TEMPORAL RAINFALL – A RISK-BASED APPROACH

A Boldero (WSP Opus), Z Matar(WSP), Dr J McConchie (WSP Opus), S Warren (WSP Opus)

Recent hydrological modelling for a major project in Australia by WSP Opus has highlighted a number of differences in the flood modelling methodologies adopted between Australia and New Zealand. One significant difference was the use of a risk-based approach to temporal rainfall patterns to enable critical events to be identified. This is required by the latest issue of Australian Rainfall and Runoff (Ball et al. 2016). The use of a risk-based approach for hydrological modelling and design purposes is increasing throughout the Australasian stormwater industry. Specifically, the use of a sensitivity analysis for assessing the potential effects of climate change is already being requested by some Local Councils in New Zealand, and Australian Rainfall Runoff 2016 (ARR 2016).

Hydrological modelling in Australia and New Zealand has highlighted the importance of the temporal pattern of the design rainfall to the outputs from hydraulic models and calculations. This paper builds on that earlier work (McConchie & Belleville 2010) which noted *"The temporal pattern of the design rainfall needs to be accommodated within any rainfall-runoff model if it is to produce realistic hydrological outputs…the actual temporal distribution of storm rainfall at any specific location may be distinctly different to the generalized distribution. This will result in unique storm runoff which must be related to that of the design event.*

KEYWORDS

Hydrology, stormwater modelling, temporal rainfall patterns, ARR, risk-based approach

PRESENTER PROFILES

Andrew Boldero is a Senior Stormwater Engineer with over 20 years' experience in the civil engineering industry including over 10 years' within the water sector. Andrew's most recent experience is within the stormwater sector having managed a number of significant stormwater modelling and design projects within the Waikato region.

Zaki Matar is a Water Resources Engineer with 6 years of professional engineering experience. He has experience in Water Resource Management across Australia with a particular focus on hydrologic and hydraulic modelling. Since the publication of the ARR 2016, Zaki lead the implementation of ARR2016 on several major transportation projects.

1 INTRODUCTION

Recent hydrological modelling for a major road upgrade project in south-east Melbourne, Australia by WSP Opus has highlighted a number of differences in the flood modelling methodologies adopted between Australia and New Zealand. One significant difference was the use of a risk-based approach to temporal rainfall patterns to enable critical events to be identified. Temporal patterns are used to represent the varying rainfall intensities found throughout the duration of a storm event. ARR2016 is the recently revised Australian standard for hydrological and hydraulic modelling.

This paper summarizes the ARR 2016 methodologies and outlines the common approaches in New Zealand before discussing the differences and considers the ARR2016 approach for New Zealand.

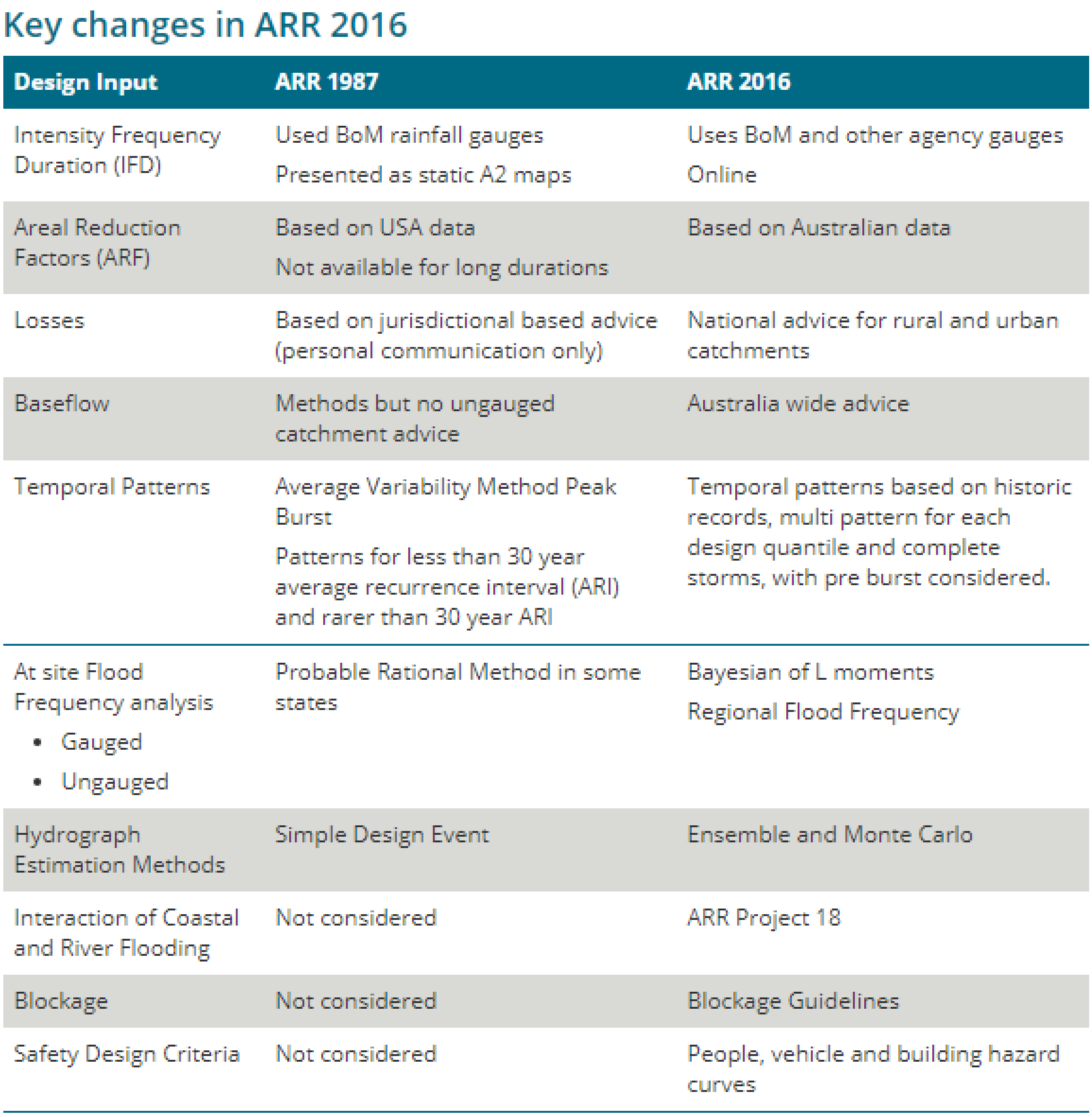
We described the ARR 2016 temporal pattern approach as 'risk based' as this methodology applies various temporal patterns to identify critical patterns within a hydraulic model. Whereas the New Zealand methodologies use various averaged, smoothed or nested temporal patterns. Critical temporal rainfall patterns are defined as resulting in a maximum parameter in the hydraulic model (ie flood level, extent or velocity). This is one of the fundamental differences between the New Zealand and Australian standard modelling methodologies, and the main focus for discussion of this paper.

This paper also briefly considers the variation likely to occur in implementing a similar approach to ARR 2016 by processing various Australian temporal patterns on an existing New Zealand based calibrated stormwater model. This comparison has significant limitations as it is only one sample, however it is the basis for additional discussions.

The purpose of this paper is to encourage further discussion on the use of a 'risk based' approach to using temporal patterns in New Zealand.

2 AUSTRALIAN RAINFALL AND RUNOFF (ARR)

ARR is a national Australian guideline for flood estimation which is administered by the Australian Federal Government through the organization Geoscience Australia. ARR has recently (2016) been revised with several changes to the derivation of design input used in runoff estimation. The changes are the result of several individual revision projects and the availability of over 30 years of additional climate data since the 1987 version. Key changes to ARR 2016 from ARR 1987 are summarised in Table 1.



Key changes in ARR 2016

Design Input	ARR 1987	ARR 2016
Intensity Frequency Duration (IFD)	Used BoM rainfall gauges Presented as static A2 maps	Uses BoM and other agency gauges Online
Areal Reduction Factors (ARF)	Based on USA data Not available for long durations	Based on Australian data
Losses	Based on jurisdictional based advice (personal communication only)	National advice for rural and urban catchments
Baseflow	Methods but no ungauged catchment advice	Australia wide advice
Temporal Patterns	Average Variability Method Peak Burst Patterns for less than 30 year average recurrence interval (ARI) and rarer than 30 year ARI	Temporal patterns based on historic records, multi pattern for each design quantile and complete storms, with pre burst considered.
At site Flood Frequency analysis • Gauged • Ungauged	Probable Rational Method in some states	Bayesian of L moments Regional Flood Frequency
Hydrograph Estimation Methods	Simple Design Event	Ensemble and Monte Carlo
Interaction of Coastal and River Flooding	Not considered	ARR Project 18
Blockage	Not considered	Blockage Guidelines
Safety Design Criteria	Not considered	People, vehicle and building hazard curves

Table 1: Key changes - ARR2016 compared to ARR1987 (source: http://arr.ga.gov.au/about)

2.1 BACKGROUND

Design temporal rainfall patterns in ARR 1987 were developed using a detailed application of the Average Variability Method (AVM) by Pilgrim et al (1969) and Pilgrim & Cordery (1975). The following text from ARR 2016 *(Babister et al. 2016, Book 2, Chapter 5, section 5.2.3)* discusses the AVM method:

The problems with the AVM method and other median or representative patterns is that it assumes the variability of actual patterns is much less important than their central *tendency. Such an approach does not account for how temporal patterns interact with catchments to produce peak flows and hydrographs. The response can be very catchment-specific, and there is no guarantee that a representative pattern will produce the medium response from an ensemble of patterns that properly captures the variability of observed patterns. These problems can become more pronounced when changes are made to the catchment response or storage characteristics.*

Issues arising from the AVM lead practitioners to question the concept of whether a single representative pattern is an appropriate design input. The development of Monte Carlo methods using observed patterns as samples has shown the value of using varied design temporal patterns as it considers an ensemble of patterns and the acknowledgement that each are equally probable outcomes.

This method applies to single bursts with a given storm duration and assumed that temporal patterns were independent of probability. This approach being probability neutral, nature tends to artificially enable specific durations to dominate (Retallic et al 2009). Other issues are that it only worked best when there was a dominant pattern in a catchment, as well as other noted issues such as embedded bursts and the need to filter embedded bursts. The development of Monte Carlo methods using observed patterns as samples has given rise to the value of using varied design temporal patterns, particularly because dominant patterns are not realistic. As expected, the effect of design temporal pattern variability was noted as most significant in catchments with large storage components (Phillips and Yu, 2015).

2.2 NEW TEMPORAL PATTERN CONCEPTS

Australian Rainfall and Runoff (ARR) 2016 has brought about considerable changes to the determination of design rainfall temporal patterns. Real-time pluviograph data collected across Australia since ARR 1987 show a wide variety of temporal patterns are possible for any storm duration (Babister et al. 2016). As flood estimation in urban catchments moves toward storage-based mitigation solutions, the relevance of testing a range of temporal patterns has grown in its importance. Figure 2 depicts the changes in modelling techniques between ARR 1987 and 2016.

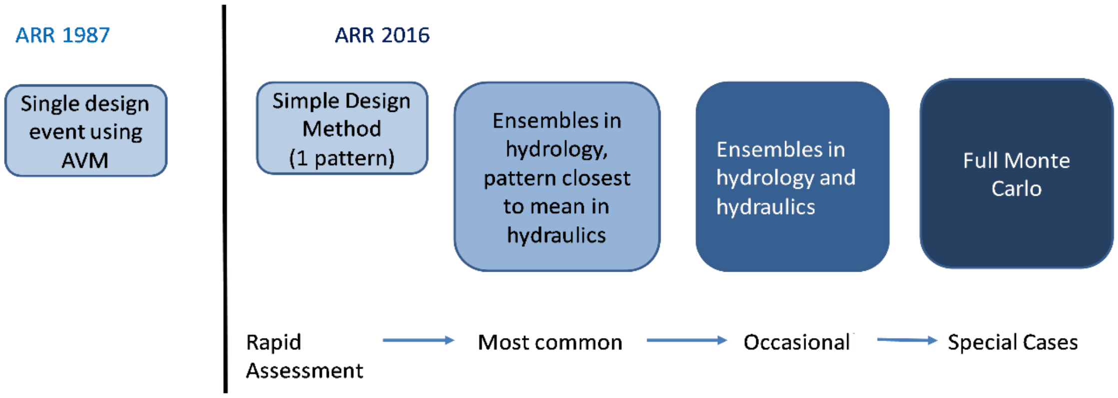


Figure 2: Changes in modelling techniques. Source: Coombes et al. 2016

In its consideration of temporal pattern, ARR 2016 has adopted the components of a typical storm event as shown in Figure 3, superseding the traditional 'single burst' methodology employed in ARR 1987.

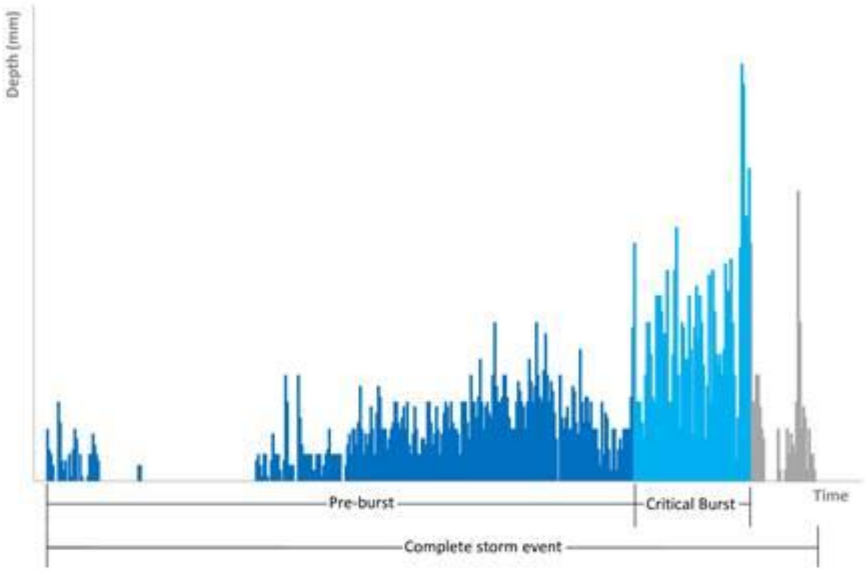


Figure 3: Typical Storm components. Source: Babister et al. (2016)

Babister et al. (2016) notes the importance of distinguishing between runoff during a complete storm and a specific burst. This is because typically in Australia, complete storms are used for calibration exercises whereas bursts are used in design. This is because the burst component (rather than pre or post burst) contains the main driver of peak flow, which itself is a key design parameter.

The Australian Bureau of Meteorology undertook an extensive review of Intensity-Frequency-Duration rainfall data across Australia. As part of this work, a pluviograph database containing a total of 2280 stations across Australia was produced.

Temporal rainfall patterns vary regionally across Australia and twelve temporal pattern regions have been defined (Figure 4). The regions follow key drainage basin boundaries and vary with 'burst loading'. 'Burst loading' is essentially a simple measure of when the heaviest part of the burst occurs, with categories labelled accordingly as front, middle and back loaded events.

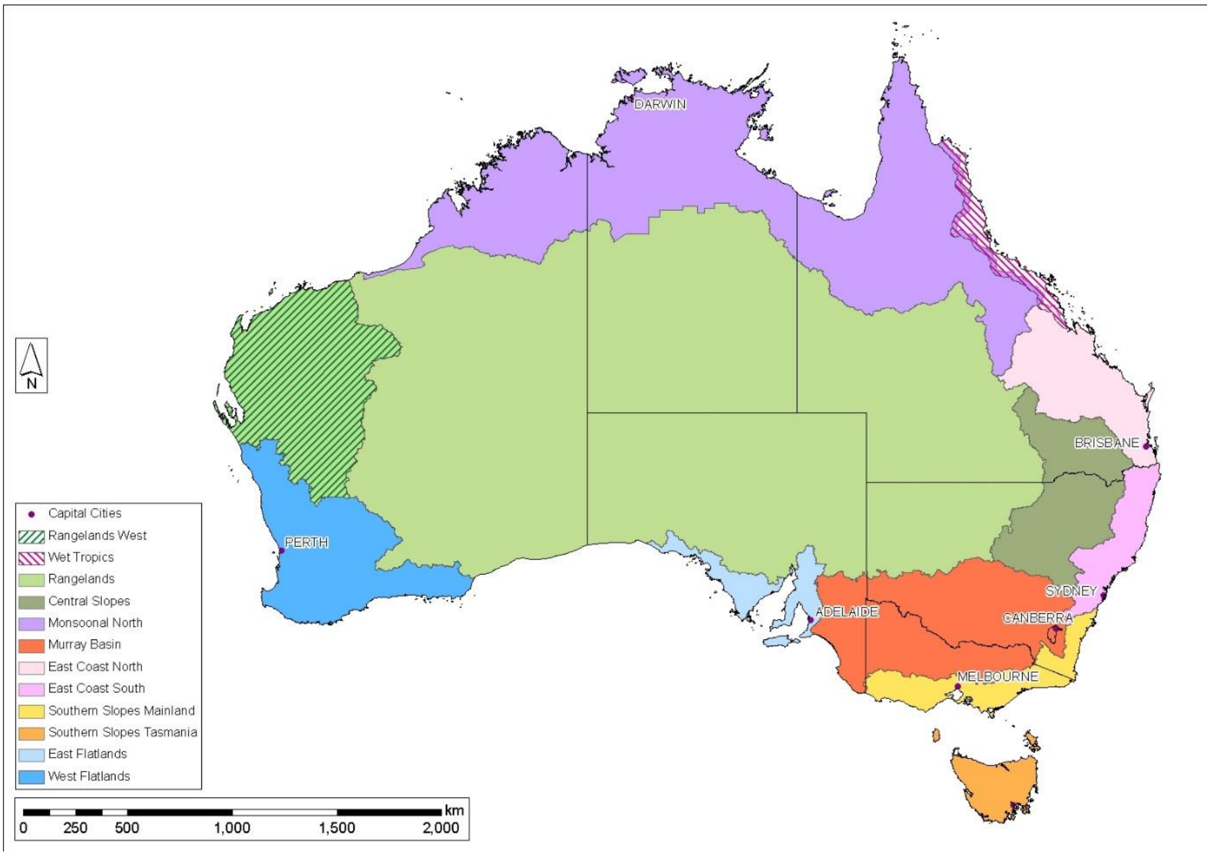


Figure 4: Temporal Pattern Regions. Source: Babister et al. (2016)

Design temporal runoff patterns across Australia were generated as part of a detailed study involving 35 test catchments (refer to ARR revision project 3 Temporal Patterns of Rainfall (WMAwater, 2015). This generated 10 ensemble temporal patterns per AEP, per duration and per temporal pattern region. Each ensemble contained carefully selected temporal patterns, based on consideration of several temporal pattern selection criteria.

Temporal patterns were extracted for the AEPs shown in Figure 5, for durations between 15 minutes and 7 days, as well as for the regions shown in Figure 4. Figure 5 shows the relationship between the AEP event and the 3 main groups of temporal patterns (ie for a 20% AEP the frequent type temporal patterns (x10) would be utilized).

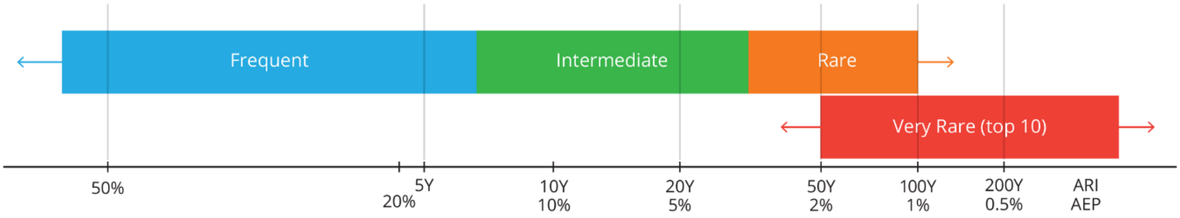
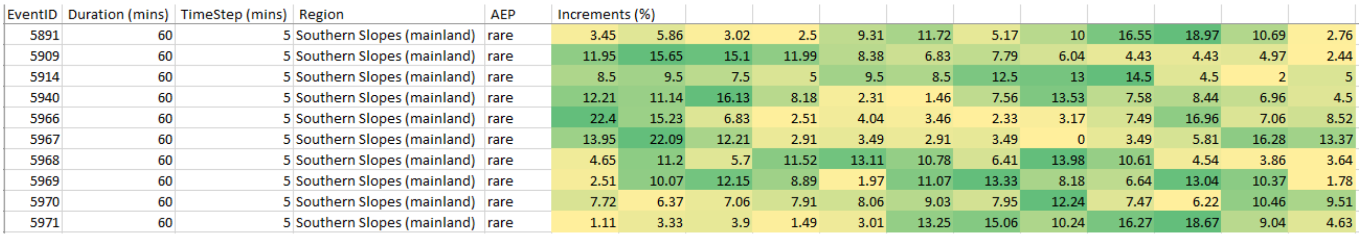


Figure 5: Temporal AEP Pattern Ranges. Source Babister et al 2016

The ensemble temporal patterns are available publicly and can be accessed through the ARR online data hub. An example of an ensemble temporal pattern file extract for the Southern Slopes Mainland Region, 1% AEP, 60 minutes duration is provided in Figure 6. In the figure, events 5909, 5966 and 5967 are each examples of front loaded temporal patterns whereas 5891 and 5971 exhibit back loaded features.



EventID	Duration (mins)	TimeStep (mins)	Region	AEP	Increments (%)											
5891	60	5	Southern Slopes (mainland)	rare	3.45	5.86	3.02	2.5	9.31	11.72	5.17	10	16.55	18.97	10.69	2.76
5909	60	5	Southern Slopes (mainland)	rare	11.95	15.65	15.1	11.99	8.38	6.83	7.79	6.04	4.43	4.43	4.97	2.44
5914	60	5	Southern Slopes (mainland)	rare	8.5	9.5	7.5	5	9.5	8.5	12.5	13	14.5	4.5	2	5
5940	60	5	Southern Slopes (mainland)	rare	12.21	11.14	16.13	8.18	2.31	1.46	7.56	13.53	7.58	8.44	6.96	4.5
5966	60	5	Southern Slopes (mainland)	rare	22.4	15.23	6.83	2.51	4.04	3.46	2.33	3.17	7.49	16.96	7.06	8.52
5967	60	5	Southern Slopes (mainland)	rare	13.95	22.09	12.21	2.91	3.49	2.91	3.49	0	3.49	5.81	16.28	13.37
5968	60	5	Southern Slopes (mainland)	rare	4.65	11.2	5.7	11.52	13.11	10.78	6.41	13.98	10.61	4.54	3.86	3.64
5969	60	5	Southern Slopes (mainland)	rare	2.51	10.07	12.15	8.89	1.97	11.07	13.33	8.18	6.64	13.04	10.37	1.78
5970	60	5	Southern Slopes (mainland)	rare	7.72	6.37	7.06	7.91	8.06	9.03	7.95	12.24	7.47	6.22	10.46	9.51
5971	60	5	Southern Slopes (mainland)	rare	1.11	3.33	3.9	1.49	3.01	13.25	15.06	10.24	16.27	18.67	9.04	4.63

Figure 6: Example temporal pattern output file (Colour variation applied to accentuate differences)

The hydrographs presented below are provided in chapter 6 of Book 9 of ARR 2016. For an urban catchment, it compares the application of the ensemble method (10 design rainfall events produced by applying ten temporal pattern variations) against a single design temporal event as per the ARR 1987 methodology (AVM). In addition to the wide variation in the shape of the hydrographs, peak flow estimates are also different across all curves.

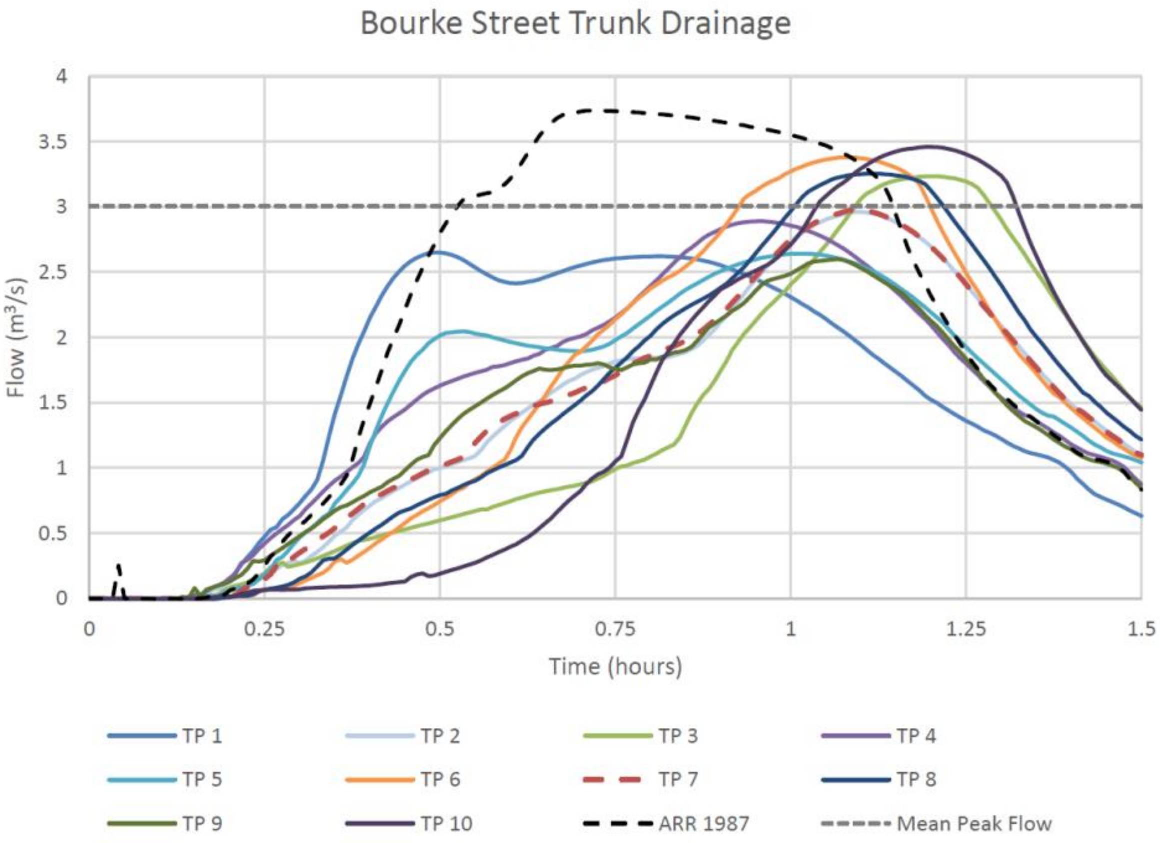


Figure 7: Example of Runoff from ARR 1987 Single Storm Burst and ARR 2016 Ensembles of Storm Bursts (1% AEP). Source: Coombes et al. 2016

3 NEW ZEALAND HYDRAULIC AND HYDROLOGICAL METHODOLOGIES AND TOOLS

The four major hydrological methodologies utilised in New Zealand are:

- Technical Publication 108 (TP108)
- Rational method
- Hydrological Simulation Modelling utilising empirical rainfall data
- Hydrological Simulation Modelling utilising HIRDs data set (short duration) or temporally adjusted distributions (long durations). For longer duration events these rainfall depths must be distributed temporally. This can be modelled using hydrological distributions provided in:
    - TP108
    - Probable Maximum Precipitation (PMP) New Zealand.

These methodologies, tools and temporal distributions are briefly summarised in the following sections.

3.1 RATIONAL METHOD

The rational method is a simple technique for estimating a design peak discharge from a small catchment area. It was developed by Kuichling (1889) for small drainage catchments in urban areas. The rational method provides peak flow discharge only (no runoff volume). As it does not use a temporal rainfall pattern it has not been considered further in this paper.

3.2 HYDROLOGICAL SIMULATION MODELLING

3.2.1 EMPIRICAL DATA

This methodology may be used when flow or rainfall data is readily available. This methodology allows results to be calibrated to actual flows or for recorded rainfall to be modelled. For this method to be suitable rain and/or flow gauges are required within or close to the catchment. This methodology has not been considered in further detail in this paper as it does not independently allow for design event consideration.

3.2.2 HIGH INTENSITY RAINFALL DESIGN SYSTEM (HIRDS) V4

In the absence of local data, design rainfall can be defined from a national database available in New Zealand. This data set is known as the High Intensity Rainfall Design System (HIRDS). HIRDS is a generalised procedure to obtain spatially and temporally specific depth-duration-frequency rainfall for ungauged locations in New Zealand. The latest version of HIRDS is version 4, was released in August 2018 and analysed empirical data up to the end of 2015.

The purpose of this work was to provide additional guidance as to likely temporal patterns of various durations for design hyetographs by climate regions across New Zealand. The new temporal pattern definitions have been separated into rainfall regions similar to the ARR2016, albeit smaller areas. These New Zealand regions (Figure 8) are North of North Island (NI), West of NI, East of NI, North of South Island (SI), West of SI and East of SI.

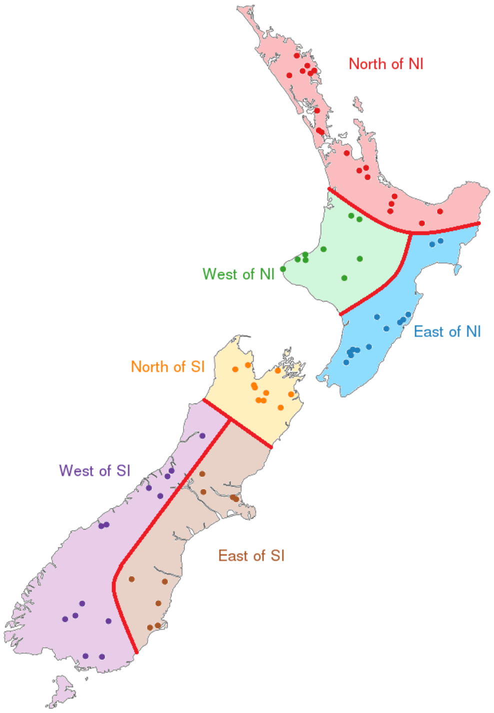


Figure 8: Location of rain gauges and climate regions (based map and gauge locations from HIRDS v4 - NIWA 2018). *Regions are indicative only*

To represent temporal rainfall patterns as a cumulative hyetograph HIRDS v4 has employed a non-dimensional asymmetric hyberbolic tangent function (HIRDS v4 - NIWA 2018). This is represented by the following sample graph (Figure 9).

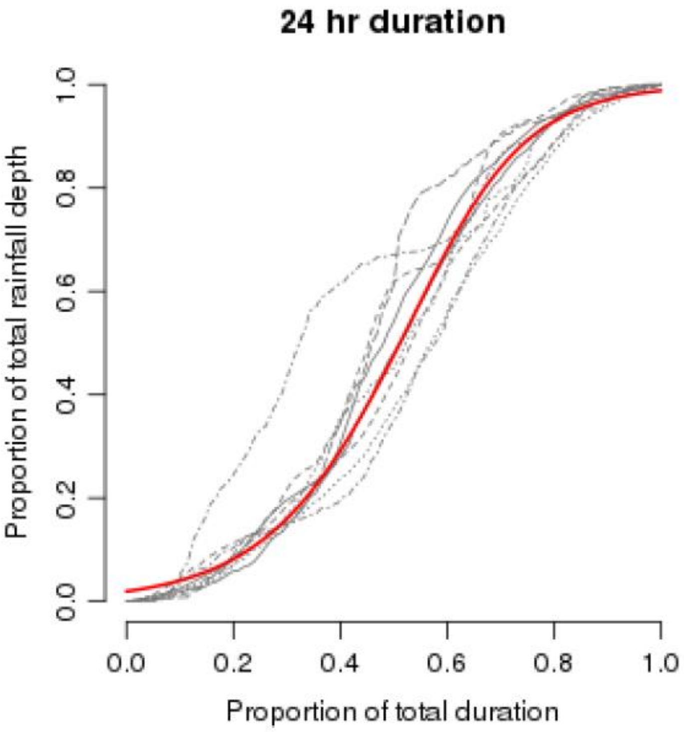


Figure 9: 24 hour fitted cumulative hyetograph (red line) South Island East Region. Raingauge observations shown by grey dashed lines.

3.2.3 PROBABLE MAXIMUM PRECIPETATION (PMP)

A temporal rainfall pattern is also provided for the PMP event over different durations for three regions in New Zealand (Tomlinson and Thompson 1992)

PMP is defined by the World Metrological Organization as: "theoretically the greatest depth of rain for a given duration that is physically possible over a given storm size area at a particular geographic location at a certain time of year under modern climate conditions"

3.3 TECHCNICAL PUBLICATION 108 (TP108)

TP108 is a recommended method for the application of the U.S. Soil Conservation Service1 rainfall-runoff model to catchments in the Auckland Region. It is based largely on Technical Release No. 55 (TR55) prepared by the U.S. Soil Conservation Service (SCS, 1986)

TP108 utilises a standard 24-hour temporal rainfall pattern, having peak rainfall intensity at mid-duration. Shorter duration rainfall bursts with a range of durations from 10 minutes to 24 hours are nested within the 24 hour temporal pattern.

The temporal rainfall pattern was derived statistically from rain gauge data representative of the Auckland Region. The model has been validated for relatively steep catchments in (up to 12 km^2) with minimal hydraulic storage.

This pattern as shown in Figure 10 consists of a highly peaked hyetograph.

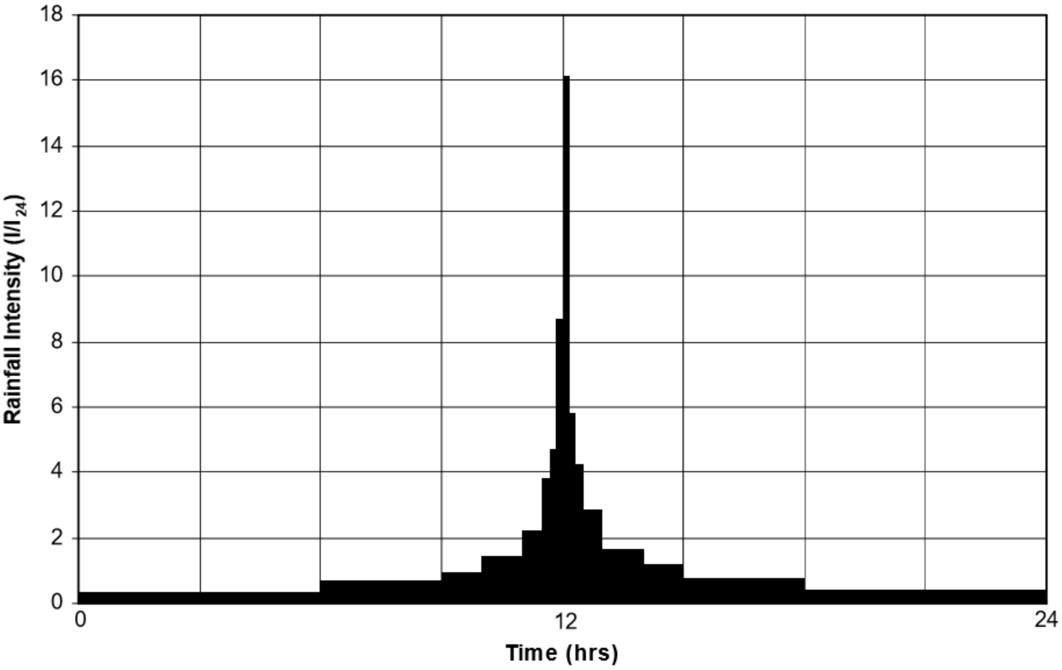


Figure 10: TP108 Temporal Distribution (Figure 2.1 from TP108)

3.4 NEW ZEALAND AND AUSTRALIAN HYDROLOGY COMPARISON

3.4.1 STANDARDISED METHODOLOGIES

The revised HIRDS v4 appears to be consistent with ARR 2016 in terms of rain gauge data processing and the use of climate regions. However, ARR2016 allows for multiple methodologies depending on complexity and risk (Figure 11).

Current New Zealand methodologies (including the recently revised HIRDS v4) do not include ensemble or critical event analysis. They are therefore comparable to the ARR1987 and 'rapid assessment' estimation methodologies (Figure 11).

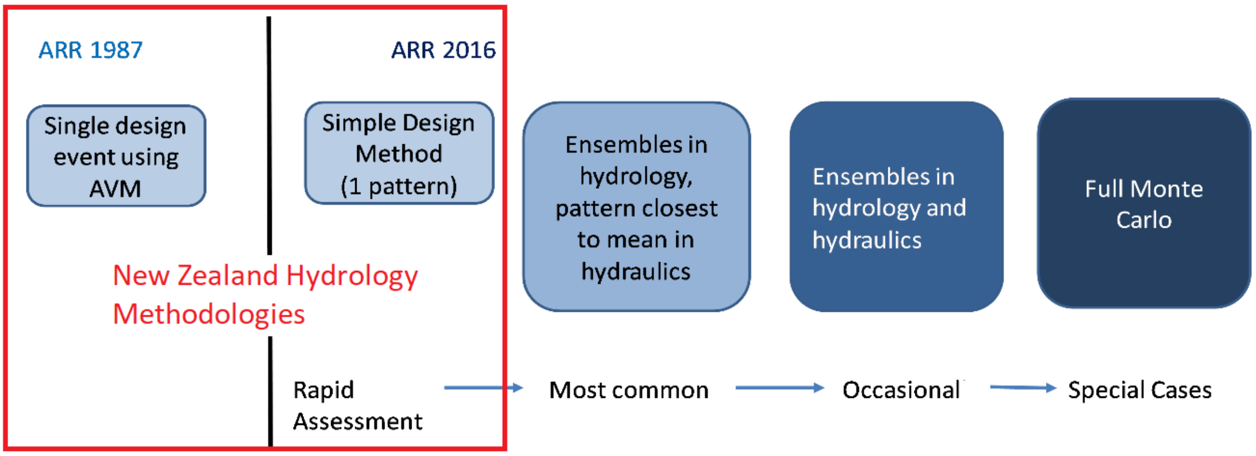


Figure 11: NZ methods compared to Australian (ARR1987 and ARR2016)

3.4.2 CRITICAL ANALYSIS (ARR 2016) – RISK BASED APPROACH

A large number of events in the ensemble patterns are clustered around the mean and median peak flow producing temporal patterns (Babister et al, 2016). As such it is common in Australian hydrologic modelling practice to select the a median or mean to then be used for design purposes which enables fewer model runs.

A further analysis of storm durations can be undertaken to determine a critical storm duration event. The critical storm duration in this context is defined as the event which causes the 'worst-case' of flooding in the study area in terms of modelled flood levels, velocities etc.

A variety of factors have the potential to vary the selected median temporal pattern or critical duration. Some key factors are listed below

- Size of the catchment
- The hydraulic characteristics of the model
- Storage within the catchment
- Annual exceedance probability

3.4.3 COMPARISON SUMMARY

The following table summarises the differences in hydrologic methodologies between Australia and New Zealand:

Methodology/ Parameter	New Zealand	Australia	Commentary
Temporal Pattern Derivation	PMP: Temporal Pattern derived from maximum precipitation calculation HIRDS: Temporal Patterns derived from rainfall data	ARR2016 Temporal Pattern derived from either Monte Carlo assessment or ensemble method (preferred), both from recorded rainfall data (ARR1987 utilised the AVM)	SIMILAR: Although slightly different methodologies the concepts are very similar in terms of utilizing recorded rainfall data to provide a temporal pattern distribution.
Number of Patterns used for an event per duration/intensity	1	10 initially Followed by the critical temporal pattern selection	DIFFERENT: Australian approach uses a 'risk based' approach with multiple temporal pattern outcomes considered.
Temporal patterns based on region	PMP: 2 + 1 mountainous regions allowance HIRDS: 6 (3 North Islandm, 3 South Island)	ARR2016: 10 + 2 tropical region allowances	SIMILAR: In terms of land area the Australian regions are significantly larger but are still based on similar climate area as per the New Zealand regions.
Rainfall Data	HIRDS v4 recently updated	Australian Bureau of Meteorology (BOM)	SIMILAR: BOM is similar to HIRDs rainfall (IFD generation based on location of gauged data)
Guidelines	Varys from Region to Region – no national compliance standard. District and Regional standards vary (ie Waikato/Auckland).	ARR2016 recently updated – Consistent country wide guideline with regionally varied temporal patterns	DIFFERENT: National guideline in Australia, but not New Zealand
Rainfall and temporal analysis timelines	PMP calculations completed in the early 1990s. HIRDS v4 updated 2018	Updated in 2016 previously 1987 (32 years apart)	SIMILAR: both countries have recently updated their temporal pattern analysis using current rainfall data
Losses/constants	Static	Initial/continuing loss model. Grid of initial and continuing losses derived for whole of Australia from prediction equations.	DIFFERENT: Australia adopts a region specific approach to determining Losses. Accordingly, losses are highly variable.

Table 12: Hydrological Methodology Comparison

4 NEW ZEALAND EXAMPLE UTILISING ARR2016 RAINFALL PATTERNS

A calibrated rainfall runoff model for an 18 km^2 catchment was used to illustrate the effects of the temporal distribution of runoff on the resulting flood hydrograph. The temporal distributions modelled were the TP108 and PMP. The resulting hydrograph for the model could be directly compared to flows measured just downstream of the model extent. The actual rainfall was also modelled when calibrating this rainfall runoff model.

After comparing the two New Zealand temporal runoff distributions (PMP and TP108) six temporal patterns from across Australia were applied (1% AEP). This was to evaluate potential fluctuations in the peak runoff between the temporal pattern derivation methodologies. The variance between the New Zealand rainfall patterns (TP108 and PMP) and ARR2016 are shown when comparing the following graphs (Figure 13 and Figure 14).

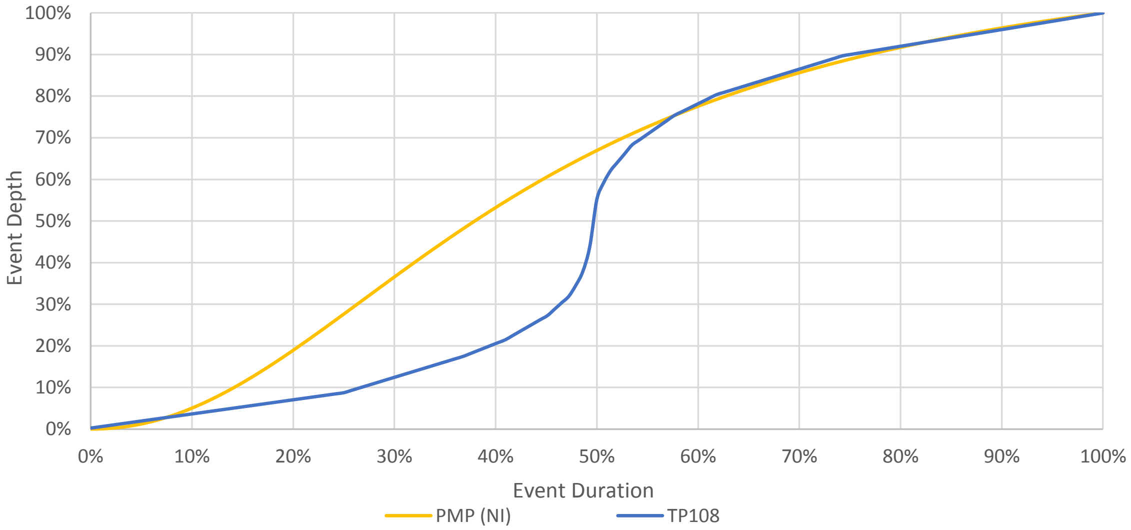


Figure 13: Auckland, New Zealand, TP108 and PMP Cumulative Graph

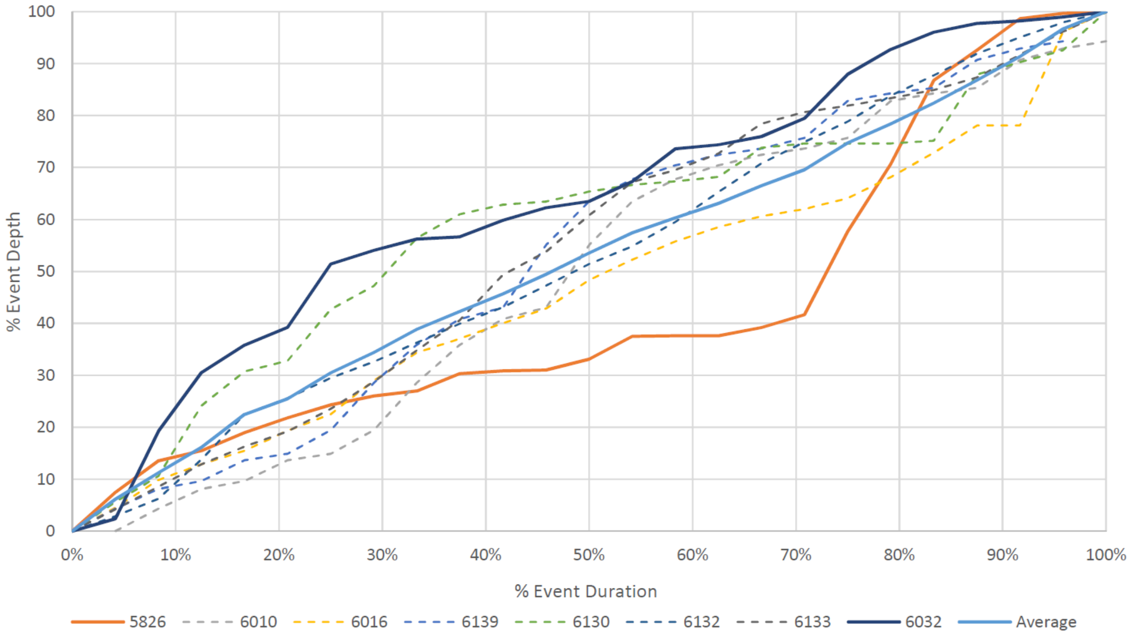


Figure 14: Melbourne, Australia Rare (1% AEP) Cumulative Graph

To enable a direct comparison to an averaged/smoothed Australian temporal pattern, the Melbourne rainfall patterns (ten total) were averaged to provide a singular smoothed temporal pattern. This was only to provide a very generalized indication as to how conceptual temporal patterns might affect the runoff results. Refer to Table 15 for the modelling results and comparisons.

Recorded Flow		**Recorded Rainfall**	**PMP**	**TP108**	**Sydney Temporal Pattern**		**Hobart Temporal Pattern**		**Melbourne Temporal Pattern**		
					6882	**6857**	**4719**	**4723**	**5826**	**6032**	**Average Melbourne Temporal Pattern**
Peak (m^3/s)	46.85	44.1	50	59.4	75.3	54.5	71.3	76.5	85.6	65.4	45.6
Volume (Mm^3)	1.52*	1.07	1.07	1.93	1.07	1.07	1.07	1.07	1.07	1.07	1.07
Peak flow % variance	Base	6%	7%	27%	**61%**	**16%**	**52%**	**63%**	**83%**	**40%**	**-3%**

Table 15: Modelling results table

Comparing the peak flows between temporal patterns located in Australia (ARR2016) identified significance variance (11%-45%):

- Sydney temporal patterns provide a peak flow variance of 45%
- Hobart (Tasmania) patterns provide a peak flow variance of 11%
- Melbourne patterns provide a peak flow variance of 43%

Averaging the 10 Melbourne temporal patterns into a singular pattern provided a peak flow of 45 m^3/s which was significantly lower than the two temporal patterns tested individually being approximately 85 m^3/s and 65 m^3/s (up to 48% reduction).

This test case indicated that we could potentially see significant variations across the different temporal patterns if we were to run multiple patterns prior to the averaging/smoothing being applied.

5 DISCUSSION: IS A RISK BASED APPROACH SUITABLE FOR NEW ZEALAND

The New Zealand example study in section 4 indicates that the smoothing of temporal patterns could have a significant effect on the results of any hydraulic model. If the temporal pattern shape has a significant influence on the hydraulic results, then this would suggest the less adjusted, the more representative the results would be. However, this is not enough evidence to say for certain if this methodology is suitable for New Zealand.

It is possible that ARR2016 does not provide significant advantages for smaller catchments, or catchments with certain characteristics that absorb the temporal fluctuations. However, its approach maybe more suitable than the current New Zealand methodologies for large complex catchments when a singular temporal pattern cannot represent all the critical events required to accurately assess the potential effects.

Additional analysis and modelling is required to ascertain the suitability of this method for New Zealand.

5.1 Conclusion

Although it is currently not clear if the risk-based approach for temporal pattern selection is suitable for New Zealand, there is a number of aspects of ARR 2016 that could be beneficial. These should be considered in more detail and tested under New Zealand conditions along with the ARR2016 temporal pattern approach. These are:

- An ensemble approach to hydraulic and hydrologically parameters/constants (ie. losses)
- A nationwide approach to modelling standards to allow consistency across the country but incorporate enough flexibility to allow for effective and efficient modelling to be undertaken (ie most common, occasional and special cases – ARR2016)
- A methodology that allows additional understanding of catchment(s) and rainfall characteristics could allow for a design process that enables specific risk management and resilience approaches.

The next stage in testing the ‘risk based’ approach is to obtain the un-refined temporal patterns from the HIRDS v4 (as shown in Figure 9 by the grey lines) to enable an ensemble temporal rainfall pattern approach to be undertaken to enable a comparison of the results.

ACKNOWLEDGEMENTS

Michael Howe (WSP)

James Reddish (WSP Opus)

REFERENCES

ARC (1999). Guidelines for stormwater runoff modelling in the Auckland Region.' TP108. Prepared for Auckland Regional Council by Beca carter Hollings & Ferner Ltd.

Thompson, C.S.; Tomlinson, A. I. 1993: Probable maximum precipitation in New Zealand for small areas and short durations. Journal of Hydrology (NZ) 31(2): 78-90.

Ball J, Babister M, Nathan R, Weeks W, Weinmann E, Retallick M, Testoni I, (Editors), 2016, Australian Rainfall and Runoff: A Guide to Flood Estimation, Commonwealth of Australia

Babister, M, Retallick, M, Loveridge, M, Testoni, I, and Podger, S, 2016. Rainfall Estimation, Book 2 in Australian Rainfall and Runoff - A Guide to Flood Estimation, Commonwealth of Australia

Coombes, P, Roso, S, and Babister, M. Runoff in Urban Areas, Book 9 in Australian Rainfall and Runoff - A Guide to Flood Estimation, Commonwealth of Australia

Dr J McConchie and R Belleville, Water issue 166 September 2010 'Smart Design Requires Understanding Rainfall' – Opus International Consultants Ltd.

Tomlinson and Craig S. Thompson 1992, Probable maximum precipitation in New Zealand: The development and application of generalised methods to provide nationwide estimates of PMP.

NIWA (2010), Probable maximum flood: guidelines for New Zealand

NIWA (2018), G Horrell, High Intensity Rainfall Design System – Version 4

ARR revision project 3 Temporal Patterns of Rainfall (WMA water, 2015)