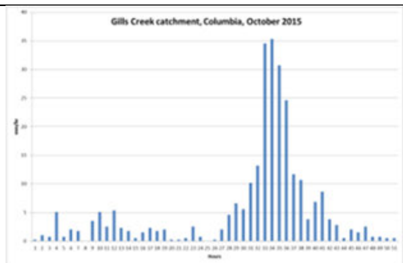
Burdekin River, 1991. Record flood at Burdekin Falls Dam. Catchment record remains higher pre-construction.



Chennai, India, 2015. (Estimated, Source NASA). Gated dam releases investigated.



Hurricane Katrina, 2005. (NOAA)



Gills Creek, South Carolina, 2015. 5 dams destroyed.(Richland County Emergency Services)