DESIGN DISCHARGE ESTIMATION FROM URBAN CATCHMENTS – A COMPARISON BETWEEN ARR1987 AND ARR2016

D Fulton[1,2,3], R Chowdhury[3], J Alam[4]
[1]Bundaberg Regional Council, Bundaberg QLD
[2]GHD, Bundaberg QLD
[3]University of Southern Queensland, Toowoomba QLD
[4]JACOBS, Sydney NSW

Introduction

Australian Rainfall and Runoff (ARR) is a national guideline to assist engineers and practitioners in estimating design flood characteristics in Australia (Geoscience Australia, 2017b). *“ARR is pivotal to the safety and sustainability of Australian infrastructure, communities and the environment”* (Geoscience Australia, 2017b). The guidelines and data included in the 3rd edition of the guideline (ARR1987) have been used by the civil engineering industry for many years. However, since the development of ARR1987, there have been major advancements in technology, the availability of rainfall data, the industry’s understanding of rainfall patterns, ground infiltration characteristics and rainfall-runoff routing procedures. In response to these advancements, the 4th edition of Australian Rainfall and Runoff (ARR2016) has recently been released and includes recommended updates to flood estimation methods.

This paper presents a comparison of the practical application of ARR1987 and ARR2016 in the regional Queensland city of Bundaberg, focusing on three major updates within ARR2016 which are likely to influence the peak design discharge: updated intensity frequency duration (IFD) data, rainfall temporal patterns (including methodology for application) and climate change recommendations

Many industry stakeholders such as Bundaberg Regional Council and local engineering consultants are often not adequately informed of updates to Australian Rainfall and Runoff and the impact that these updates may have on existing infrastructure as well as the design and construction of new infrastructure. This investigation aimed to provide information, recommendations and expected outcomes resulting from the practical application of the new ARR2016 guidelines in comparison to the previous ARR1987 guidelines with a focus on the Bundaberg region.

More specifically, this investigation aimed to identify any general increase or decrease in the peak design discharge (and the magnitude of the increase or decrease) for urban catchments within the Bundaberg Region through adoption of the new flood estimation methods detailed in ARR2016. The peak design discharge resulting from the new ARR2016 methods and data was compared with the peak design discharge resulting from the flood estimation methods and data used over the past 30 years, detailed in ARR1987.

Background

IFD Data

As a result of an increase in available rainfall data and updated statistical methods, there are differences between the ARR1987 IFDs and ARR2016 IFDs. These differences vary spatially across Australia, across different durations, AEPs, and in some cases, result in differences greater than 30% (Green et al., 2014). The differences are either due to additional rainfall data that was not previously available or the more advanced statistical distribution methods (Green et al., 2015).

A direct comparison between the ARR1987 IFDs and ARR2016 IFDs for the Bundaberg CBD is shown below in Table 1.

Table 1 – Percentage Difference: ARR2016 IFDs to ARR1987 IFDs for Bundaberg CBD (April, 2018)

	AEP	63.2%	39.3%	18.1%	10%	5%	2%	1%
	ARI	1 Year	2 years	5 years	10 years	20 years	50 years	100 years
Duration	5 min	26.55%	19.86%	12.43%	12.44%	10.37%	8.10%	6.60%
	10 min	34.79%	27.68%	19.01%	19.38%	16.76%	13.76%	11.89%
	20 min	35.77%	29.54%	21.15%	21.37%	18.52%	16.46%	14.69%
	30 min	34.79%	28.15%	20.00%	20.55%	18.18%	16.28%	15.28%
	1 hour	31.83%	25.44%	18.02%	19.08%	17.49%	15.65%	14.72%
	2 hour	28.07%	22.03%	15.61%	17.02%	15.90%	15.11%	14.67%
	3 hour	25.29%	19.91%	14.38%	16.22%	15.46%	14.72%	14.40%
	6 hour	20.37%	15.49%	12.30%	14.81%	14.17%	13.40%	13.54%
	12 hour	14.94%	11.66%	9.09%	11.35%	10.71%	9.76%	9.36%
	24 hour	9.69%	6.74%	3.03%	4.57%	2.63%	1.42%	-0.61%
	48 hour	7.36%	3.15%	-3.73%	-4.19%	-6.94%	-10.41%	-12.89%
	72 hour	8.60%	3.14%	-6.28%	-8.26%	-11.75%	-16.27%	-19.49%

With reference to the above table, a positive percentage difference (blue) indicates an increase in the IFD data and a negative percentage difference (red) indicates a decrease in the IFD data. The above comparison demonstrates that for most design storm events, there is an increase in the design rainfall for the Bundaberg area of approximately 15-30%. The storm durations with a reduction in design rainfall are those greater than 24 hours which are unlikely to be critical for stormwater design in small urban catchments.

Temporal Patterns

Only a single burst temporal pattern was provided in ARR1987 for each zone and duration for two probability bins, developed using the Average Variability Method (AVM) (Testoni et al., 2016). However, according to Loveridge et al. (2015), this method is known to result in storm bursts that have higher temporal correlations than exist in real storm events. To capture the variability of real storm events within design temporal patterns, it was proposed to use an ensemble approach where multiple temporal patterns are trialled for a particular zone, storm duration and within a probability bin. ARR2016 therefore provides an ensemble of ten temporal patterns for twelve regions with four probability bins and 24 storm durations (Testoni et al., 2016).

An example of catchment peak discharge results using the ARR2016 temporal pattern ensembles is shown below in Figure 1. ARR2016 recommends that the mean peak discharge (represented by the stars in Figure 1) from the ensemble of ten temporal patterns should be calculated for each storm duration. The critical or peak design discharge for the catchment is the maximum of the mean peak discharges calculated for each different storm duration.

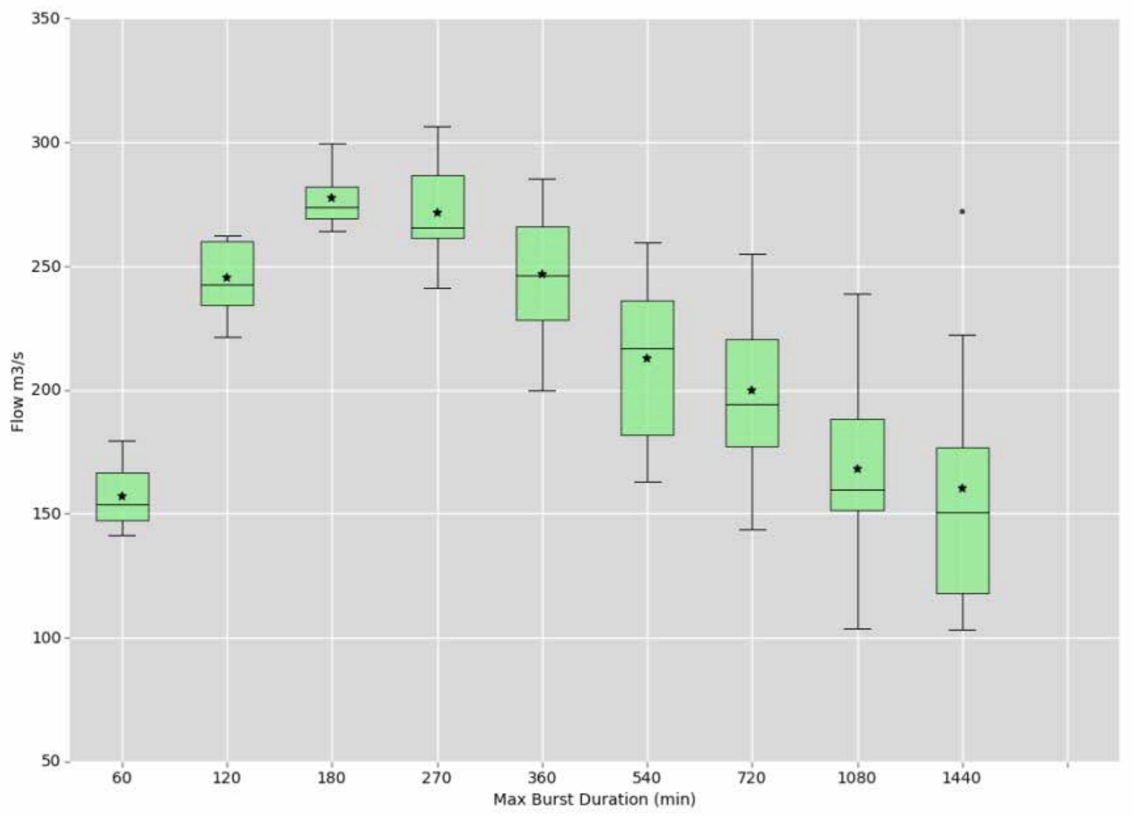


Figure 1 - Tenant Creek Catchment Results (Ball et al., 2016)

Climate Change

It is now widely accepted that human activity is contributing to climate change and that this has the potential to alter the prevalence and severity of rainfall extremes, storm surge and floods (Ball et al., 2016). While no recommendations for climate change were included in ARR1987, ARR2016 (Ball et al., 2016) adopts a risk-based approach to climate change based on the most recent climate science, particularly the CSIRO and Bureau of Meteorology projections for Australia.

The recommended climate change decision tree for design is shown below in Figure 2 and considers regional risks, effective service life or the planning horizon of the decision, the social acceptability, consequences of failure and the cost of retrofits (Ball et al., 2016).

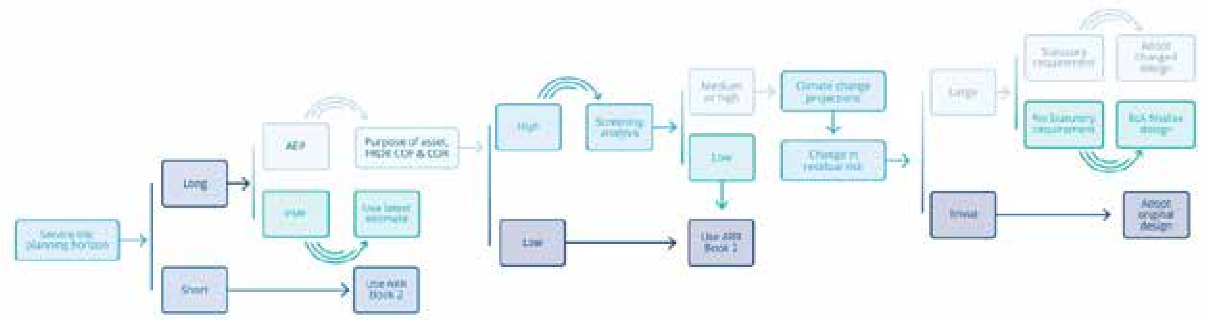


Figure 2 - Decision Tree for Incorporating Climate Change (Ball et al., 2016)

Hydrologic Modelling (XPRAFTS)

As stated within the Queensland Urban Drainage Manual (QUDM), XPRAFTS is a computer-based runoff-routing model used for the calculation of flood hydrographs, widely used for both rural and urban catchments (Department of Energy and Water Supply, 2013). In modelling the runoff from urban or partially urban catchments, a comparison of available runoff routing programs undertaken by Adams (1991) concluded that RAFTS (or XPRAFTS) is more appropriate than alternatives such as WBNM. XPRAFTS utilises the non-linear runoff routing method developed by Laurenson (1964).

The method developed by Laurenson (1964) involves considering each catchment as consisting of ten sub-areas with a concentrated, non-linear storage existing between each adjacent pair of sub-areas to conceptually represent the catchment storage effects. The equations and solution process originally formulated by Laurenson (1964), yet with some terminology altered to align with that used by XPRAFTS is demonstrated below.

For each individual sub area, the storage delay time K(q) is defined as:

$$K(q) = Bq^n \tag{1}$$

Where $K(q) = sub\ area\ storage\ delay\ time$

$B = storage\ delay\ time\ coefficient$

$q = discharge\ (m^3/s)$

$n = storage\ non-linearity\ exponent$

The storage function is defined as:

$$S = K(q) \times q \qquad (2)$$

Where $S = volume\ of\ storage\ (m^3)$

The storage function is used in the continuity equation in finite difference form:

$$(i_1 + i_2)\frac{\Delta t}{2} - (q_1 + q_2)\frac{\Delta t}{2} = S_2 - S_1 \qquad (3)$$

Where $i = sub\ area\ inflow\ (m^3/s)$

$q = sub\ area\ outflow\ (m^3/s)$

$\Delta t = routing\ period$

$Subscripts\ 1\ and\ 2\ refer\ to\ beginning\ and\ end\ of\ routing\ period$

Substituting (1) into (2) gives:

$$S = Bq^{n+1} \qquad (4)$$

This is the general non-linear runoff routing equation used within XPRAFTS.

Substituting (2) into (3) and solving through an iterative process provides a solution for the discharge at the end of the routing period (q_2).

The exponent ‘n’ is a measure of the catchment non-linearity and the coefficient ‘B’ is a measure of the catchment storage which increases with catchment area and decreases with catchment slope (Aitken, 1975).

Methodology

Investigation Sites

Six small urban catchments with a total catchment size of less than 5km^2 and an impervious area greater than 50% were selected from different areas within the Bundaberg region. The selected sites are listed below and their location is shown in Figure 3.

Site 1.	Avoca (City Vue Terrace)
Site 2.	Burnett Heads (Ocean Street)
Site 3.	East Bundaberg (Skyring/Eastgate Street)
Site 4.	Elliott Heads (Bathurst Street)
Site 5.	Millbank (River Terrace)
Site 6.	North Bundaberg (Jefferis Street/Fairymead Road)

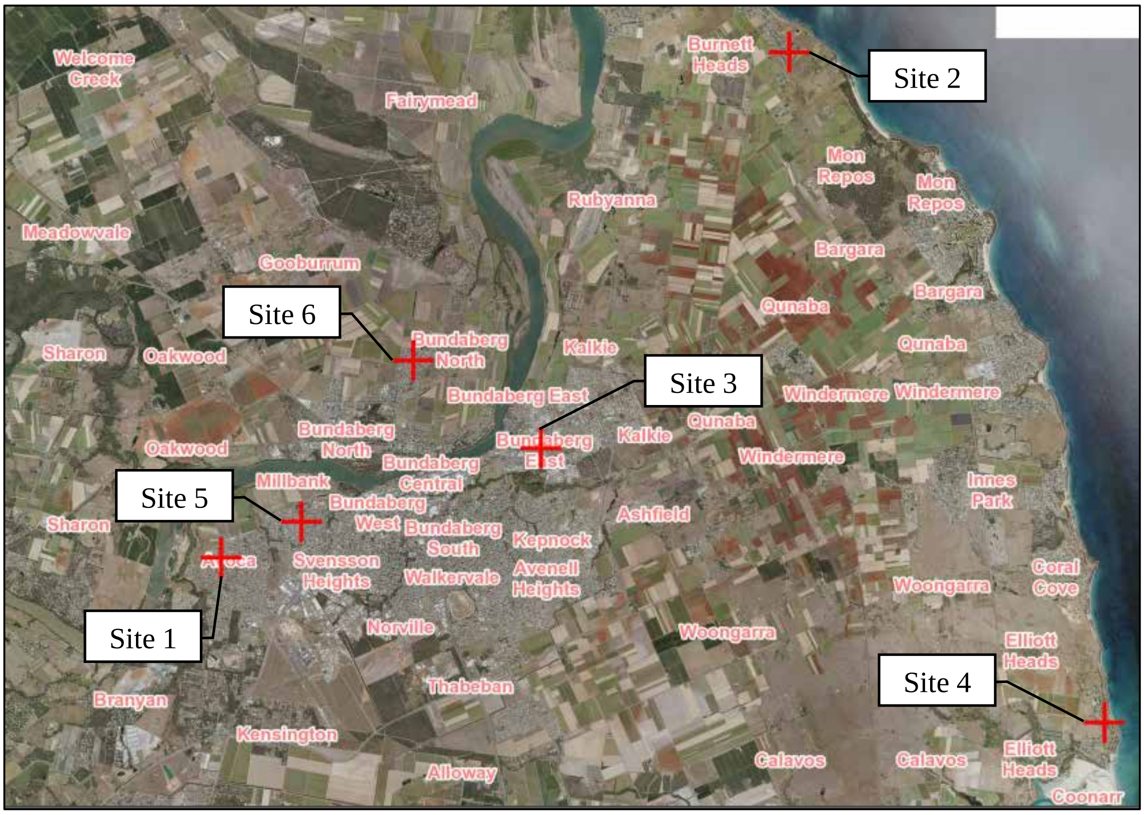


Figure 3 – Catchment Locations (Bundaberg Regional Council, 2018)

Each investigation site is primarily zoned as ‘low density residential’ in accordance with the Bundaberg Regional Council Planning Scheme 2015.

Model Data and Parameters

IFD Data and Temporal Patterns

ARR2016 IFD and temporal pattern data was downloaded from the ARR online data hub (Geoscience Australia, 2017a). ARR1987 IFD data was downloaded from the Bureau of Meteorology's web page (Bureau of Meteorology, 2017) and the ARR1987 temporal patterns were sourced from Chapter 3, Volume 2 of the 1987 document.

Aerial Imagery, LiDAR Survey & GIS Information

Bundaberg Regional Council supplied high resolution aerial imagery, LiDAR survey (1m grid) and GIS information for each investigation site. The provided GIS information included the existing stormwater infrastructure (sizes, types, locations etc) and other necessary information. The supplied LiDAR survey, aerial imagery and GIS information was used to delineate each overall catchment and the division of the catchment into appropriate subcatchments. The LiDAR survey was also used to determine the equal area slope for each of the subcatchments.

Other Design Details

To simulate a typical design scenario in Bundaberg, the design storms and model parameters were sourced from the Bundaberg Regional Council (BRC) Planning Scheme Policy for Development Works and QUDM where possible. The design storms and model parameters used in the investigation are shown below in Table 2.

Table 2 – Design Storms and Model Parameters

Design Storm AEP	Minor – 18% AEP (5 year ARI) Major – 1% AEP (100 year ARI)
Fraction Impervious	Low density residential = 50% Parks/Community Facilities = Aerial Photography
Initial (IL) and Continuing (CL) Losses	Urban impermeable surfaces: IL = 0mm/hr, CL = 0mm/hr Urban permeable surfaces: IL = 0mm/hr, CL = 2.5mm/hr
Manning's Roughness	Urban impermeable surfaces: n = 0.014 Urban permeable surfaces: n = 0.025

Catchment Delineation

For each investigation site, the overall catchment was first delineated and then subdivided into an appropriate number of homogenous subcatchments. Homogeneity of the subcatchments considered the catchment slope, roughness and the degree of urbanisation.

The catchment delineation for each investigation site is shown below in Figures 4-9.

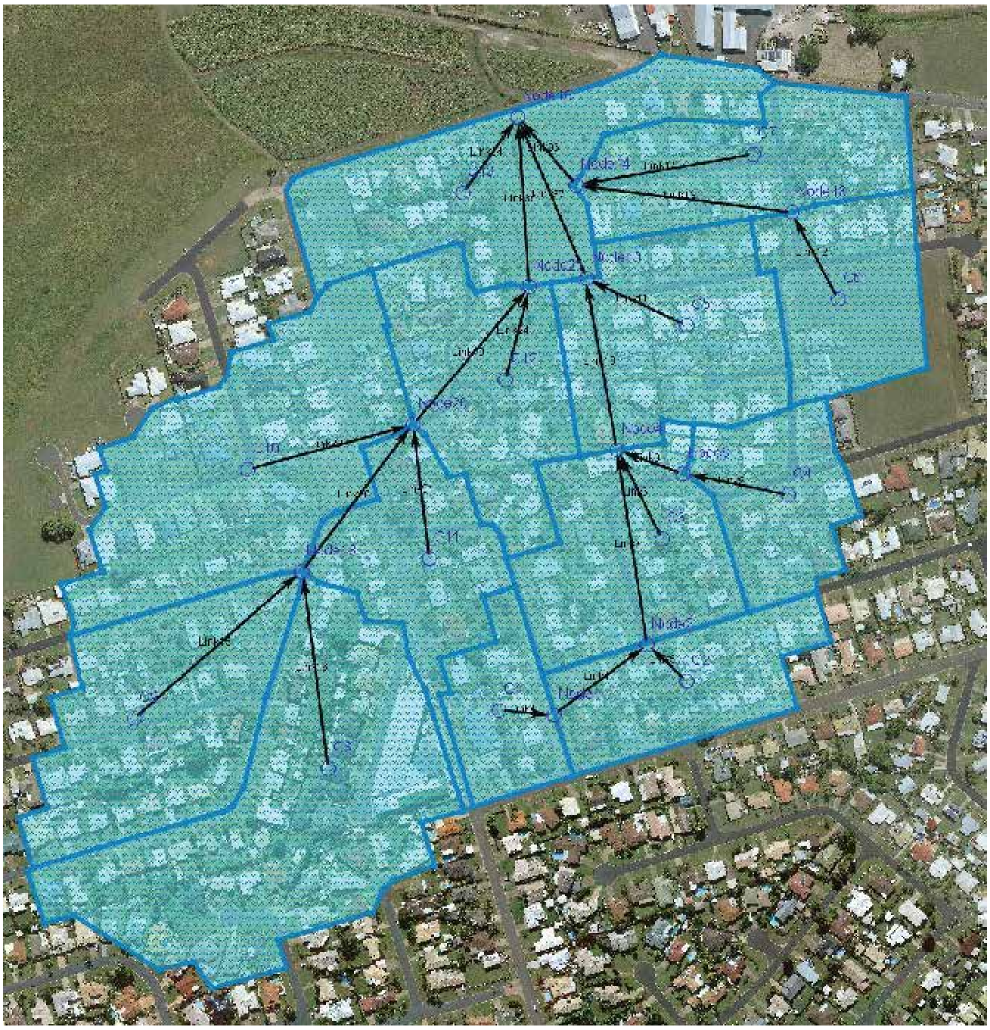


Figure 4 - Catchment Delineation: Site 1 (Avoca)

Figure 5 - Catchment Delineation: Site 2 (Burnett Heads)

Figure 6 - Catchment Delineation: Site 3 (East Bundaberg)

Figure 7 - Catchment Delineation: Site 4 (Elliott Heads)

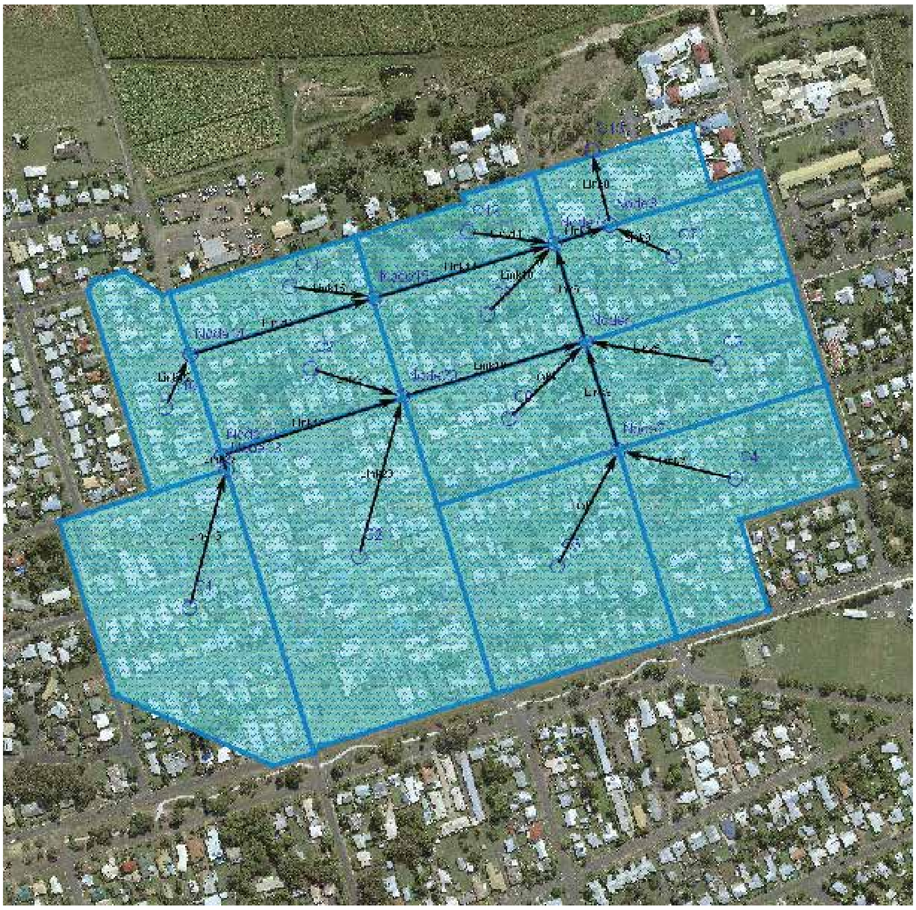


Figure 8 - Catchment Delineation: Site 5 (Millbank)

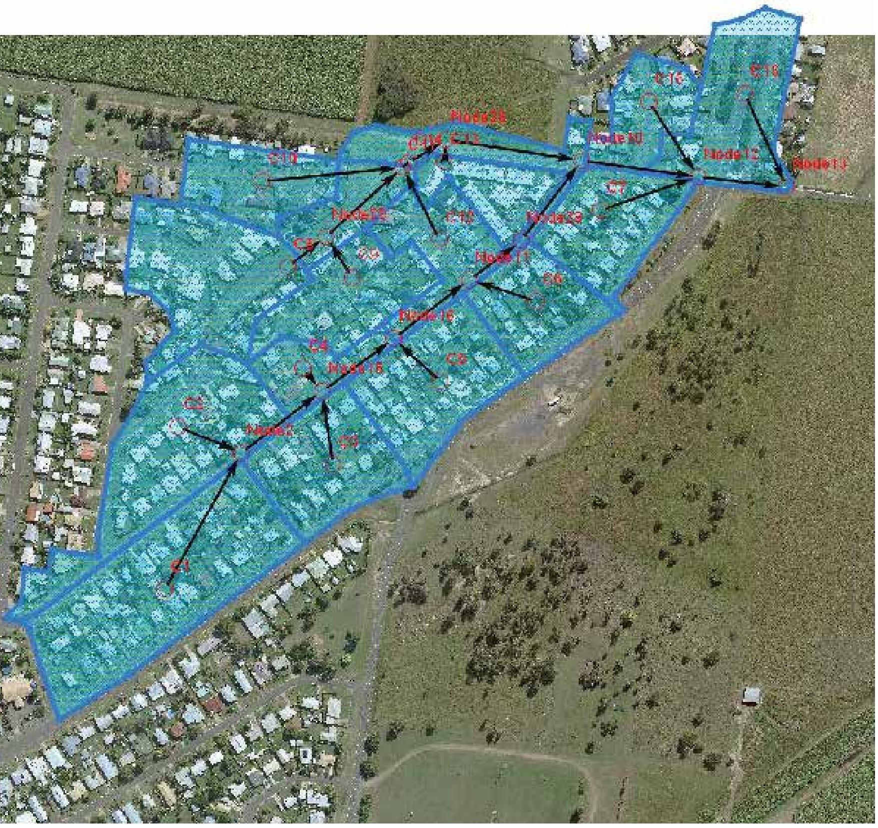


Figure 9 - Catchment Delineation: Site 6 (North Bundaberg)

Equal Area Slope

The equal area slope for each subcatchment was calculated using the Lidar survey data and a line representing the flow path from the top of the catchment to the outlet in accordance with the figure shown in QUDM and reproduced below in Figure 10.

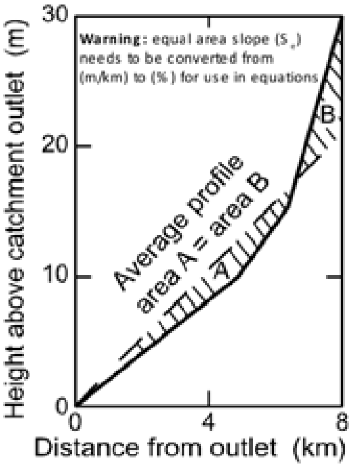
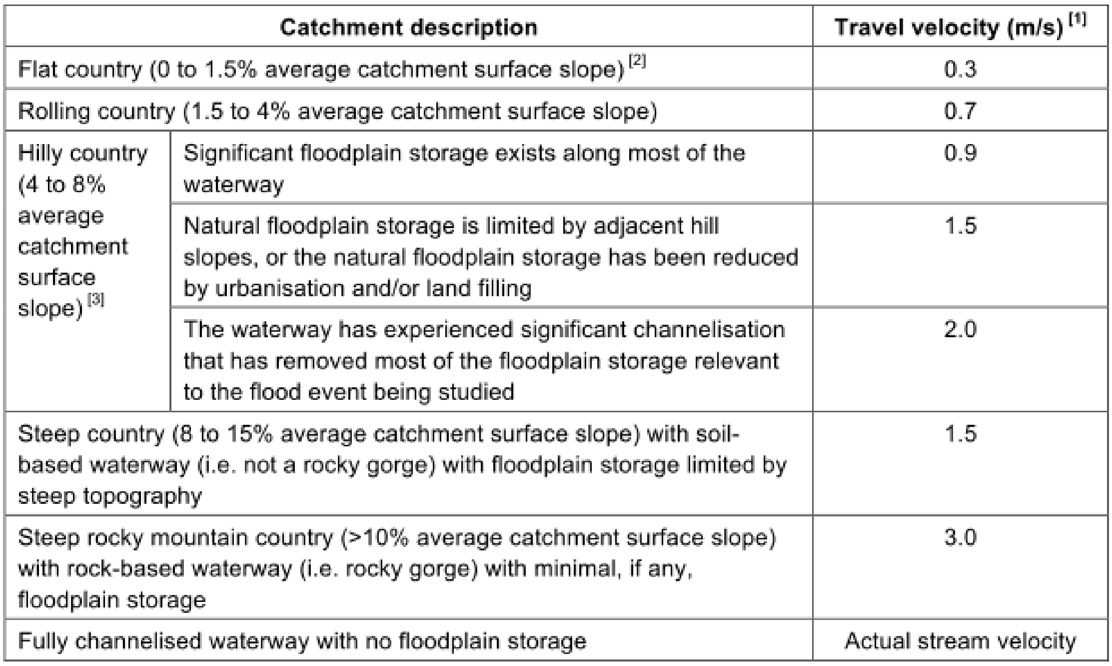


Figure 10 - Derivation of the Equal Area Slope (IPWEA, 2016)

Hydrograph Lag Times

The hydrograph lag times adopted between nodes in the XPRAFTS models was determined using assumed average stream velocities from QUDM (IPWEA, 2016) Table 4.6.6 and the distance between nodes. This table is reproduced below in Figure 11.



Catchment description		Travel velocity (m/s) [1]
Flat country (0 to 1.5% average catchment surface slope) [2]		0.3
Rolling country (1.5 to 4% average catchment surface slope)		0.7
Hilly country (4 to 8% average catchment surface slope) [3]	Significant floodplain storage exists along most of the waterway	0.9
	Natural floodplain storage is limited by adjacent hill slopes, or the natural floodplain storage has been reduced by urbanisation and/or land filling	1.5
	The waterway has experienced significant channelisation that has removed most of the floodplain storage relevant to the flood event being studied	2.0
Steep country (8 to 15% average catchment surface slope) with soil-based waterway (i.e. not a rocky gorge) with floodplain storage limited by steep topography		1.5
Steep rocky mountain country (>10% average catchment surface slope) with rock-based waterway (i.e. rocky gorge) with minimal, if any, floodplain storage		3.0
Fully channelised waterway with no floodplain storage		Actual stream velocity

Figure 11 - Stream Velocity Method (IPWEA, 2016)

XPRAFTS Modelling

Following the catchment delineation and finalisation of input parameters for each of the investigation sites, the hydrologic nodes and links were finalised within XPRAFTS. For each investigation site, the equal area slopes and average surface slopes representative of the original Bundaberg catchments were first modelled. These values were subsequently increased by constant values of 2% and 6% (creating artificial catchments) to investigate the effects of reduced storage on the comparison between ARR1987 and ARR2016.

Storm Scenarios

The following storms were modelled for both the original Bundaberg catchments and the artificial catchments with increased slope:

1. Minor Storm AEP (18% AEP) – ARR1987
2. Major Storm AEP (1% AEP) – ARR1987
3. Minor Storm AEP (18% AEP) – ARR2016 – No Climate Change
4. Major Storm AEP (1% AEP) – ARR2016 – No Climate Change
5. Minor Storm AEP (18% AEP) – ARR2016 – Climate Change
6. Major Storm AEP (1% AEP) – ARR2016 – Climate Change

For each storm listed above, a range of storm durations up to 2 hours were modelled to determine the critical storm duration and peak design discharge.

Selection of Critical Storm and Peak Design Discharge

For each ARR2016 model run, the results were visually interrogated at the most downstream node for each investigation site through a box and whisker plot (similar to that shown in Figure 1). From the array of storm durations, the maximum *mean* and *median* peak discharge was recorded for each model run. The maximum of the *maximum* peak discharges was recorded for the original Bundaberg catchment model runs only. In addition to the peak discharges, the critical storm duration, IFD value and temporal pattern number associated with the mean, median and maximum peak discharge was also recorded.

For each ARR1987 model run, the results were visually interrogated at the most downstream node at each investigation site through numerous hydrographs representing the results from each storm duration (single temporal pattern only). The critical storm and peak design discharge was then selected as the highest peak discharge. The peak discharge, corresponding IFD value and critical storm duration was recorded for each model run.

Climate Change Model Runs

Due to the limited scope of this investigation, a number of assumptions were made in order to progress through the climate change decision tree shown in Figure 2 and increase the design rainfall. Based on these assumptions, the projected increase to rainfall intensities was calculated to be approximately 12%.

Therefore, based on the assumptions made, the ARR2016 IFD rainfall was increased by 12% for all climate change model runs. A similar process to that described previously was then undertaken to determine the peak design discharge for each climate change model run.

Review of Results

As stated previously, the peak design discharges, critical storm durations, temporal pattern numbers (ARR2016 only) and IFD values for each model run were recorded. The percentage differences between ARR1987 and ARR2016 peak design discharges were then calculated and graphs prepared displaying the temporal variations of rainfall for selected critical storms where a relatively large difference in peak design discharge was observed between the two standards.

Results

Basic Catchment Data

Following the setup of each model, basic catchment data for each site was recorded. The total catchment area, average catchment slope and average fraction impervious for each site is shown below in Table 3.

Table 3 - Basic Catchment Data

Site No.	Site Name	Total Catchment Area (ha)	Average Catchment Slope (%)	Average Fraction Impervious (%)
1	Avoca (City Vue Terrace)	38.36	2.7%	49%
2	Burnett Heads (Ocean St)	3.288	1%	50%
3	East Bundaberg (Skyring/Eastgate St)	26.795	0.3%	56%
4	Elliott Heads (Bathurst St)	12.363	0.8%	54%
5	Millbank (River Terrace)	45.222	0.7%	53%
6	North Bundaberg (Jefferis St/Fairymead Rd)	21.719	0.6%	47%

Catchment Peak Design Discharges

The data recorded for each investigation site included:

- ARR1987 peak design discharge;
- ARR2016 maximum *mean* peak discharge;
- ARR2016 maximum *median* peak discharge; and
- ARR2016 maximum *mean* peak discharge including climate change.

The peak design discharge results for the original catchments are shown below in Table 4.

Table 4 – Peak Design Discharge Results (Original Catchments)

Site No.	Site Name	Storm AEP (%)	ARR1987 Peak Flow (m3/s)	ARR2016 Mean Peak Flow (m3/s)	ARR2016 Median Peak Flow (m3/s)	ARR2016 + Climate Change Mean Peak Flow (m3/s)
1.1	Avoca (City Vue Terrace)	18.1%	9.568	9.857	9.796	11.133
		1%	17.274	16.217	16.754	18.279
2.1	Burnett Heads (Ocean St)	18.1%	0.832	0.893	0.885	1.016
		1%	1.548	1.547	1.498	1.76
3.1	East Bundaberg (Skyring/Eastgate St)	18.1%	4.924	4.93	4.965	5.572
		1%	8.745	8.416	8.334	9.503
4.1	Elliott Heads (Bathurst St)	18.1%	2.681	2.687	2.672	3.042
		1%	4.739	4.49	4.471	5.082
5.1	Millbank (River Terrace)	18.1%	7.362	7.713	7.68	8.734
		1%	13.555	13.239	13.23	14.985
6.1	North Bundaberg (Jefferis St/Fairymead Rd)	18.1%	3.738	3.64	3.63	4.119
		1%	6.696	6.21	6.172	7.029

As discussed previously, following analysis of the original catchments, artificial catchments were created by increasing the slope of each subcatchment by 2% and 6%. The peak design discharge results for each of the artificial catchments is shown below in Table 5 and Table 6.

Table 5 - Peak Discharge Results (Original Catchments + 2% Slope)

Site No.	Site Name	Storm AEP (%)	ARR1987 Peak Flow (m3/s)	ARR2016 Mean Peak Flow (m3/s)	ARR2016 Median Peak Flow (m3/s)	ARR2016 + Climate Change Mean Peak Flow (m3/s)
1.2	Avoca (City Vue Terrace)	18.1%	11.754	11.95	12.144	13.506
		1%	20.884	20.088	19.969	22.641
2.2	Burnett Heads (Ocean St)	18.1%	1.45	1.453	1.447	1.647
		1%	2.551	2.456	2.431	2.782
3.2	East Bundaberg (Skyring/Eastgate St)	18.1%	7.675	7.848	7.957	8.872
		1%	13.434	13.221	13.081	14.922
4.2	Elliott Heads (Bathurst St)	18.1%	3.739	3.455	3.477	3.904
		1%	6.331	5.819	5.768	6.585
5.2	Millbank (River Terrace)	18.1%	12.275	12.27	12.313	13.882
		1%	21.955	20.773	20.611	23.508
6.2	North Bundaberg (Jefferis St/Fairymead Rd)	18.1%	5.68	5.936	5.916	6.715
		1%	9.931	9.699	9.643	10.95

Table 6 - Peak Discharge Results (Original Catchments + 6% Slope)

Site No.	Site Name	Storm AEP (%)	ARR1987 Peak Flow (m3/s)	ARR2016 Mean Peak Flow (m3/s)	ARR2016 Median Peak Flow (m3/s)	ARR2016 + Climate Change Mean Peak Flow (m3/s)
1.3	Avoca (City Vue Terrace)	18.1%	14.936	14.348	14.259	16.227
		1%	25.508	24.339	23.752	27.47
2.3	Burnett Heads (Ocean St)	18.1%	1.999	1.819	1.789	2.058
		1%	3.367	3.061	3.068	3.468
3.3	East Bundaberg (Skyring/Eastgate St)	18.1%	9.959	9.762	9.772	11.025
		1%	16.934	16.355	15.995	18.445
4.3	Elliott Heads (Bathurst St)	18.1%	4.78	4.292	4.156	4.858
		1%	7.763	7.208	7.183	8.149
5.3	Millbank (River Terrace)	18.1%	16.771	16.025	15.995	18.146
		1%	28.832	27.431	27.084	31.005
6.3	North Bundaberg (Jefferis St/Fairymead Rd)	18.1%	8.402	7.884	7.72	8.914
		1%	14.171	13.364	12.88	15.094

Critical Storm Duration, Temporal Pattern & IFD

The critical storm duration along with the associated temporal pattern number (ARR2016 only) and IFD depth was recorded for the maximum *mean* peak discharge and maximum *median* peak discharge for each of the original catchments as well as each of the artificial catchments. These results are shown below in Table 7, Table 8 and Table 9. The site names within each of the below tables have been omitted for clarity.

Table 7 - Critical Storm Results (Original Catchments)

Site No.	Storm AEP (%)	ARR1987 Critical Storm	ARR2016 Critical Storm (Mean Temporal Pattern)	ARR2016 Critical Storm (Median Temporal Pattern)	ARR1987 Critical Storm IFD (mm)	ARR2016 Critical Storm (Mean Temporal Pattern) IFD (mm)	ARR2016 Critical Storm (Median Temporal Pattern) IFD (mm)
1.1	18.1%	45 min	30 min (3)	25 min (5)	51.1	50.7	46.6
	1%	45 min	45 min (10)	45 min (5)	86.9	99.7	99.7
2.1	18.1%	60 min	60 min (5)	60 min (5)	57.8	66.3	66.3
	1%	60 min	45 min (5)	45 min (3)	97.7	96.3	96.3
3.1	18.1%	60 min	30 min (7)	30 min (3)	57.8	51.1	51.1
	1%	60 min	45 min (4)	45 min (5)	98.4	100	100
4.1	18.1%	25 min	30 min (7)	30 min (9)	39	49.3	49.3
	1%	20 min	25 min (8)	25 min (8)	58.7	72.5	72.5
5.1	18.1%	60 min	45 min (9)	60 min (7)	57.7	60.3	67.4
	1%	60 min	45 min (8)	45 min (8)	98.9	99.7	99.7
6.1	18.1%	60 min	60 min (10)	45 min (9)	57.8	67.8	60.6
	1%	60 min	45 min (5)	45 min (5)	98.5	99.6	99.6

Table 8 - Critical Storm Results (Original Catchments + 2% Slope)

Site No.	Storm AEP (%)	ARR1987 Critical Storm	ARR2016 Critical Storm (Mean Temporal Pattern)	ARR2016 Critical Storm (Median Temporal Pattern)	ARR1987 Critical Storm IFD (mm)	ARR2016 Critical Storm (Mean Temporal Pattern) IFD (mm)	ARR2016 Critical Storm (Median Temporal Pattern) IFD (mm)
1.2	18.1%	25 min	25 min (2)	25 min (1)	38.8	46.6	46.6
	1%	20 min	25 min (8)	25 min (10)	59	75.9	75.9
2.2	18.1%	60 min	30 min (9)	30 min (9)	57.8	49.9	49.9
	1%	60 min	25 min (4)	25 min (4)	97.7	73.2	73.2
3.2	18.1%	60 min	25 min (1)	25 min (2)	57.8	47	47
	1%	60 min	25 min (3)	25 min (8)	98.4	75.8	75.8
4.2	18.1%	25 min	30 min (6)	30 min (6)	39	49.3	49.3
	1%	25 min	15 min (9)	15 min (9)	65.6	55.4	55.4
5.2	18.1%	60 min	30 min (10)	30 min (10)	57.7	50.8	50.8
	1%	60 min	25 min (8)	25 min (8)	98.9	75.8	75.8
6.2	18.1%	25 min	25 min (5)	25 min (5)	38.9	46.8	46.8
	1%	25 min	25 min (10)	45 min (2)	65.8	75.6	99.6

Table 9 - Critical Storm Results (Original Catchments + 6% Slope)

Site No.	Storm AEP (%)	ARR1987 Critical Storm	ARR2016 Critical Storm (Mean Temporal Pattern)	ARR2016 Critical Storm (Median Temporal Pattern)	ARR1987 Critical Storm IFD (mm)	ARR2016 Critical Storm (Mean Temporal Pattern) IFD (mm)	ARR2016 Critical Storm (Median Temporal Pattern) IFD (mm)
1.3	18.1%	25 min	15 min (5)	15 min (5)	38.8	35.8	35.8
	1%	20 min	15 min (5)	10 min (5)	59	57.9	45.4
2.3	18.1%	25 min	15 min (7)	15 min (6)	39.1	35.1	35.1
	1%	25 min	15 min (9)	10 min (7)	65.8	55.9	43.9
3.3	18.1%	25 min	15 min (5)	15 min (5)	39	36	36
	1%	20 min	15 min (5)	15 min (6)	59	57.8	57.8
4.3	18.1%	25 min	10 min (5)	10 min (10)	39	27.2	27.2
	1%	25 min	10 min (7)	10 min (7)	65.6	43.5	43.5
5.3	18.1%	25 min	15 min (6)	15 min (5)	38.9	35.8	35.8
	1%	25 min	15 min (5)	15 min (9)	65.9	57.9	57.9
6.3	18.1%	25 min	15 min (6)	15 min (7)	38.9	35.9	35.9
	1%	25 min	15 min (2)	15 min (3)	65.8	57.7	57.7

Comparison of ARR1987 and ARR2016 Peak Design Discharges

Using the recorded data presented above, the ARR2016 maximum *mean*, maximum *median* and maximum *mean* climate change catchment peak design discharges were compared with the ARR1987 catchment peak design discharges. Additionally, the ARR2016 *mean* and *median* peak discharges were also compared. These comparisons are shown below in Table 10, Table 11 and Table 12. The comparisons are shown using a percentage difference where a positive percentage indicates that the ARR2016 peak design discharge is higher than the ARR1987 peak design discharge (highlighted in green) and a negative percentage indicates that the ARR1987 peak design discharge is higher (highlighted in red).

Table 10 - ARR1987 and ARR2016 Catchment Peak Design Discharge Comparison (Original Catchments)

Site No.	Site Name	Storm AEP (%)	ARR2016 Mean Peak Flow (m3/s) % Difference	ARR2016 Median Peak Flow (m3/s) % Difference	ARR2016 + Climate Change Mean Peak Flow (m3/s) % Difference	ARR2016 Mean vs. Median Peak Flow % Difference
1.1	Avoca (City Vue Terrace)	18.1%	3.02%	2.38%	16.36%	0.62%
		1%	-6.12%	-3.01%	5.82%	-3.21%
2.1	Burnett Heads (Ocean St)	18.1%	7.33%	6.37%	22.12%	0.90%
		1%	-0.06%	-3.23%	13.70%	3.27%
3.1	East Bundaberg (Skyring/Eastgate St)	18.1%	0.12%	0.83%	13.16%	-0.70%
		1%	-3.76%	-4.70%	8.67%	0.98%
4.1	Elliott Heads (Bathurst St)	18.1%	0.22%	-0.34%	13.47%	0.56%
		1%	-5.25%	-5.66%	7.24%	0.42%
5.1	Millbank (River Terrace)	18.1%	4.77%	4.32%	18.64%	0.43%
		1%	-2.33%	-2.40%	10.55%	0.07%
6.1	North Bundaberg (Jefferis St/Fairymead Rd)	18.1%	-2.62%	-2.89%	10.19%	0.28%
		1%	-7.26%	-7.83%	4.97%	0.62%

Table 11 - ARR1987 and ARR2016 Catchment Peak Design Discharge Comparison (Original Catchments + 2% Slope)

Site No.	Site Name	Storm AEP (%)	ARR2016 Mean Peak Flow (m3/s) % Difference	ARR2016 Median Peak Flow (m3/s) % Difference	ARR2016 + Climate Change Mean Peak Flow (m3/s) % Difference	ARR2016 Mean vs. Median Peak Flow % Difference
1.2	Avoca (City Vue Terrace)	18.1%	1.67%	3.32%	14.91%	-1.60%
		1%	-3.81%	-4.38%	8.41%	0.60%
2.2	Burnett Heads (Ocean St)	18.1%	0.21%	-0.21%	13.59%	0.41%
		1%	-3.72%	-4.70%	9.06%	1.03%
3.2	East Bundaberg (Skyring/Eastgate St)	18.1%	2.25%	3.67%	15.60%	-1.37%
		1%	-1.59%	-2.63%	11.08%	1.07%
4.2	Elliott Heads (Bathurst St)	18.1%	-7.60%	-7.01%	4.41%	-0.63%
		1%	-8.09%	-8.89%	4.01%	0.88%
5.2	Millbank (River Terrace)	18.1%	-0.04%	0.31%	13.09%	-0.35%
		1%	-5.38%	-6.12%	7.07%	0.79%
6.2	North Bundaberg (Jefferis St/Fairymead Rd)	18.1%	4.51%	4.15%	18.22%	0.34%
		1%	-2.34%	-2.90%	10.26%	0.58%

Table 12 - ARR1987 and ARR2016 Catchment Peak Design Discharge Comparison (Original Catchments + 6% Slope)

Site No.	Site Name	Storm AEP (%)	ARR2016 Mean Peak Flow (m3/s) % Difference	ARR2016 Median Peak Flow (m3/s) % Difference	ARR2016 + Climate Change Mean Peak Flow (m3/s) % Difference	ARR2016 Mean vs. Median Peak Flow % Difference
1.3	Avoca (City Vue Terrace)	18.1%	-3.94%	-4.53%	8.64%	0.62%
		1%	-4.58%	-6.88%	7.69%	2.47%
2.3	Burnett Heads (Ocean St)	18.1%	-9.00%	-10.51%	2.95%	1.68%
		1%	-9.09%	-8.88%	3.00%	-0.23%
3.3	East Bundaberg (Skyring/Eastgate St)	18.1%	-1.98%	-1.88%	10.70%	-0.10%
		1%	-3.42%	-5.55%	8.92%	2.25%
4.3	Elliott Heads (Bathurst St)	18.1%	-10.21%	-13.05%	1.63%	3.27%
		1%	-7.15%	-7.47%	4.97%	0.35%
5.3	Millbank (River Terrace)	18.1%	-4.45%	-4.63%	8.20%	0.19%
		1%	-4.86%	-6.06%	7.54%	1.28%
6.3	North Bundaberg (Jefferis St/Fairymead Rd)	18.1%	-6.17%	-8.12%	6.09%	2.12%
		1%	-5.69%	-9.11%	6.51%	3.76%

Following analysis of the above results, the ARR2016 maximum of *maximum* catchment peak discharges were also recorded for each of the sites (original catchments only) and compared to the ARR1987 catchment peak design discharges. The ARR2016 maximum of *maximum* catchment peak discharges and a percentage comparison to the ARR1987 catchment peak design discharges is shown below in Table 13.

Table 13 - ARR2016 Maximum Peak Flow Comparison (Original Catchments)

Site No.	Site Name	Storm AEP (%)	ARR2016 Maximum Peak Flow (m3/s)	ARR2016 Maximum Peak Flow (m3/s) % Difference
1.1	Avoca (City Vue Terrace)	18.1%	11.402	18.61%
		1%	18.23	5.90%
2.1	Burnett Heads (Ocean St)	18.1%	1.023	21.39%
		1%	1.627	5.11%
3.1	East Bundaberg (Skyring/Eastgate St)	18.1%	5.515	11.99%
		1%	9.403	7.82%
4.1	Elliott Heads (Bathurst St)	18.1%	3.075	14.66%
		1%	5.205	10.38%
5.1	Millbank (River Terrace)	18.1%	8.803	18.68%
		1%	14.169	4.64%
6.1	North Bundaberg (Jefferis St/Fairymead Rd)	18.1%	4.076	9.29%
		1%	6.809	1.82%

Key observations from the modelling results include:

- Despite an increase in the IFD depths as demonstrated in Table 1, the ARR2016 *mean* and *median* peak discharges for the original Bundaberg catchments are generally within 5% of the ARR1987 peak design discharges. Further still, 7 of the 12 design storms (minor and major) resulted in ARR1987 peak design discharges exceeding the ARR2016 *mean* peak discharges and 8 of the 12 design storms resulted in ARR1987 peak design discharges exceeding the ARR2016 *median* peak discharges.

- When climate change recommendations are included (i.e. IFD depths increased by a further 12%), the ARR2016 *mean* peak discharges are consistently higher than the ARR1987 peak design discharges.

- The ARR2016 maximum of *maximum* peak discharges are consistently higher than the ARR1987 peak design discharges.

- There is minimal difference between the ARR2016 *mean* and *median* peak discharges, particularly for the original Bundaberg catchments. The difference in peak discharge was generally less than 1%. Despite the minimal difference, the *mean* peak discharge is generally slightly greater than the *median* peak discharge and therefore represents a more conservative design approach.

- The ARR1987 peak design discharges for the major design storm (1% AEP) were higher than the ARR2016 *mean* and *median* peak discharges for every site and for both the original Bundaberg catchments and the artificial catchments with increased slope.

- The difference between the ARR1987 peak design discharges and ARR2016 peak design discharges changed with the increased slope of the catchments. This is demonstrated by the artificial catchment results shown in Table 12 where the ARR1987 peak design discharges are consistently greater than the ARR2016 peak design discharges, ranging from a 4% difference to a 14% difference.

Temporal Pattern Analysis

To investigate the reasons for the ARR1987 peak design discharges being slightly higher than or approximately equal to the ARR2016 *mean* and *median* peak discharges, a comparison of the critical storm temporal patterns was undertaken for a select number of model runs. For each selected model run, the relevant IFD depth and temporal pattern were plotted to produce a graph showing the depth of rainfall over the duration of the storm. As each of the catchment parameters (i.e. fraction impervious, catchment slope, lag times etc) remained constant while changing the input rainfall, this comparison provided a reasonable explanation for many of the recorded results.

In the majority of model runs where ARR1987 peak design discharges were greater than the ARR2016 *mean* and/or *median* peak discharge, the analysis indicated that the ARR1987 temporal pattern was highly front loaded and/or produced a higher peak in the graph, indicating a higher intensity of rainfall at a specific time in the storm. While the volume of water in the ARR2016 design storms is increased (indicated by the higher IFD depths), a higher intensity of rainfall is likely to produce a higher peak discharge from the catchment (i.e. more water in a short period of time). Three scenarios where the ARR1987 temporal patterns and IFD depths produced higher peak design discharges than ARR2016 is shown in Figure 12, Figure 13 and Figure 14 below.

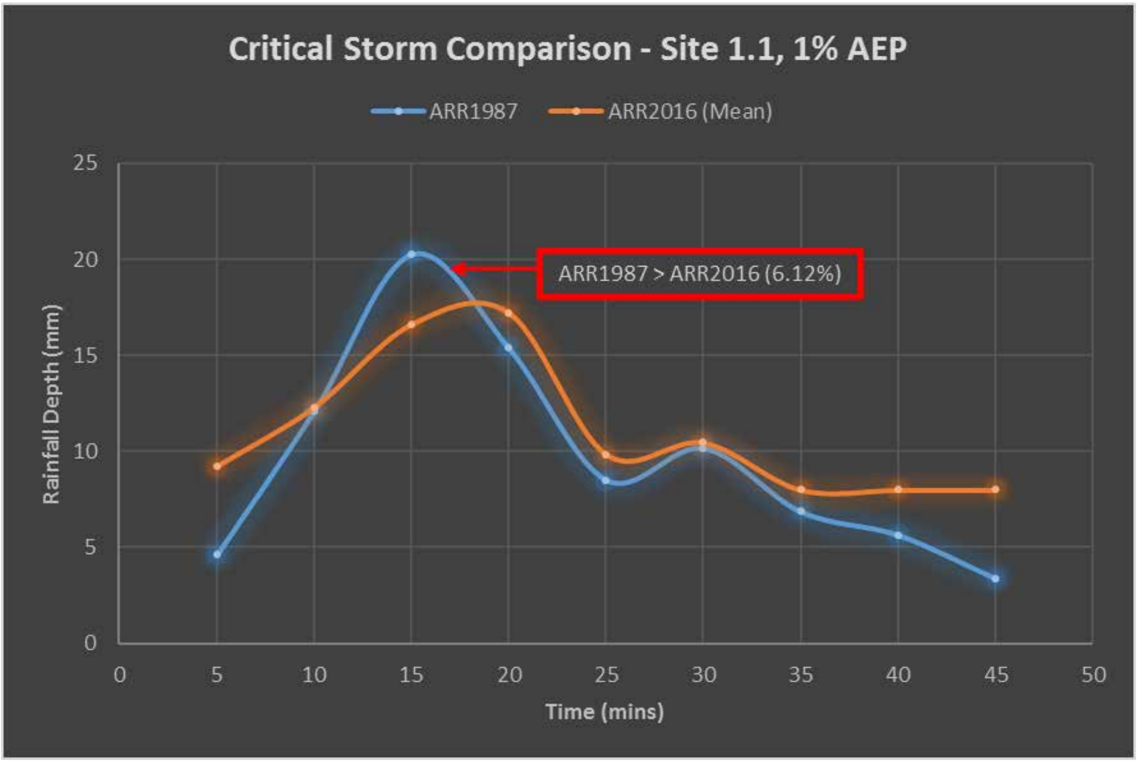


Figure 12 - Critical Storm Comparison: Site 1.1, 1% AEP

As demonstrated in Figure 13, the ARR2016 storm volume and IFD (indicated by the area under the orange line) is greater than the ARR1987 storm. However, the ARR1987 temporal pattern in conjunction with the ARR1987 IFD values produce a higher intensity of rainfall at a specific time in the storm (i.e. 15mins), resulting in a higher peak discharge.

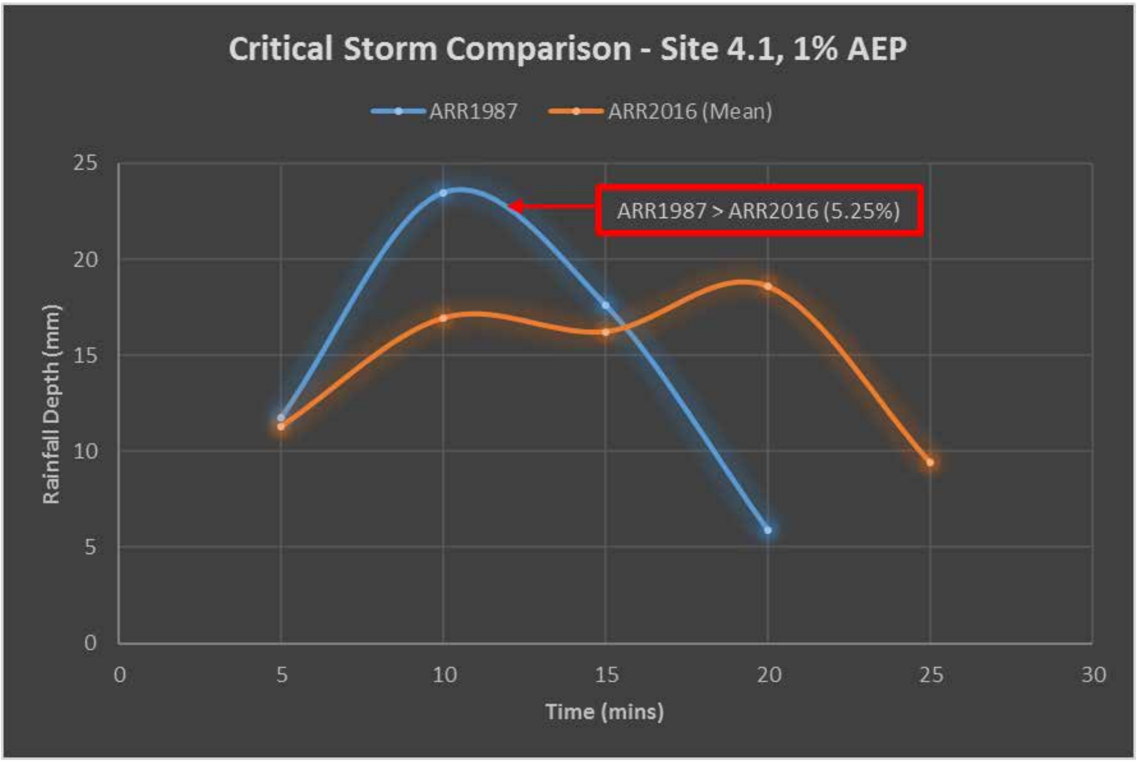


Figure 13 - Critical Storm Comparison: Site 4.1, 1% AEP

Figure 13 demonstrates a scenario where the ARR1987 temporal pattern is highly front loaded and produces a very intense period of rainfall early in the storm before significantly reducing. The different temporal pattern structures again result in the ARR1987 peak design discharge being greater than the ARR2016 *mean* peak discharge.

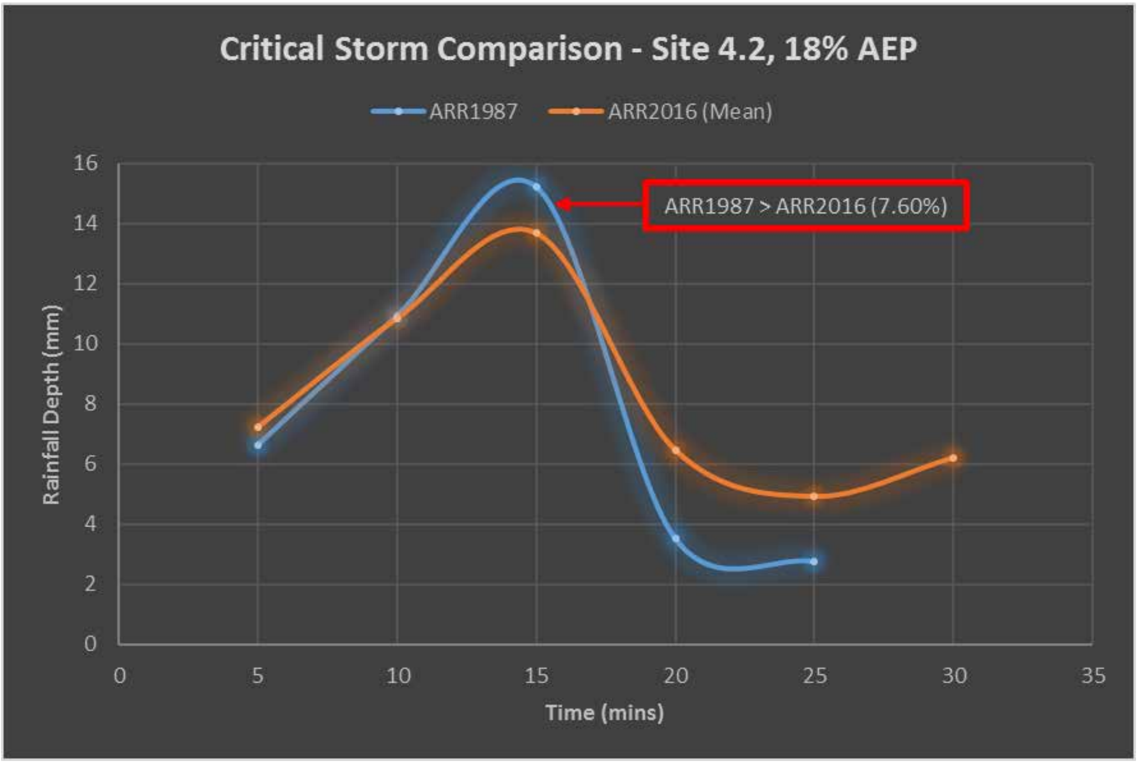


Figure 14 - Critical Storm Comparison: Site 4.2, 18% AEP

Figure 14 demonstrates a scenario where the shape of the ARR1987 and ARR2016 temporal patterns are relatively similar, yet the ARR1987 temporal pattern again produces a higher intensity of rainfall at a specific time in the storm, resulting in a higher peak discharge.

Each of the above examples demonstrate that the ARR1987 temporal patterns generally have a higher percentage of the overall design storm rainfall falling during the peak of the storm in comparison to the ARR2016 *mean* peak temporal patterns. As demonstrated, this produces higher intensity rainfall and generally results in a higher catchment peak discharge.

ARR2016 Maximum of Maximum Peak Discharges

The comparison of ARR1987 peak design discharges and ARR2016 maximum of *maximum* peak discharges (as opposed to the *mean* or *median*) shown in Table 12 demonstrates a percentage difference that would be more expected due to the increased ARR2016 IFD depths. Adoption of the ARR2016 maximum peak temporal patterns for design purposes is not specifically recommended in ARR2016 and therefore an analysis of these temporal patterns has not been undertaken. However, it is presumed that these temporal patterns are more similar to the ARR1987 temporal patterns in which a higher percentage of the overall design storm rainfall falls during the peak of the storm. Therefore, with further increases in IFD depth, it would be expected that the peak design discharge percentage comparison would closer reflect the direct IFD depth comparison shown in Figure 1.

This analysis indicates that the ARR2016 temporal pattern ensembles comprise storms with peaks in rainfall similar to the ARR1987 temporal patterns. However, the temporal pattern selection process associated with ARR2016 (i.e. selection of the *mean* or *median* temporal pattern) often results in selected temporal patterns for design that exhibit lower peaks in rainfall and therefore typically produce lower peak design discharges than ARR1987. The temporal pattern selection and associated peak design discharge is therefore a critical step in the design process in which reasonable engineering judgment should be applied. While the work of Loveridge et al. (2015) indicates that the mean and median temporal patterns could likely fit the flood frequency analyses undertaken for 35 test catchments, Loveridge et al. (2015) also states that uncertainties regarding losses were influencing the results and significant differences were observed. Further research should be undertaken to investigate the suitability of adopting the maximum of *maximum* peak discharge for design purposes.

ARR2016 Mean vs. Median Peak Discharge

As stated previously, there is minimal difference between the ARR2016 *mean* and *median* peak discharges. For each of the original Bundaberg catchments, there was a difference of generally less than 1%. The results of this analysis align with the work of Loveridge et al. (2015) and discussed in ARR2016 where the differences between the two approaches was found to be minimal. For each of the original Bundaberg catchments, the *mean* peak discharge was found to be generally higher due to particular temporal patterns producing a comparatively high peak discharge. An example of this is demonstrated in the box and whisker plot for the results of Site 1.1 (18% AEP), shown below in Figure 15.

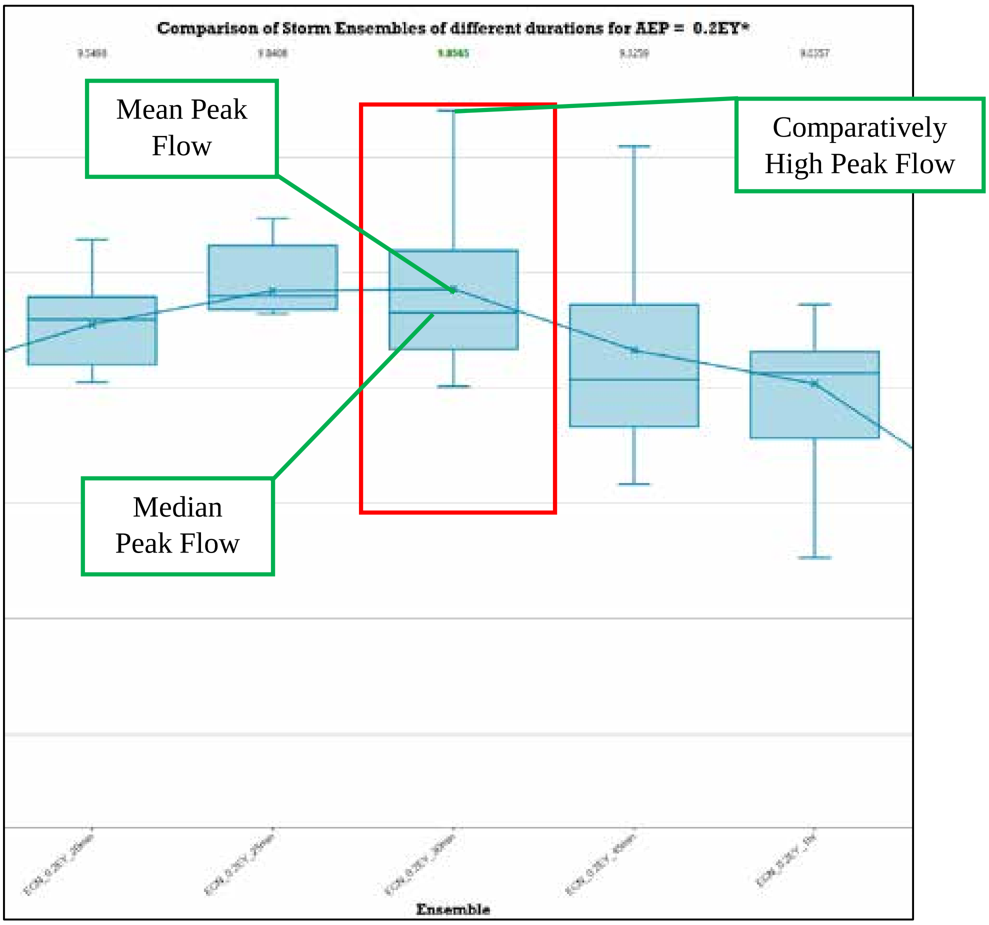


Figure 15 - Mean Peak Flow Skew due to Outliers

It is arguable that the *median* peak discharge generally represents a better average of the peak discharges as it doesn’t consider outliers in the data (whether high or low). However, adoption of the *mean* peak discharge for many of the original Bundaberg catchments would result in a conservative design approach and may therefore produce a more robust design. Nonetheless, for any design scenario, the difference between the *mean* and *median* peak discharge should be calculated and the effect on the design considered before adopting either value.

Effect of Catchment Slope on the Peak Design Discharge Comparison

As stated previously, the difference between the ARR1987 and ARR2016 peak design discharges was found to change with steeper catchments. The artificial catchment results shown in Table 11 (original catchments + 6% slope) demonstrate ARR1987 peak design discharges that are consistently higher than the ARR2016 *mean* and *median* peak discharges for each site and for both the minor and major design storms. According to Laurenson’s equation, the effect of increasing the catchment slope is to reduce the catchment storage. This increases the catchment peak design discharge as demonstrated by the results shown in Table 11. The effect of increasing the catchment slope is also to reduce the travel time from the top of the catchment to the outlet. This reduces the critical storm duration as a larger area of the total catchment can now contribute to the peak outlet flow during the shorter, more intense storm events. As the shorter, more intense storm events are critical with catchments of greater slope, the peak discharge is therefore increased.

With no consideration given to the different temporal patterns, it would be expected that the difference between ARR1987 and ARR2016 peak design discharges would remain constant for catchments with increased slope. However, the results demonstrate that in most cases, the ARR1987 peak design discharge is increased by a higher percentage than the ARR2016 peak design discharges. Again, this is primarily due to the ensemble of temporal patterns and the selection process for the critical temporal pattern.

Analysis of the critical storm temporal patterns for each of the artificial catchments with original slope + 6% demonstrate that the ARR1987 temporal patterns consistently produce periods of peak rainfall which are more intense than the periods of peak rainfall produced by the ARR2016 mean temporal patterns. As stated previously, the more intense periods of peak rainfall are likely to produce a higher peak discharge.

From these results, it can be stated that for small catchments or steeper catchments which result in a shorter duration critical storm, the ARR1987 rainfall and temporal patterns will consistently produce a higher peak design discharge than the ARR2016 rainfall and mean/median temporal patterns. Again, this is a result of the ARR2016 temporal pattern selection process.

Conclusion

From the results of this investigation, it can be concluded that there are minimal differences in peak design discharge calculated using the approaches described by ARR1987 and ARR2016 for urban catchments within the Bundaberg region. This is despite ARR2016 rainfall depths that are approximately 15-30% greater than those included in ARR1987. However, it can also be concluded that consistently higher peak design discharges are likely to be calculated when the ARR2016 rainfall depths are further increased to allow for climate change considerations in accordance with the decision tree and relevant formula presented in ARR2016.

The results of this investigation also indicate that the difference between ARR2016 and ARR1987 peak design discharges are likely to be larger for sites with steeper catchments where the critical storm duration is reduced. This is primarily due to the structure of the shorter storm duration temporal patterns included in ARR2016.

This investigation confirms the results of previous studies by concluding that there is minimal difference between selection of the *mean* and *median* temporal patterns in almost all scenarios. Further research should be undertaken to determine the suitability of adopting the ARR2016 *maximum* temporal pattern for design purposes or as a ‘check’ storm for risk management.

This investigation offers a positive outcome for Bundaberg Regional Council in that the immunity of existing infrastructure designed based on peak design discharges can be assumed to be relatively unchanged by adopting the new guidelines. While the implementation of ARR2016 may result in a significant increase in design time, Bundaberg Regional Council and engineering consultants can have confidence that designs undertaken using the ARR2016 guidelines will not be dissimilar to the ARR1987 equivalent designs and that existing infrastructure will allow for a continuity of drainage outcomes from past to present.

This investigation has undertaken a comparison based on rainfall and temporal patterns unique to the Bundaberg region. It is therefore likely that similar comparisons undertaken in different areas around Australia will yield different results.

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