3 September 2024

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Dear Chris

Estimating Cyclone Pool premiums with 168 hour coverage period

Scope and background

The Cyclone Pool covers damage occurring within 48 hours after the end of a declared cyclone event ('DCE'). Some recent events (Cyclones Ellie, Jasper and Kirrily), each unique in their own way, all had significant rainfall associated with them leading to flood losses, with a reasonable proportion of the flooding occurring outside the current 'end of DCE + 48 hour' limit.

Australian Reinsurance Pool Corporation (ARPC) engaged Finity and Risk Frontiers to help expand on the cyclone related flooding analysis done as part of the Cyclone Pool's initial pricing in 2022 with regards to the coverage period. Specifically, to improve ARPC's understanding and estimate the potential impacts of increasing the coverage period after the end of a DCE from 48 hours to 168 hours. ARPC has now asked Finity to document the work in a report suitable for publication.

Impacts of extending the coverage period

The main impacts to consider are:

- How much additional claims cost would be covered by the pool; and therefore,
- How much additional premium would the pool need to collect to meet this cost
- What the net impact would be on consumer premiums, which will in turn depend on how insurers reflect the coverage change in their premiums.

If the coverage period after the end of a DCE was increased from 48 hours to 168 hours, there are several possible causes of additional claims on the Pool:

1. The 168-hour period means that there is more time for rainfall to cause flooding. For example, the ex-TC stays in the region after downgrade with rainfall continuing.
2. Continuing movement of ex-TCs means that there can be wind and rain outside the main cyclone affected area that can now be attributed to a Cyclone Event. This picks up ex-TC movements after the cyclone is downgraded, and which may then cause wind or flood damage.
3. More time for water to flow downstream of a river basin. This is mainly an issue for larger river basins where it can take some time for the flood water to arrive.

We anticipate the largest impact to derive from riverine flooding given that as a cyclone is downgraded rain can continue to be extreme, while wind is diminished. For this reason the additional modelling carried out by Risk Frontiers and our analysis as documented in this letter focus on riverine flooding impacts only.

Summary of Findings

The modelling indicates that the additional riverine flood risk from extending the coverage period will cost the Cyclone Pool an estimated average of $20-35m each year in additional claims costs, although the amount will vary widely from year to year. This additional cost is roughly ~5% of the Cyclone Pool's current estimate of expected annual claims costs. This in effect is also the additional total premium that the pool will need to collect in aggregate to meet these increased costs.

Under an extended coverage period, the Cyclone Pool would update current address-level flood risk bands for impacted addresses to reflect the increased flood cover being provided by the Pool. Despite this, it is likely that there would need to be changes to the Cyclone Pool's premium rates and/or the premium rating formula as maintaining the current structure and premium rating parameters will not collect the additional premium needed to meet the increased costs. This report considers one specific option of how the additional costs may be funded by the Cyclone Pool in a way that is intended to be consistent with its current pricing principles.

The impact on end consumers' premiums depends on how insurers adjust their premiums in response to increased coverage offered by the pool. Across most regions, the number of Home Building insurance consumers receiving premium increases will be greater than those receiving premium reductions, although the vast majority of policies receiving increases will see very small (under ~$5 on average) increases whereas those benefitting from premium reductions are likely to see more substantial premium reductions ($100+ on average).

This is how the whole pool was designed to operate: to deliver the greatest benefit to the highest risk properties and therefore, the higher risk properties end up paying premiums well below what they would otherwise be charged based on their level of risk.

Regionally, consumers in high flood risk regions (such as SEQ) stand to benefit the most from the increased coverage as, depending on insurer responses, their non-cyclone premium reduction might outweigh the cyclone pool premium increases, which are capped.

There are uncertainties and limitations in the analysis set out in this letter and the reader is referred to the *'Limited basis of our estimate'* and *'Reliances and Limitations'* sections at the end of this letter. Our estimates are most sensitive to the cyclone related flooding assumption for SEQ and Northern NSW, where exposures are large. There is also a smaller dataset available for Risk Frontiers' latest analysis for flooding in these areas. For this reason, we have included an additional scenario with higher cyclone-related flood proportions for this region. Under this scenario, consumers in these regions would stand to benefit the most from the increased coverage offset by modest premium increases across lower risk consumers.

Relevant previous reports

In ARPC's previous Cyclone Pool premium determination, the flood component of the premium was estimated by applying the end of DCE + 48 hour coverage period. This was estimated based on analysis and assumptions documented in the following reports (jointly referred to as Previous Reports in this letter):

- 'Cyclone Reinsurance Pool – Determination of Cyclone Related Flood Proportions', dated 13 May 2022
- 'Cyclone Reinsurance Pool – Summary of the Actuarial Premium Rate Assessment', dated 28 June 2022 (setting out rates effective from 1 July 2022)

- ‘Cyclone Reinsurance Pool – Premium determination applying from 1 October 2022’, dated 28 September 2022

Overview of the approach

The approach to estimating the impact of extending the coverage period is similar to that set out in in the Previous Reports; the reader is referred to the Previous Reports for details. The estimation of the cost and premium increase to the Cyclone Pool uses the same underlying flood models, approach, and key decisions as previously adopted, with the only change being the extra riverine flood risk that would be brought into the Cyclone Pool.

The key parameters are the proportion of flood costs in the relevant river basins that Risk Frontiers estimate as arising from extending the coverage period. Risk Frontiers previous analysis had assumed an end of DCE + 48-hour coverage period. We understand the Risk Frontiers Report summarising their study will be provided by ARPC alongside this letter[1]. We have included a brief summary of Risk Frontiers’ modelling approach and how we have applied it below.

Risk Frontiers modelling

Risk Frontiers updated their River Basin Study, documented in the report “Flood related to Tropical Cyclone” dated January 2022, to estimate the proportion of floods with a cyclonic-source in different regions (river basins) that would be reinsured by the Cyclone Pool under the end of DCE + 48-hour (current coverage) and end of DCE + 168-hour (extended coverage) periods. The Risk Frontiers analysis measures river basin Discharge Events, i.e. when the water level is raised above usual levels, and attempts to identify if Discharge Event in the affected river basin can be linked to a known cyclone and ex-tropical cyclone (ex-TC) track.

Risk Frontiers’ previous report is available on ARPC’s website as an attachment to Finity’s “Cyclone Reinsurance Pool – Determination of Cyclone Related Flood Proportions” report, dated 13 May 2022.

There are a few noteworthy data and modelling changes in Risk Frontiers’ current vs previous analysis. These are:

1. **Consideration of the extended time period (168 hours or 7 days)** – In order to understand the impact of the coverage extension, Risk Frontiers have modelled flood impacts over a longer time frame (7 days) following the end of a declared cyclone.
2. **Using Ex-Tropical Cyclone (ex-TC) tracks** – The longer coverage time period means that the path of downgraded cyclones may cause flooding that would be covered by the Cyclone Pool. The updated analysis considers the track of a cyclone that has been downgraded to a tropical low-pressure system and/or extra-tropical low-pressure system.
3. **Shorter timeframe of historical data used** – The previous analysis used data between 1911-2021, whereas the latest analysis uses 1979-2022 data. This is due to low reliability of ex-tropical cyclone track data prior to 1979.
4. **Modelling changes** – Risk Frontiers have made a number of specific modelling changes including how the likelihood (ARI[2]) of discharge events is measured, adjusting for some biases in their previous modelling and an additional scenario (300km) for the ‘buffer region’ around the cyclone track where rainfall is measured.

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[1] Note that the Risk Frontiers methodology has changed slightly, but this means the results are not directly comparable between the latest Risk Frontiers’ analysis and analysis considered in our Previous Reports.

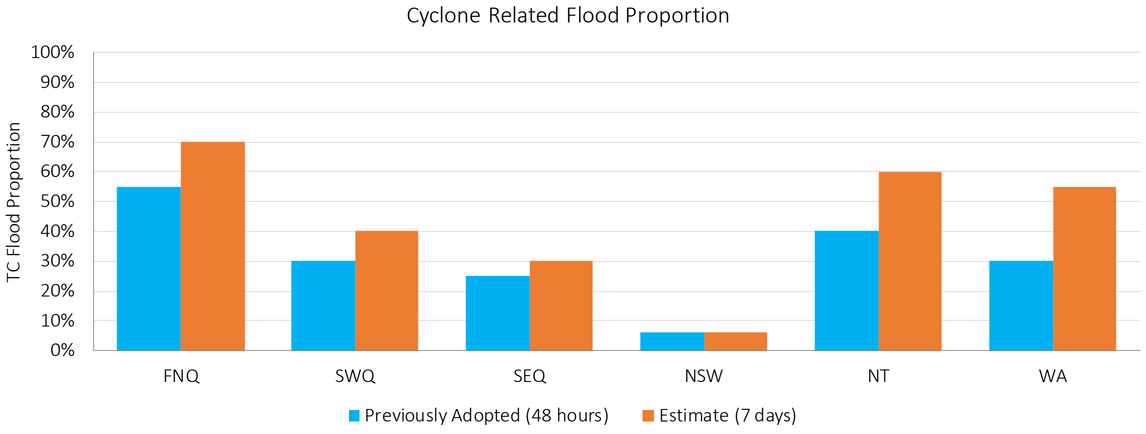
[2] Annual Recurrence Intervals

The latest Risk Frontier analysis shows that more Discharge Events are attributed to cyclones with a 168-hour limit compared to the current 48-hour limit. The number of Discharge Events that could be attributed within 168 hours of a Cyclone Event is ~30% higher than at the 48-hour limit, with increases for Far North Queensland, Northern Territory and Western Australia. The modelling results for South East Queensland and Northern NSW suggest little to no increase for these regions. We note that only 5 river basins in the Northern NSW region north of Port Macquarie were included in the analysis (in addition to the Murray Darling River basin, which spans QLD, NSW and VIC).

Assumed proportion of flood damage caused by Cyclones

Our approach to estimating cyclone related flooding considers various sources, as noted in our Previous Reports, to inform our assumed proportions. We have reconsidered these proportions using the updated Risk Frontiers analysis.

The figure below summarises revised assumed cyclone related flood damage by region with a 168-hour limit compared to our 'previously adopted' selections under the 48 hour definition based on the information available in 2022. The assumed cyclone-related flood damage proportions above are applied to flood model estimates of loss, which include flood arising from storms.



The shorter history of data used introduces additional uncertainty in the modelling results as it is possible that differences relative to the previous analysis may simply be down to data changes and not necessarily a reflection of the change in risk. The differences in methodology in the latest analysis compared to the previous analysis mean that direct comparison to the previous outcomes may not give a correct picture. For the purposes of our modelling, we have relied mainly on Risk Frontiers' assessment of the *change in cyclone related flooding proportions* at 48 and 168-hour thresholds.

From discussions with Risk Frontiers and historic cyclone events, we also understand that the analysis of ex-TC tracks show that these systems can travel southward, which means that the geographical areas where Cyclone Pool claims can arise may include more southern areas. Therefore, we have considered a further scenario in this letter if the estimated cyclone related flooding in SEQ/Northern NSW was higher than those noted in the chart above.

Cyclone Pool premium changes

The additional riverine flood risk assumed from extending the coverage period is estimated to cost an average of \$20-35m (~5% of the Cyclone Pool's current estimate of expected annual claims costs) to the Cyclone Pool each year. This represents the increase in the expected annual cyclone related flooding claims[3] cost (also

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[3] Including expenses

referred to as the "technical cost") to the pool. This is also the amount of additional premium that the pool will need to collect to meet these increased costs.

The way in which the premium is collected is a separate question from the amount. It is essentially the same question as the way in which the premium savings from the pool are distributed across policyholders.

In the analysis set out in this letter, we have assumed that there are no premium rating formula changes and premium rates for different flood risk levels are also unchanged. This means that:

- Certain affected properties pay a higher flood premium due to their increased risk, i.e. they move up to higher premium rate bands because of higher coverage provided to them by the pool under end of DCE + 168 hours versus end of DCE + 48 hours
- However, this doesn't meet all of the increased costs as the pool's current premium structure caps premiums for the highest risk properties, financed by cross-subsidies elsewhere. This means that there remains a residual deficit that the pool has to fund by making other changes to the premium rating formula. A detailed consideration of those changes was outside the scope of this analysis, but for illustrative purposes we have shown a scenario where:
    - 50% of the deficit is funded through an increase in wind premiums for all policies in the Cyclone Pool and
    - the remaining 50% is funded through an increase in the flood premiums for those policyholders paying flood premiums,

The approach indicated here would be subject to further review and pricing decisions if the change were to be implemented. The scenario is intended to balance higher premiums for policies with higher flood risk (i.e. maintaining a risk signal) and spreading/pooling the increase more broadly across all policies so that the premium can be subsidised for the highest risk polices.

Potential insurer pricing response to this change

The impact on end consumers will depend on how insurers adjust their premiums in response to the increased coverage offered by the pool. As a reinsurer, the Cyclone Pool does not set consumer premiums.

The Cyclone Pool's premium to insurers will increase to reflect the additional flood coverage provided, both for individual addresses and in aggregate.

For the purpose of considering and estimating consumer impacts we assume that insurers directly pass on Cyclone Pool premiums to their consumers, while at the same time reducing the premium for risks retained by the insurer based on their assessment of the change in risk.

For an individual consumer, the premium impact of the Cyclone Pool increasing coverage from end of DCE + 48 hours to end of DCE + 168 hours will therefore be the net of the following:

- The degree to which their cyclone related flood risk increases and this translates to an increase in the Cyclone Pool premiums they pay.
- The extent to which insurers recognise the transfer of risk to the Cyclone Pool through premium reductions for the non-cyclone component of consumer premiums.

The insurer's response could span the following:

- If an insurer had already assumed that all cyclone-related flooding occurred within end of DCE + 48 hours, then there may be no offsetting reduction to the premium charge for its retained risk, in which case the consumer would observe an increase as the Cyclone Pool's increased premium is passed on.
- Conversely, if the insurer has previously priced for its estimate of the retained flooding risks occurring between 48 and 168 hours after the end of a DCE, then the increase in Cyclone Pool premiums would be offset by an insurer reducing its premiums. In theory, the greater the flood risk in this extended coverage period, the larger should be the reduction in insurer premium.

The actual impact on an individual consumer's premium is complicated, and will depend on factors such as:

- The insurer's own assessment of flooding risk and the models they use. Even where the same models are used, an insurer might differ in how they translate these models to consumer premiums.
- The margins the insurer adds, which will differ between insurers.
- The approach the insurer has adopted already to pass on Cyclone Pool rates to its consumers.
- The sophistication of consumer premium calculation algorithms to directly reflect the Cyclone Pool rates, if this is the insurer's strategy.
- Renewal premiums may be affected by capping and collaring of increases/reductions that will also need to be considered by the insurer.
- Some flooding might theoretically be attributed to cyclones in regions like Southern NSW and Victoria. In our experience, insurers do not charge for cyclone risks in these areas and flooding is considered to not be cyclone related.

The above factors, and others, will mean that there will be "noise" in consumer outcomes beyond that implied in our analysis.

Cyclone Pool premium impacts – Base scenario

As noted above the consumer impact will be a combination of the change (increase) in Cyclone Pool premium and the change (decrease) in the insurer premium for the insurer's retained risk. We deal first with the Pool premium increases and then with the insurer premium reductions.

If we assume the technical cost increase is $27m (i.e the middle of the $20-35m range), we estimate that increases to the Cyclone Pool premiums, under the current formula, for these affected properties will collect an extra $12m as some properties move into a higher flood risk rating band.

This is shown by region in the table below.

	Change in Flood Tech Cost	Change in ARPC Flood Premium
State group	*$m*	*$m*
SEQ	14	9
FNQ	4	1
SWQ	6	2
NT	1	0
WA	3	1
NSW	-	-
Total	27	12

SEQ accounts for more than 50% of the overall increase in the risk cost and Cyclone Pool premiums. The estimates are most sensitive to the cyclone related flooding assumption for SEQ and Northern NSW, where insured exposures are large. Also the cyclone-related exposure is more likely to arise from tracking of an ex-TC than from a direct hit.

To maintain cost neutrality of the pool, the $15m gap between technical cost and extra premium collected will need to be funded by increases in premium elsewhere. There are a number of ways that the Cyclone Pool may adjust the Pool's cross-subsidies structure to share these increases, but as noted earlier our illustration is based on an approach where:

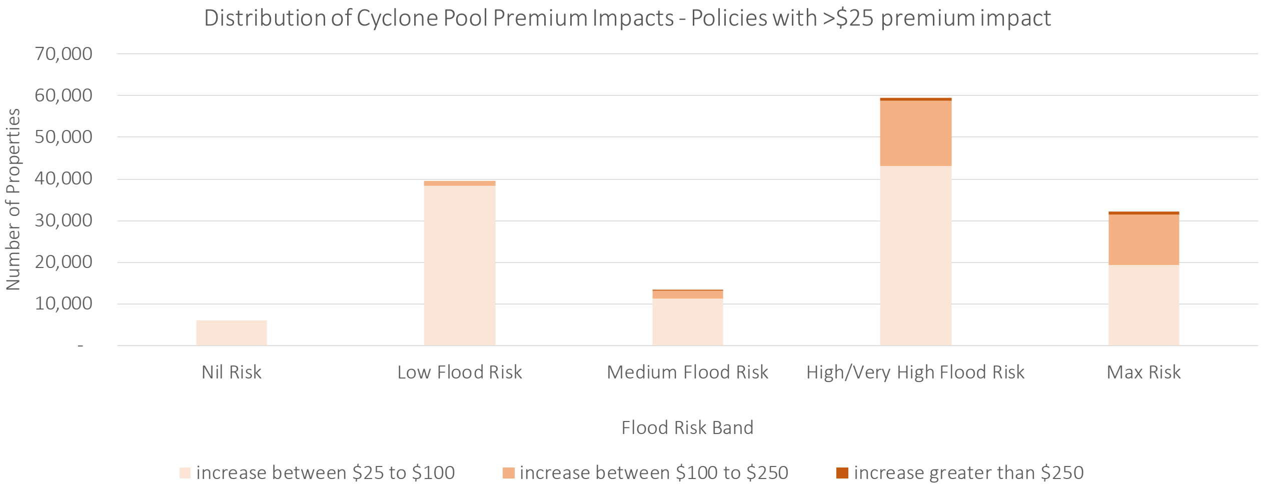
- 50% of the deficit is funded through an increase in wind premiums for all policies in the Cyclone Pool
    - ~1.5% increase in Wind premiums under this base scenario
- 50% is funded through an increase in flood premiums
    - ~10% increase in Flood premium under this base scenario

For the vast majority of Home building properties that do not have flood risk (~90%), there is a negligible Cyclone Pool premium increase (in the order of $2 on average) as the premium algorithm would increase their wind premium component to fund some of the deficit in the pool.

Roughly half of flood exposed properties (4.6% of all properties) will see pool premium increases of less than $25 each ($8 on average), with the other half of flood exposed properties seeing more substantial increases of $77 each on average.

	168 hr base scenario	
ARPC Premium impact	Proportion of policies	Average increase ($)
Nil Flood Risk	90.0%	2
With Flood Risk	10.0%	45
Increase <$25	4.6%	8
Increase >$25	5.4%	77

The chart below shows how much the Cyclone Pool premium would increase (normalised for a $500k sum insured property) for Home building policies with premium increases above $25 (5.4% of properties).



Some Nil Flood risk policies, in high Wind risk regions, see premium increases of around $34 on average. This is an outworking of the way that we have assumed half of the Pool's funding shortfall will be addressed through a 1.5% Wind premium increase. The same occurs for low Flood risk policies in high Wind risk regions.

Around ~22% of flood exposed properties (mostly the High-Maximum flood risk ones) have an increase in their Cyclone Pool premium of more than $100; the remainder would have premium increases of less than $100. This is predominantly due to the increase in the level of flood cover they are provided by the Cyclone Pool under the 168 hours extended coverage.

Just over half of the Very High-Maximum flood risk properties with $100+ pool premium increases are located in the Northern NSW and SEQ region. These regions have considerable underlying flood risk (cyclone and non-cyclone related) and are large population centres, which means that a small increase in the attribution of flood risk to cyclones results in a reasonable increase in the Cyclone Pool premium for consumers. However, these consumers stand to benefit most from an offsetting premium reduction from insurers (depending on how the insurer assesses its corresponding reduction in risk).

Consumer premium impacts – Base scenario

In the event that insurers do not adjust its premiums for the extra risk that would be carried by the Cyclone Pool (i.e. insurers do not offset the Cyclone Pool premium increases), the Cyclone Pool premium impacts shown above will also reflect the final consumer premium outcomes.

However, if we assume the insurer reduces its retained premium for extra flood risk transferred to the Cyclone Pool, then we would expect those with very high flood risk to have an overall premium reduction (subject to the "noise" described earlier).

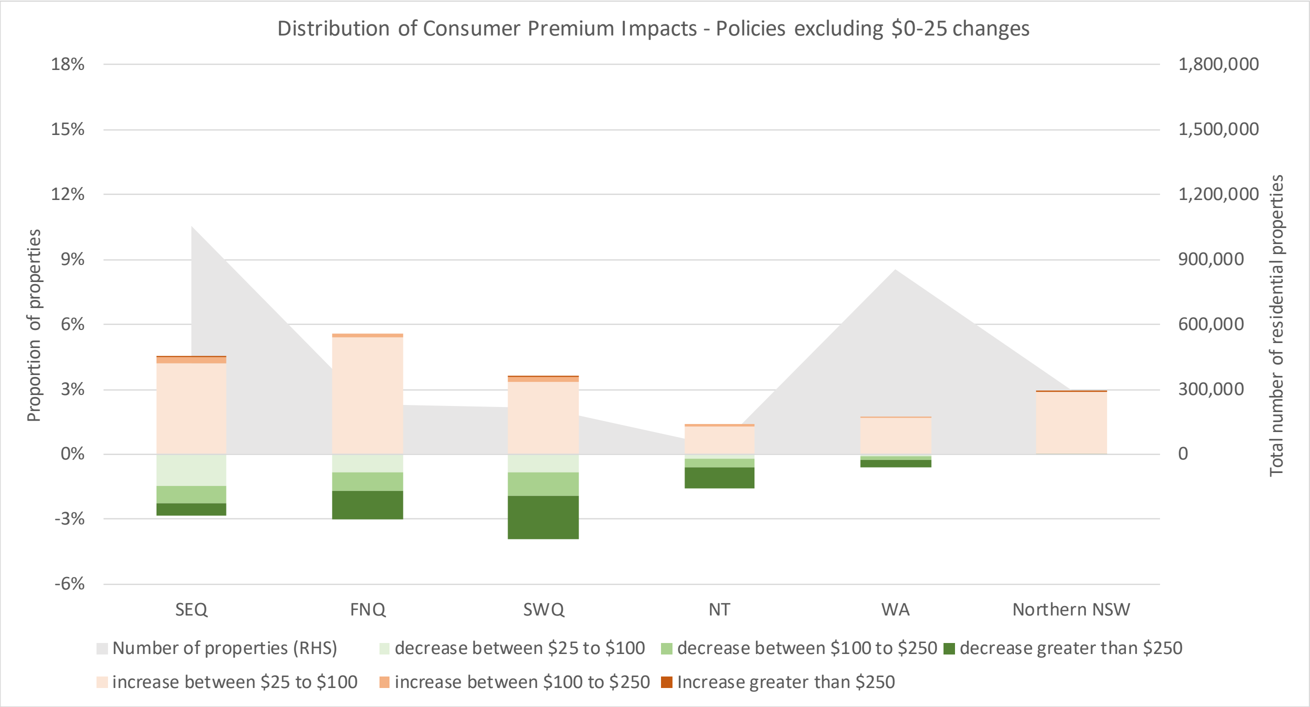
Below we assume that the insurer removes only the technical cost estimate (i.e. without margins) to offset the Cyclone Pool change ; in this theoretical example the aggregate reduction in insurer premiums is equal to the extra premium collected by the Cyclone Pool reflecting the transfer of risk from the insurers to the Pool, but with overs and unders by policy. The table shows the proportion of Home buildings policies receiving a premium decrease versus those receiving a premium increase at the consumer premium level under this scenario.

	168 hr base scenario	
Customer Premium impact	Proportion of policies	Average increase/ decrease ($)
Decrease	3.9%	(134)
Decrease >$250	0.6%	(604)
Decrease <$250	3.2%	(44)
Increase	**96.1%**	4
Increase <$25	92.7%	2
Increase >$25	3.4%	48

The vast majority of policies (92.7%) receive a small premium increase averaging $2 as they fund the gap in the pool i.e their final premium increase is the same as their Cyclone pool premium increase. 3.4% of policies face a higher increase of greater than $25, with an average of $48.

3.9% of policies receive a premium reduction averaging $134. For the most extreme 0.6% of policies the reduction would average $604.

The chart below shows the regional breakdown of the consumer premium impact with all regions, except South West Queensland, seeing a slightly greater proportion of policies with premium increases than premium reductions.



While more policies by number have premium increases than have decreases, this is consistent with the overall pool design where premium is collected from lower risk groups (of a smaller average amount) to enable subsidies to the highest risk groups (of a larger average amount).

Higher Northern NSW/SEQ scenario

The updated Risk Frontiers analysis covered a shorter historical period (43 years) than in their previous analysis (111 years). This was because the updated analysis considered the tracks of ex-TC storms, which was more reliably estimated with satellite data that only became available from the late 1970s. This meant that any differences in the cyclone experience in the last 43 years compared to the longer 111 year history can affect their results. In light of this, we have considered a scenario assuming 5% higher cyclone flood proportions in SEQ and Northern NSW. For SEQ we increase the proportion from 30% to 35% and Northern NSW from 11% to 16% to allow for the longer time period for Cyclone/ex-TCs to travel southward into SEQ and NSW and cause damage that is covered by the Pool.

Cyclone Pool premium impacts - higher Northern NSW/SEQ scenario

The technical cost of moving to an end of DCE + 168 hour coverage period under this scenario increases by $43m compared to the end of DCE + 48 hour coverage period. The Cyclone Pool premium, again assuming that the same approach is followed for setting the premium rates, will collect an extra $17m from the existing Flood premium formula, leaving a $27m gap.

	Baseline scenario vs 48 hours			Higher SEQ/NSW scenario vs 48 hours			Difference	
	Change in Flood Tech Cost	Change in ARPC Flood Premium	**Gap**	Change in Flood Tech Cost	Change in ARPC Flood Premium	**Gap**	Tech Cost	ARPC Flood Premium
State group	*$m*	*$m*	***$m***	*$m*	*$m*	***$m***	*$m*	*$m*
SEQ	14	9	**6**	25	12	**13**	11	3
FNQ	4	1	**2**	4	1	**2**	-	-
SWQ	6	2	**4**	6	2	**4**	0	0
NT	1	0	**1**	1	0	**1**	-	-
WA	3	1	**2**	3	1	**2**	-	-
NSW	-	-	**-**	5	1	**5**	5	1
Total	27	12	**15**	43	17	**27**	16	4

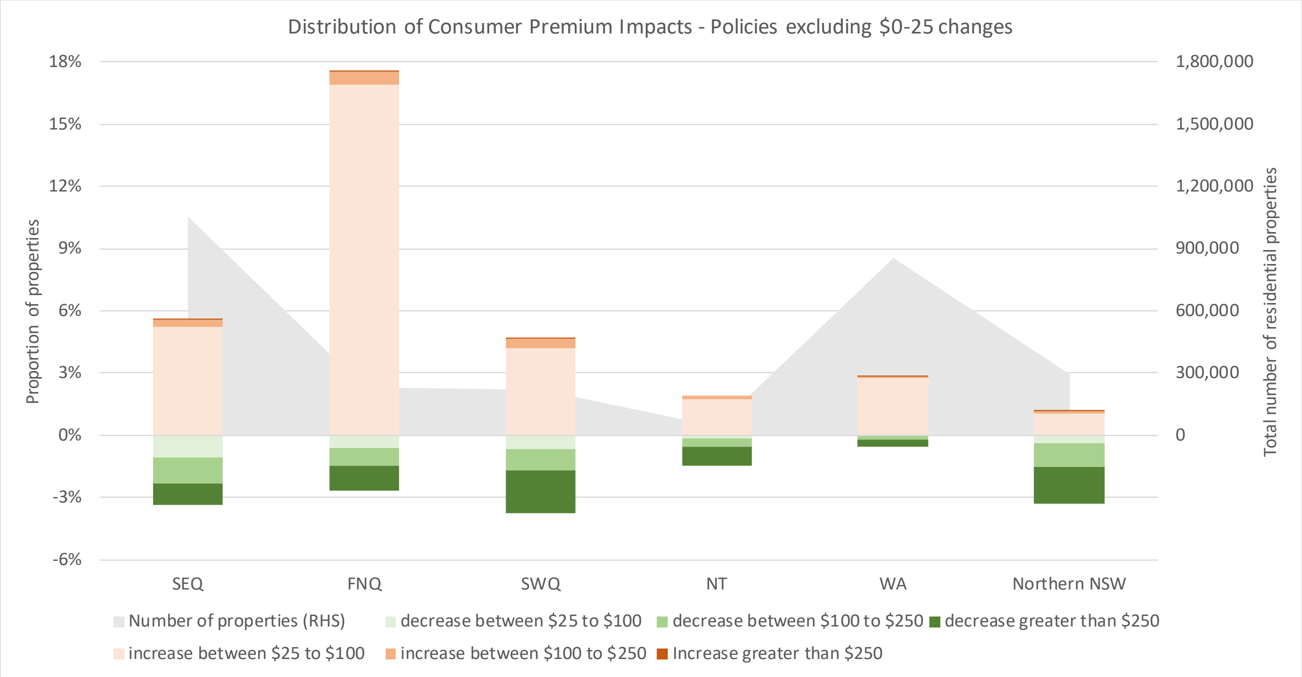
The extra gap will need to be funded by increasing the Cyclone Pool's premium rates more generally. To illustrate the point, if we take the initial $15m gap in our base estimate and average that across ~3 million insured Residential properties in cyclone affected regions, it would give an average increase of $5 per property for the Cyclone Pool premium. In this higher Northern NSW/SEQ scenario, the average Cyclone Pool premium increases would have to roughly double from $5 to $9 per policy to meet the larger funding gap.

Consumer premium impacts - higher Northern NSW/SEQ scenario

At a consumer premium level, we note that a similar proportion of policies (albeit not the same ones) receive a premium decrease, with the average premium reductions increasing to $187. Offsetting this is a greater proportion of policies (5.1% vs 3.4% in the earlier scenario) that will have a premium increase of more than $25.

	Higher NSW/SEQ scenario		168 hr base scenario	
Customer Premium impact	Proportion of policies	Average increase/ decrease ($)	Proportion of policies	Average increase/ decrease ($)
Decrease	3.8%	(187)	3.9%	(134)
Decrease >$250	1.0%	(540)	0.6%	(604)
Decrease <$250	2.8%	(65)	3.2%	(44)
Increase	**96.2%**	6	**96.1%**	4
Increase <$25	91.1%	3	92.7%	2
Increase >$25	5.1%	52	3.4%	48

The figure below shows the estimated consumer impact under this scenario by the location of the policyholder.



A greater proportion of policies in SEQ and Northern NSW receive premium reductions in excess of $100 under this scenario. For SEQ and NSW, there are an additional 9,700 and 8,400 policies receiving $100+ premium reductions. Of these, 10,000 additional policies receive $250+ premium reductions.

Offsetting these reductions are smaller premium increases ($25-$100) for policies mainly in FNQ, WA and SEQ, with an estimated premium increase for close to 50,000 additional policies under this scenario. This is an inevitable consequence of redistributing costs, and reflects the necessary trade-offs in the operation of the Cyclone Pool i.e that smaller cross subsidies from a large number of policies are used to provide larger benefit to a much smaller number of higher risk policies.

Other considerations

Extending flood coverage periods may lead to some practical issues that we have not explicitly considered in our scenarios presented in this letter, but would need to considered. This may include the following circumstances:

- Additional wind damage and water ingress post the Cyclone being downgraded but within the 168-hour window
- More time for the ex-cyclone system to join up with other weather systems and cause practical claims cost apportionment issues between what's covered by the pool versus private market
- Coverage for ex-cyclones that go out to sea and then re-emerge on land as a storm.
- Cyclone rain causing a dam to fill up followed by a subsequent relatively minor rainfall that causes flooding because of the dam is already at capacity (and vice-versa).
- Changing to a 168-hour time limit will also increase the potential for pluvial flood (flash flood) to be covered by the Cyclone Pool. Pluvial flood losses under the current 48-hour limit would typically occur near the cyclone affected areas, and therefore may be considered as part of the cyclone loss estimates. Pluvial losses after 48-hours but within 168-hours have not been quantified as part of this analysis.

Coverage under 48 hours vs 168 hours limits

The Cyclone Pool provides coverage for 48 hours AFTER the end of a declared cyclone. The change being discussed is for this to be extended to 168 hours. That is, there is a further 168 hours of coverage after the declared cyclone has ended.

Private sector reinsurance arrangements have a range of hours clauses, with a 168-hour clause being common for flood. The way this operates is that the insurer can choose a 168-hour period within which it can aggregate its insured losses for the purpose of calculating reinsurance recoveries. Insurers typically start from the first instance of loss arising from an event, from which cover extends to losses 168 hours thereafter; however, the insurer can choose a 168 hours period that is most favourable (i.e., when it will receive the most recoveries).

The operation of the Cyclone Pool's hours clause has not been generally well understood. The current legislation provides insurers coverage for losses for the duration of the declared cyclone, up to when it ceases having cyclonic wind speeds, and then 48 hours after that. A cyclone lasting 30 hours will mean the Cyclone Pool covers a total of 78 hours. That is, the total coverage from the Cyclone Pool will always be more than 48 hours.

If the Cyclone Pool coverage were to be extended from end of DCE + 48 hours to end of DCE + 168 hours, without other offsetting changes to coverage, the total coverage period would be the duration of the cyclone plus 168 hours; in the case of a 30-hour cyclone, this will be a total of 198 hours coverage. This is more coverage than typically available in the private excess of loss catastrophe reinsurance programs.

While a change to 168 hours will be seen by industry as being comparable to current reinsurance programs, the reality is that this may not be the case. The subsequent cyclone-related flooding for Cyclone Ellie (discussed below) would not be covered under the extended time limit, while conventional reinsurance programs may have (depending on the 168 hours block of highest loss to the insurer, noting the limited damage during the time Ellie was still classified as a cyclone).

Flood damage examples from Cyclone Ellie, Cyclone Jasper and Cyclone Kirrily

Three recent cyclones, Ellie (December 2022), Jasper (December 2023) and Kirrily (January 2024), led to widespread flooding after the cyclones had weakened to ex-tropical cyclones.

Cyclone Ellie, occurring on 22 and 23 December 2022 over NT and WA, caused relatively minor damage at the time. Much of the damage occurred as the ex-TC remained in the region, leading to significant rainfall. The river peaks measured in the Risk Frontiers' analysis occurred on 1-3 January 2023, more than 168 hours after the cyclone was downgraded.

Data for Cyclone Jasper was not included in the Risk Frontiers analysis because it occurred after the period of the data relied upon. Jasper made landfall on 13 December 2023, and decreased to an ex-tropical cyclone on 14 December 2023. Risk Frontiers' report comments that floods peaked on 17 December 2023, which would be more than 48 hours, but less than 168 hours, after. The BOM website also provides the following commentary:

"As a result, heavy to intense rainfall fell over the north tropical coast area. This rainfall fell in river catchments that were already wet due to earlier rainfall from Jasper's landfall and produced widespread flooding in the region."[4]

The 48-hour time limit would likely mean that some flooding would be covered by the pool and some would not. Extending the time limit would probably have meant that all flooding would have been covered by the pool,

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[4] http://www.bom.gov.au/cyclone/history/jasper23.shtml

which has an operational benefit of avoiding disputes about when the flood damage occurred at a particular property.

Tropical Cyclone Kirrily, occurring 24 - 26 January 2024, brought heavy rainfall and flooding in the Townsville area and as an ex-TC continued to track west and impacted inland QLD for several days and weeks following its initial landfall, and interacting with other weather systems in the process. The 7-day window from when the cyclone was downgraded also included significant rainfall and flooding in the SEQ region. While this flooding hasn't been attributed by BOM to Cyclone Kirrily, it is not at all clear how an extended 168 hour coverage period might have responded to Kirrily. This is a good example of one of the practical considerations arising from extending the coverage period.

Limited basis of our estimate

Unlike our Previous reports where the purpose was to inform the setting of Pool premiums, this letter has a narrower scope, being to assess the potential impacts of increased coverage, and the work was completed over much shorter timeframes. Therefore, the indicative estimates presented in this letter assume no changes to the premium rate setting process. That is, we make all the same decisions in setting the premium rates with the only change being the higher flood costs from the longer coverage period and a simple apportionment of the resulting deficit in the pool's premiums. The premium setting process is complicated and involves a number of decisions being made in the process, each of which would be reviewed when determining premium rates.

We had limited time to undertake this analysis and test our findings with relevant experts. Subsequent analysis with the fullness of time, including considering other information sources and discussions with experts, may result in a different methodology or assumptions being adopted compared to those in this note.

Only one source of information, the updated Risk Frontiers analysis, was relied upon to estimate the impact of moving from a 48 hour to a 168 hour coverage period. As with any modelling exercise, there are proxies and limitations in the Risk Frontiers analysis, such as the short historical time period of data analysed (long time horizons are needed for low frequency and volatile events such as cyclones) and that the analysis uses basin discharge events as a proxy to a flood occurring. We would investigate if other approaches or models were available if this change were to be implemented, which would plausibly lead to different assumptions being made by Finity.

We have also relied on previous models of flood losses. Updates to flood models may lead to different modelled costs.

We have not included estimates of additional pluvial losses that might be covered.

We have not assumed any changes to the propensity of currently uninsured consumers or consumers that have opted out of flood cover to now purchase flood cover given the additional coverage provided by the pool.

Reliances and limitations

This letter and the analysis contained herein summarises work completed solely for ARPC. The reader acknowledges the limited basis (set out above) of the analysis shown in this letter.

Insurers, or any other third party, should recognise that the furnishing of this report is not a substitute for their own due diligence and should place no reliance on this report or the data contained herein which would result in the creation of any duty or liability by Finity to the third party.

We have relied on the findings of Risk Frontiers' report commissioned by ARPC for the purpose of informing this work. We have not independently verified Risk Frontiers' findings nor have we independently validated its data or research. We have reviewed the findings for reasonableness and suitability for the purpose of this report.

We remain available to answer any questions which may arise regarding our report and conclusions. We assume that users of this report will seek such explanation and/or amplification of any portion of the report that is not clear.

Yours sincerely

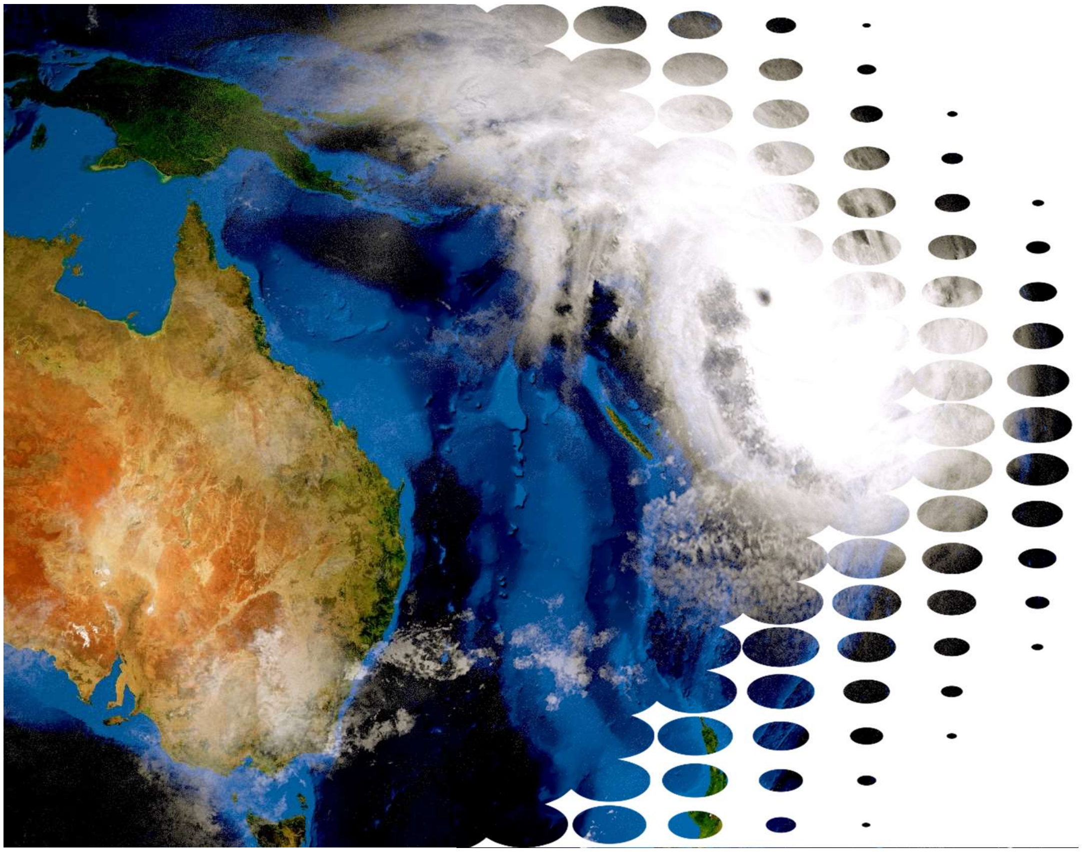
Gokul

Stephen Lee

Gokul Chandrasekaran

Tropical Cyclone Flooding

2024 Review



Australian Reinsurance
Pool Corporation

May 2024

	Release history	Date	Author	Reviewer
V0.1	**Interim Draft**	**03/04/2024**	**M. Marin**	
V0.2	Final Draft	15/04/2024	M. Marin	J. O'Brien
V0.3	**Final**	**17/04/2024**	**M. Marin**	**J. O’Brien**
V1.0	Draft including additional validation	24/05/2024	M. Marin	J. O’Brien

Risk Frontiers Disclaimer

Table of Contents

Overview

The Cyclone Pool established by the Australian government and overseen by the Australian Reinsurance Pool Corporation (ARPC) commenced operation on July 1st, 2022. The reinsurance pool covers residential, strata and small businesses property insurance policies in all regions of Australia under Tropical Cyclone (TC) threat.

In 2022, Risk Frontiers was tasked by ARPC to investigate the frequency and severity of flooding events attributable to TCs in Australia. Results were calculated based on the current definition of a cyclone event (i.e., 48 hours after the end of a cyclone) as well as an extended period of 72 hours. Results at the time indicated that the 48-hour period was not sufficient to capture the majority of flooding peak timing especially in larger river basins. This is because in larger basins, river flow accumulation takes longer to reach the downstream most point than in a smaller basin. This first study did not take into consideration that after a TC has decayed to a Low, its associated rainfall can remain extreme and cause major flooding with extensive insured losses. This was the case of TC Jasper which made landfall in northern Queensland on December 13th, 2023, as a Category 2 TC just north of Cairns. Despite minimal wind damage, Jasper lingered over northern Queensland for several days as a Tropical Low with record breaking rainfall falling in nearby catchments causing major flooding, peaking on December 17th, 48 hours after the declared end of the TC event.

Here, we review the work that was done previously in several ways. First, we investigate how many more TC related floods would be captured with extended periods of 4 (96 hours) and 7 (168 hours) days. We also explore the impacts of extending the 150 km buffer used to select impacted catchments for a given TC track in the 2022 analysis to 300 km. Further, we attempt to correct any biases in the Synthetic Unit Hydrograph (SUH) discharge model by validating and calibrating the timing of the modelled flood peak against observations. An in-depth analysis of the impact of the extended definition in a region spanning southeast Queensland and northeast New South Wales is also performed. Finally, we repeat the analysis for two distinct historical periods, 1979-2000 and 2001-2022, to identify changes due to a possible slowdown of TCs (Kossin, 2018) leading to extended rainfall periods and totals, increasing the severity of TC related flooding.

Methodology

Dataset

Although we intended to use the same data and methods used for the 2022 work, the additional scope of this project necessitates utilising different datasets.

Extra-tropical cyclone tracks

Extending the event definition period from 2 to 4 and 7 days after a TC has ended requires that tropical Low and extra-tropical Low transitions of TCs are tracked to extend the path of the TC and correctly assess where TC induced rainfall is occurring, even after the TC is downgraded. For this purpose, the TC tracks are from a database which is a combination of extra-tropical cyclone (XTC) tracks derived by Risk Frontiers and the Bureau of Meteorology best track historical TC database. The XTC tracks extend the Bureau's best track database and the combined database (Figure 1) covers all TCs occurring within the Australian region from the 1979-1980 to the 2021-2022 cyclone seasons. When considering extra-tropical cyclones, tracks extend much further south, covering basins south of 25°S where TCs tend to decay rapidly.

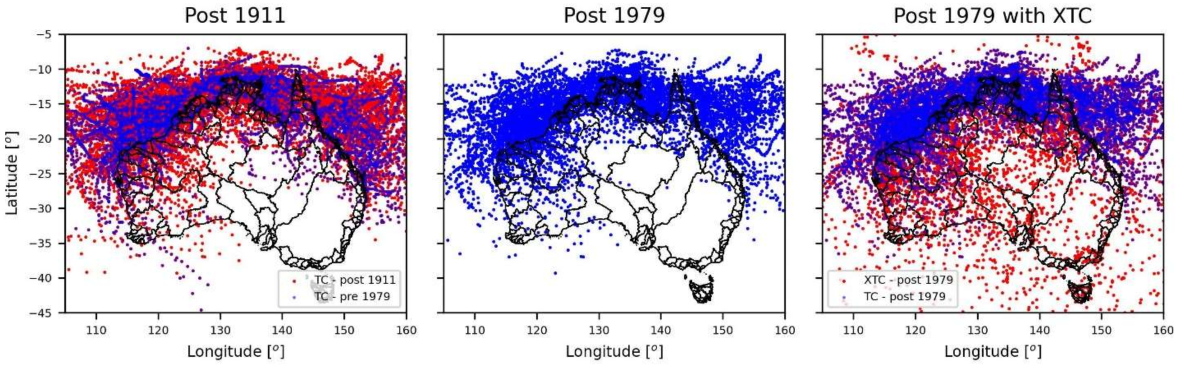


Figure 1: Distribution of historical tropical cyclone locations from the Bureau of Meteorology best track database. The left panel shows the distribution of all locations in red from the 1910-1911 to 2021-2022 cyclone season and only locations prior to the 1979-1980 season in blue. The middle panel shows the distribution of tropical cyclone locations after 1979 used here is shown in the middle and right panels. The right panel adds to this the distribution of the extratropical cyclone track locations (red) derived by Risk Frontiers. Only tropical cyclones that tracked within 200km of the Australian coastline were plotted. Note that the left panel shows the distribution of tracks used in the initial tropical cyclone flooding analysis which differs slightly (for events after 1979) to the one used here shown in the middle and right panels.

Note that our analysis only covers TCs after the 1979-1980 season. While the previous work used the Bureau's cyclone database extending back to 1911, the accuracy and reliability of TC tracks prior to the beginning of satellite era (1979) is reduced. Using this shorter time series dataset increases our confidence in the results for the project.

Streamflow Observations

Validation of the discharge model was done against the streamflow discharge timeseries database provided by the Bureau of Meteorology and available on Water Data Online (2014). This database collects streamflow data from a range of local organisations, totalling more than 6000 gauges across Australia. The data is provided as hourly maximum discharge values in cubic meters per second (cumec).

Model Validation

To estimate the flood timing and intensity of a given rainfall event for all catchments, we use the Synthetic Unit Hydrograph (SUH) discharge model as was used in the 2022 work (Sherman, 1932). A SUH describes the direct runoff response of a river to one unit of constant intensity uniform excess rainfall (runoff) occurring over the basin and is therefore representative of the discharge state at the downstream most point of the basin. Discharge events were modelled from the same AWRA-L daily runoff event-set used previously but only for the period 1979-2022. While this method is necessary to model discharge in catchments with no relevant observations, this might lead to a delayed flood peak timing for larger basins in the case of a localised intense rainfall event or a bias in the peak discharge value due to the assumptions of the model misrepresenting the characteristics of a basin.

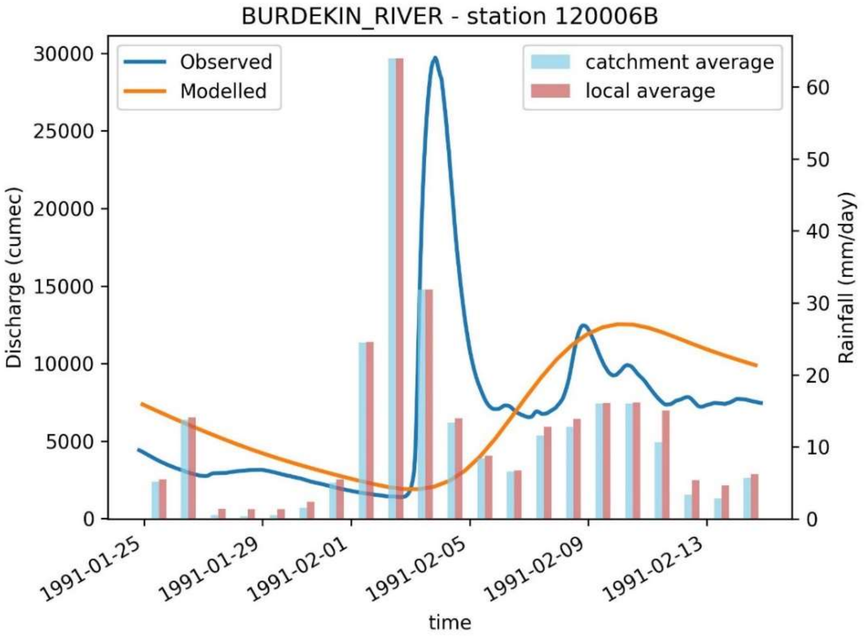


Figure 2: Example of a rainfall event in the Burdekin River basin. Observed (blue) and modelled discharge (orange) timeseries are shown on the left axis in cubic meters per second. The corresponding observed daily cumulated rainfall totals (mm/day) are shown on the right axis (bars). Both catchment-averaged (blue) and event-averaged (red) rainfall totals are shown. Event-averaged rainfall is derived by dividing total catchment rainfall by the area where rainfall was observed. Differences in values show that a given rainfall event was localised (not distributed over the whole catchment).

To validate the model to observations, the downstream most streamflow gauge was selected for a given catchment which was determined by selecting the gauge with the highest 90th percentile value. The validation was undertaken for six catchments of interest chosen to represent a range of total catchment areas, climate, and that have seen significant historical floods in the past:

- Brisbane River
- Barron River
- Ross River
- Burdekin River

- Pioneer River
- Swan Coast Avon River

For all observed discharge peaks, modelled peak discharge values and time were extracted to assess the error and lag of our model. In some cases, observed discharge events were not associated with modelled discharge events due to the absence of any significant rainfall. This might be due to a range of factors including streamflow instrument errors or errors in the rainfall (i.e., runoff) observations. These events were discarded from the validation.

Model Calibration

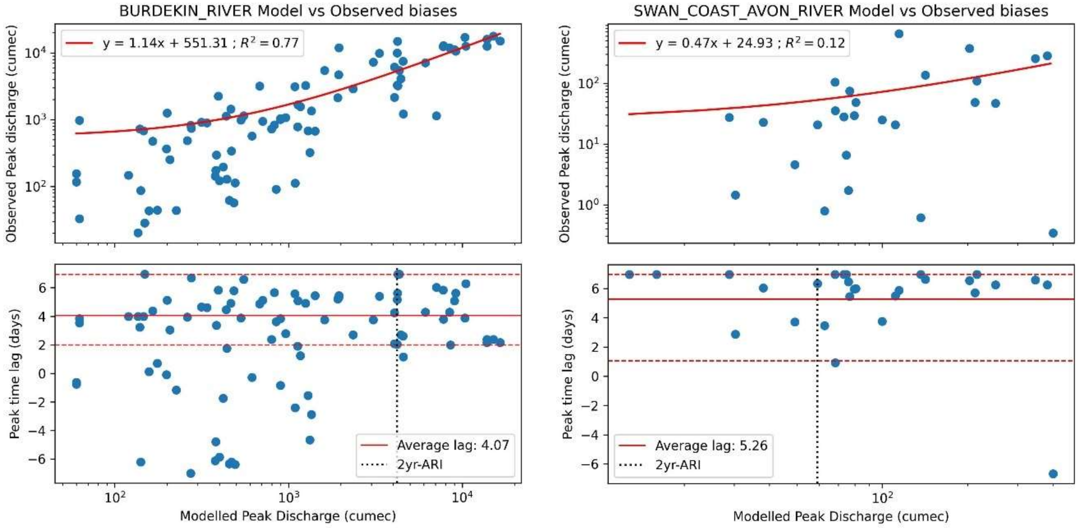


Figure 3: Synthetic Unit Hydrograph validation for the Burdekin River (left) and the Swan Coast Aon River basin (right). top) Scatterplot of modelled vs observed peak discharge from the downstream most gauge. The best linear fit and the line equation is shown in red. bottom) Scatterplot of modelled peak discharge vs the lag between the observed and modelled peak. A positive lag corresponds to a delayed modelled flood peak compared to observations. The average lag of modelled events above the 2-year ARI is shown in red, along with the 10th and 90th lag percentile (dashed).

The validation process detailed above allows for an assessment of the quality of our model for estimating the intensity and timing of an event (Figure 3). Using validation results, we can calibrate our model to remove any consistent errors leading to biases in the results. We focus on the calibration of the modelled flood peak timing as it plays a crucial role in assessing if a given TC event definition captures a given flood peak or not. Biases in discharge values tend to have a linear relationship where bias correcting would be difficult to implement and have minimal impact on results. To correct for any consistent biases in the timing of modelled flood peaks, we construct a model of the average lag as a function of basin area from the validation results of the six basins of interest. Due to a larger spread of peak timing for weaker events, only modelled events above the 2-year Average Recurrence Interval (ARI) were used to extract the average lag so that the bias correction is more representative of extreme events.

Flood Distribution Modelling

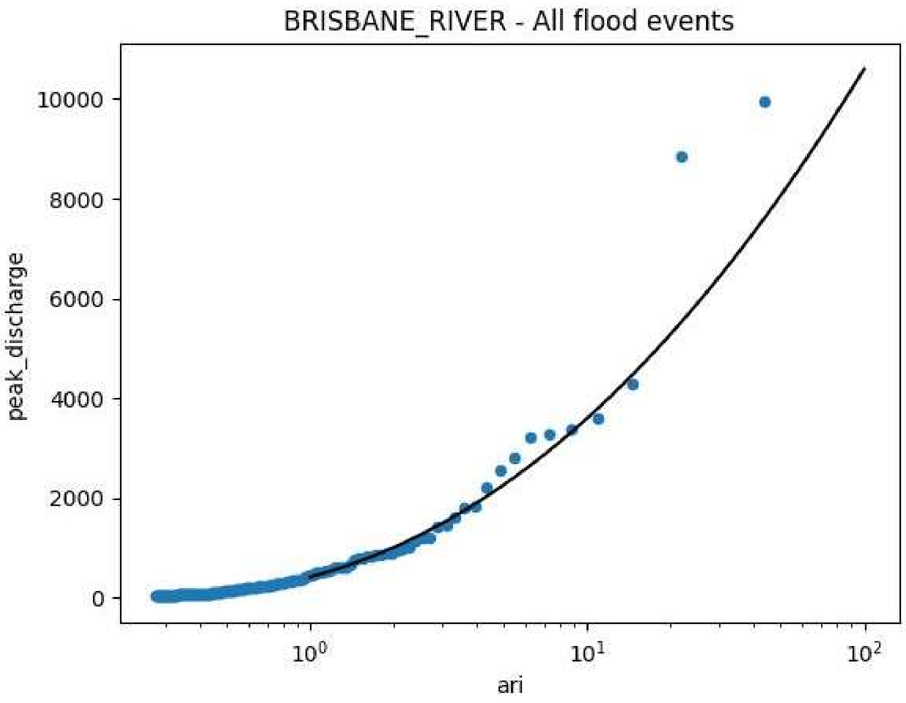


Figure 4: Example of modelled exceedance probability curve from all modelled flood events in the 1979-2022 period at the Brisbane River catchment.

A generalised extreme value (GEV) distribution is fitted to all modelled flood peaks using the method of linear moment (L-Moments, Hosking and Wallis, 1997) for each basin (Figure 4). This model is used to assign an estimated return period for a given discharge value. In contrast to the work of 2022, distributions were fitted to all flood peaks (modelled from runoff events above the 90th percentile), and not solely using annual peak discharges. This modification was made to be more consistent with attributing return periods to TC-related flood events which can occur several times a year and might be over-estimated if only using annual peaks to model the distribution (i.e., discharge values for a given ARI are higher here compared to the 2022 version). This translates to a lower number of events being equal or above a given ARI.

Attribution of Flood Events to Tropical Cyclones

The attribution of flood events to a given TC was calculated for each basin within a 150-km and 300-km radius of the TC track. For all basins within this radius, the maximum modelled river discharge during a flood event (see 2022 report) intersecting with the period of the TC track was selected as the maximum flood attributable to that TC. If no significant rainfall was observed during a given TC event at a given basin, the maximum flood is set as null.

To investigate how well a TC event definition (as defined by ARPC) captures the maximum flood peak, the maximum flood within the window spanning from the beginning of the event (i.e., first time when a TC reaches Category 1) to 48/96/168 hours after the end of the event (i.e., time when the TC decays to tropical/extra-tropical low and doesn't re-intensify within a 48/96/168 hours, respectively). To account for the calibration of the flood peak timing, the time window was extended by the 2-year ARI average lag identified in the model validation.

Please note that the implementation of the ARPC TC event definition for periods of 48,96 and 168 hours may cause a given TC track to be split into two (or more) events if there is a period equal or larger to the hours clause where the TC is downgraded to a Low but subsequently re-intensifies. The TC tracks used to select the maximum attributable flood to a given TC was the one resulting from the 168 hours definition, which had the least amount of re-intensification (i.e., the smallest count of TC events).

Eastern Basins Analysis

The southeast Queensland and northeast New South Wales regions are of particular interest as they are located at the limit of TC track locations (Figure 1) and boast an extensively more significant exposure than northern regions of Australia. Extending the definition of an event and considering XTC transitions is expected to increase TC flooding risk in these regions. Therefore, we investigate the changes in hazard risk in basins included in these regions (western boundary: 150°E, eastern boundary: 160°E, southern boundary: 40°S, northern boundary: 25°S) with a particular focus on the Brisbane River and Richmond River catchments.

The runoff data used to model discharge at each basin is extracted for each XTC event that impacted the region in the last 44 years to compare the return periods of the rainfall and discharge events. The length of a runoff (rainfall) episode is important when considering flooding. For example, an intense 1-day rainfall episode might be enough to drive flooding in a small sized catchment. On the contrary, larger catchments are less likely to be sensitive to short episodes. Therefore, we extract 1-day 2-day and 3-day cumulative runoff maximums during each XTC event at the basin resolution and compute return periods relative to all cumulative runoff peaks from 1979 to 2022. For a given XTC event, only runoff occurring between the start and end of the event (defined by ARPC, considering the 168 hours definition) is considered. Return periods are estimated using the same technique used to model discharge return periods.

Results

Validation & Calibration

Validation of the SUH discharge model against streamflow observations for the 6 catchments of interests showed significant correlation for all catchments of interest except for the Swan Coast Avon River catchment (Figure 3)

Model discharge peak

Swan Coast Avon River is a large coastal catchment extending well inland. Rainfall events in large catchments are more likely unevenly distributed, favouring more intense rainfall near the coast. Therefore, a runoff event would be concentrated in a smaller region and the SUH model would underestimate discharge values. This was the case for the July 1983 event when the rainfall event stalled near the coast of western WA (not shown). In contrast, when rainfall events are more evenly distributed over the catchment (such as in January 2000), the model performs better (Figure 5). We note that the Swan Coast Avon River catchment did not have any significant flooding caused by TCs during the studied period.

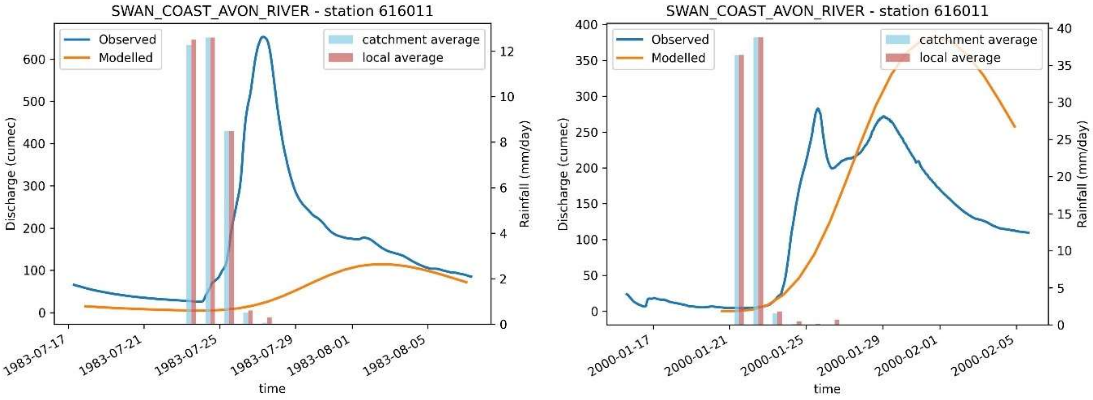


Figure 5: Example of significant rainfall event occurring in July 1983 (left) and January 2000 (right) in the Swan Coast Aon River catchment. Observed (blue) and modelled (orange) discharge timeseries are shown in cubic meters per second. Catchment (blue) and event footprint (red) averaged daily runoff amounts are shown by the bars on the right axis. Footprint averages are runoff totals averaged over the total are of the runoff footprint (not including the area where it did not rain).

While the Burdekin River catchment is of comparable size to the Swan Coast Avon River catchment, validation results showed a significant positive correlation between observed and modelled discharge (Figure 3). This might indicate that extreme runoff events have an evenly distributed pattern across the catchment. The Burdekin River catchment is in northern Queensland with a sub-tropical climate characterised by extremely wet summers, especially on the coast. Therefore, extreme runoff events might be occurring when significant additional rainfall falls in inland parts of the catchment, in which case the assumptions of the SUH model are good.

Model discharge lag

Differences in modelled and observed flood peak timing showed that modelled peaks were consistently delayed compared to observed peaks in most catchments of interest. Although the spread of timing differences was large for weaker events, modelled peak timing showed a consistent bias for more severe events (Figure 3).

Figure 6 shows the relationship between catchment area and the average model lag of all events above the 2-year ARI at the 6 catchments of interest. The 2-year ARI was chosen to better capture the model lag of extreme flood events, which is the focus of the project, while having a large enough number of events. Results show that the model lag increased with the catchment area exponentially.

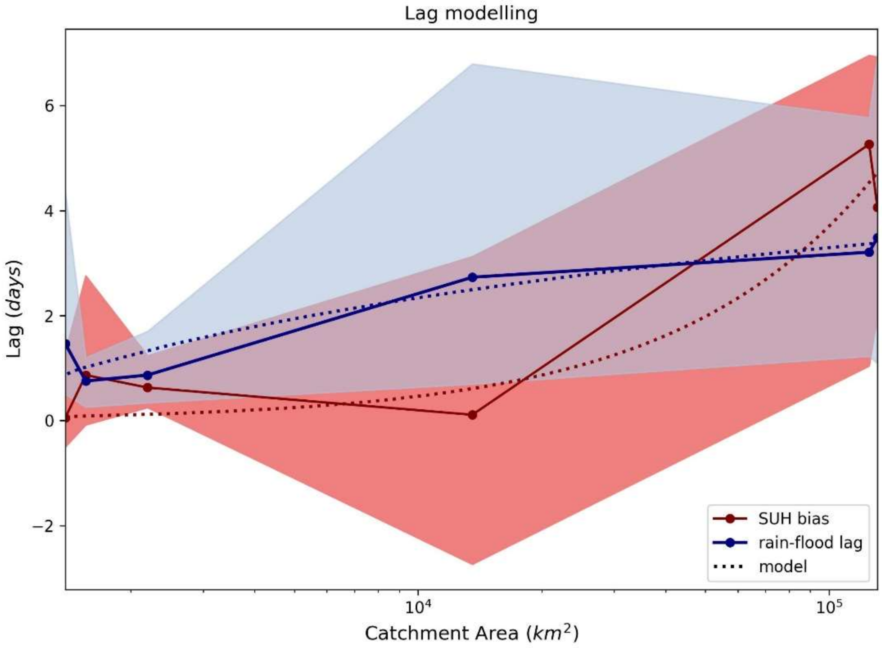


Figure 6: Average model lag (red) for events above the 2-year ARI as a function of catchment area for the six validation catchments. The shading represents the 80% confidence interval. The corresponding lag between observed flood peak and observed maximum daily rainfall total is shown in blue. The best exponential and logarithmic fit are shown by the dotted lines for the model lag and flood-rainfall lag, respectively.

To calibrate the model peak flood timing, we fitted an exponential function to model the lag difference as a function of catchment area (dotted line in Figure 6). The model lag correction was given by the following equation:

$$Lag(x) = 0.031068 * \ e^{0.902345\frac{x}{500}}$$

Where x is the total catchment area in km². Please note that for catchments larger than 150,000 km², we cap the model lag to 5.34 days, as this exponential behaviour might not hold for large catchments.

Tropical Cyclone Flooding

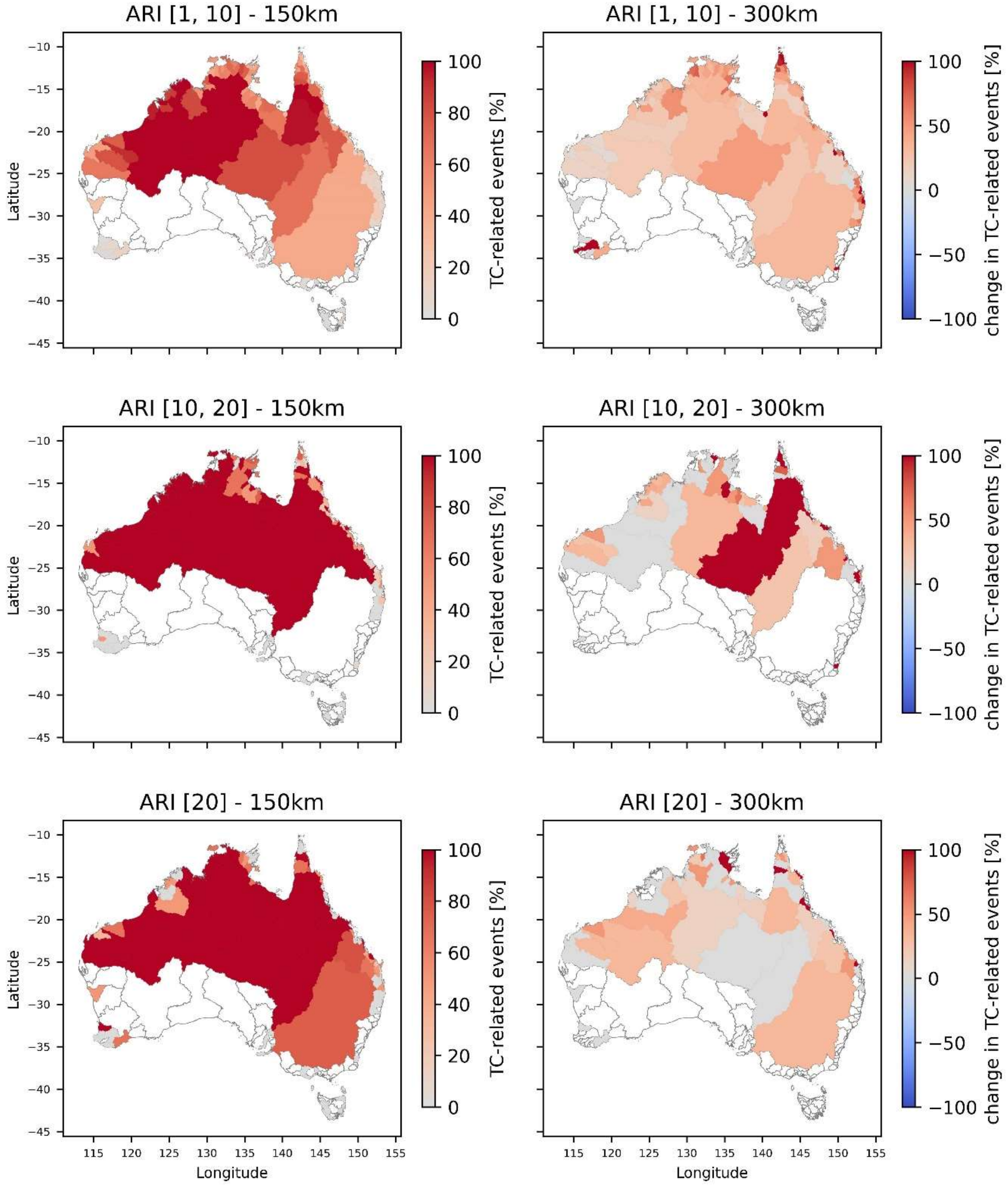


Figure 7: Proportion of flood events with a return period of 1 to 10 years (top), 10 to 20 years (middle) and above 20 years (bottom) related to tropical cyclones when considering a 150km buffer around cyclone tracks for catchment selection (left). The change in the proportion of flood events related to tropical cyclones when considering a 300km buffer is shown on the right.

In most medium to large size river catchments spanning from northwest Western Australia to Queensland, a large proportion of flooding events above the 1-year ARI are related to TCs (Figure 7). On the other hand, results indicate that extreme flood events are not often associated with TCs in small catchments especially for events above the 20-year ARI. We note that TCs do not cause major flood events in most catchments below 25°S latitude.

When considering a larger (300km) track buffer radius to select catchments potentially impacted by TCs, results show an increase of ~20% of the number of flood events caused by TCs globally. This increase is more pronounced in some small coastal catchments where a small percentage of flood events are related to TCs. This suggests that some extreme rainfall events caused by TCs might occur outside a 150km radius. In the case where a given rainfall event expands further than 150km away from the track into a larger catchment, the extreme rainfall footprint would have likely been limited to a small fraction of the catchment, yielding low catchment-averaged rainfall totals and therefore no significant flooding. Despite a less significant increase in larger catchments, the 300km radius does capture more events which can relate to an increase in rainfall footprint for TCs reaching inland areas and decaying to extra-tropical Lows. Increasing the radius of catchment selections might however lead to an increase in false positives, where a large basin is "clipped" by the increased radius, while another, TC or non-TC rainfall system is causing most of the rainfall.

Event definitions Comparison

To assess how well various definitions of a TC event period can capture the flood peak of TC-related flood events, we compute the percentage of the number of TC-related flood events captured for a given definition. A value of 100% suggests that the definition captures all TC-related event flood peaks.

For TC-related flood events above the 1-year ARI, results show that the 48-hour definition only captures most of the peak flood events in small coastal catchments, while 0-20% of events are captured in medium- large catchments. Increasing the event definition to 96 and 168 hours after the end of a TC increases the number of events captured in medium-large catchments. However, the proportion of events captured remains below 50% for these catchments, even when considering a 168-hour definition (Figure 8). Similar results are observed when only considering the more severe TC-related flood events above the 10-year ARI (Figure 9).

Bias correcting the modelled flood peak lag allowed for a larger number of TC-related flood events to be captured in medium-large catchments. On average, 50% more events above the 1-year ARI were captured when using a 48-hour definition (Figure 8). Although the bias correction impact was slightly decreased when using a 168-hour definition, it appeared critical in capturing events above the 10-year ARI. Between 50 and 100% more events were captured in medium-large basins when using bias-corrected results for the 48-hour and 96-hour event definitions (Figure 9).

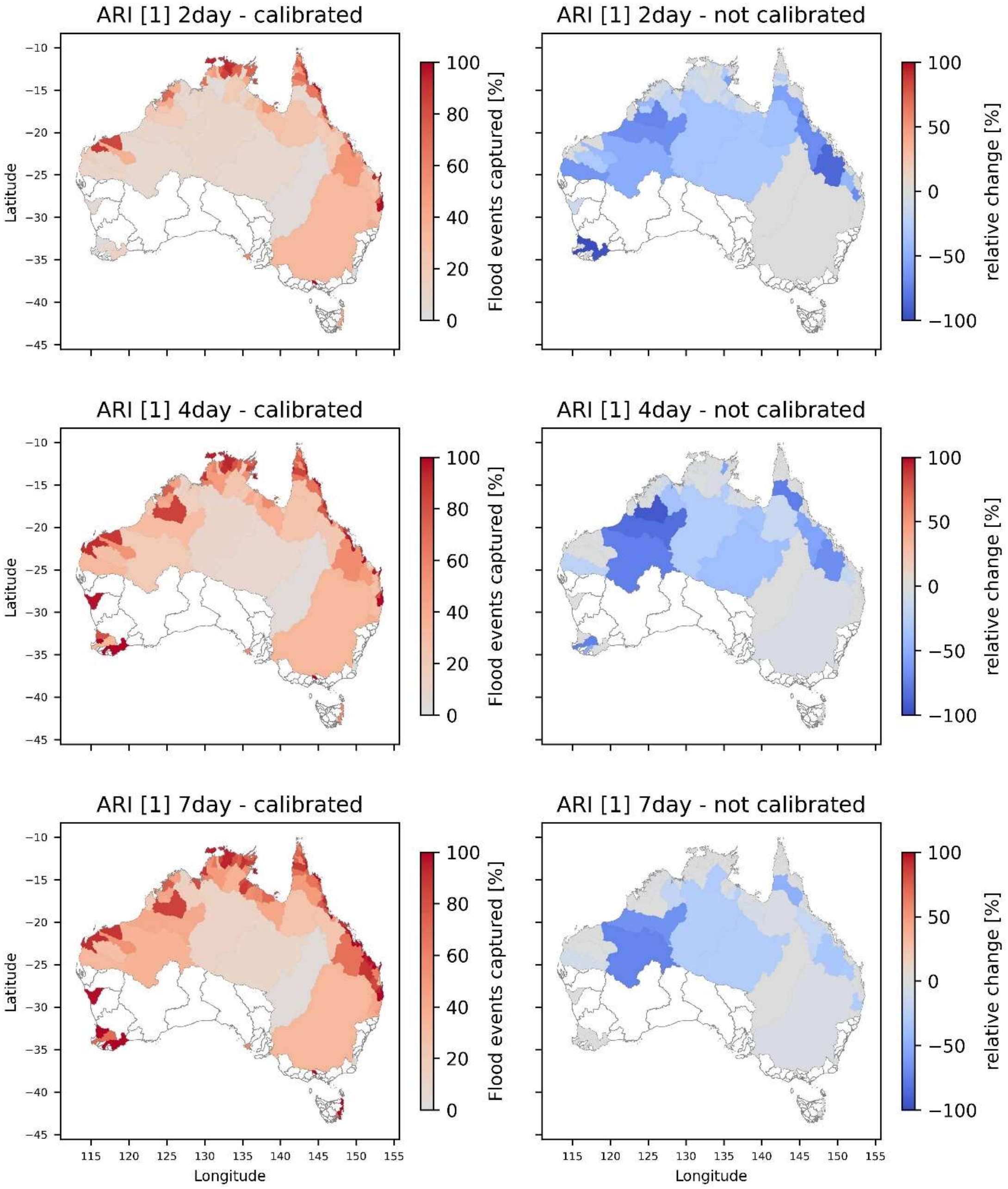


Figure 8: Percentage of TC-related flood peaks captured by the 48h,96h and 168h event definition for events above the 1-year ARI (left). Results are derived from bias-corrected modelled flood peaks using a 150km buffer around TC tracks. The relative change of percentage of TC-related flood peaks captured by a given definition using non calibrated results is shown on the right. A decrease in percentage suggests that the bias correction allows a higher percentage of events to be captured.

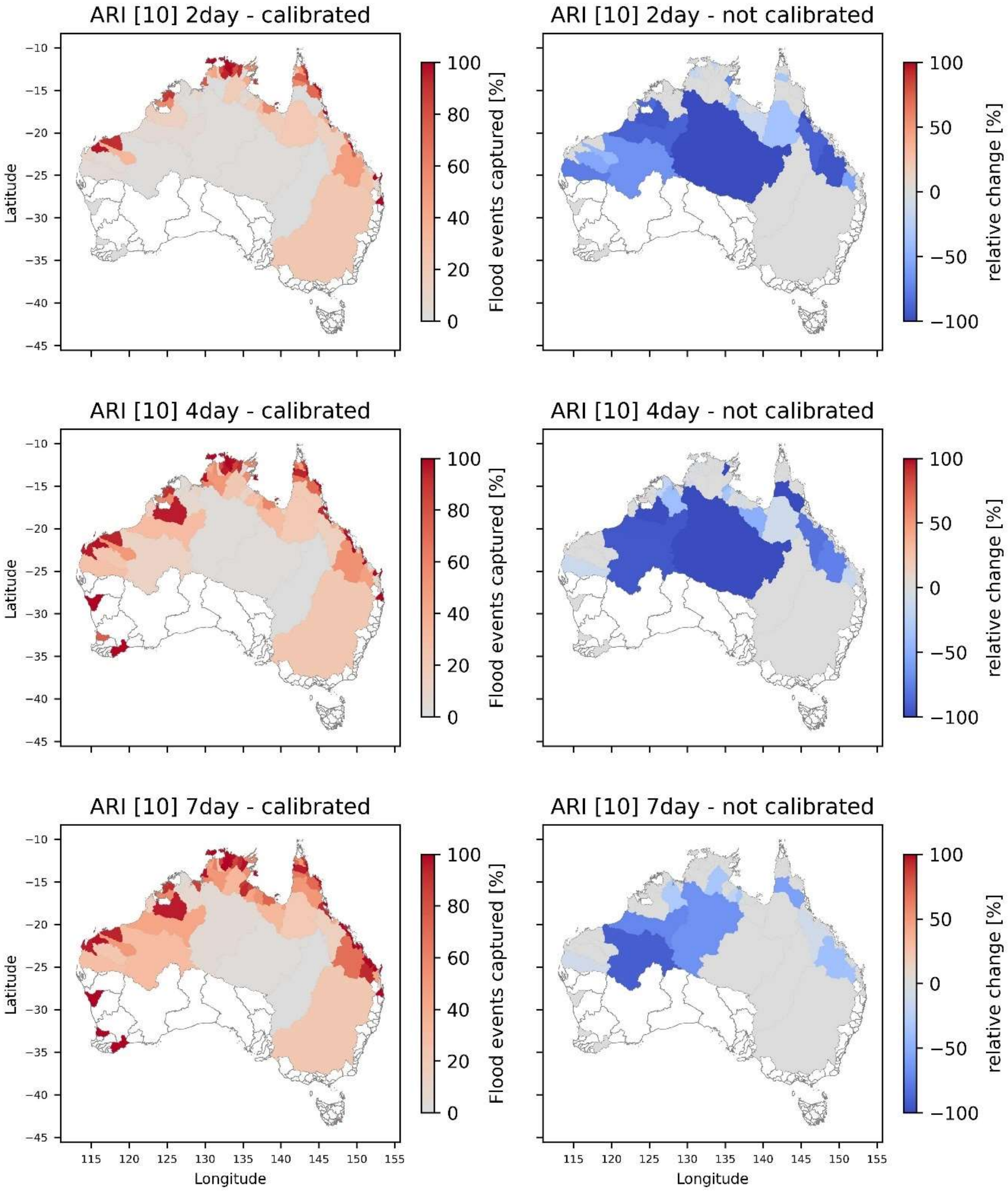


Figure 9: Same as Figure 8 for TC-related flood events above the 10-year ARI.

Figures 10 and 11 show the proportion of TC-related flood peaks captured by the three event definitions as a function of catchment area for events between the 1-year to 10-year ARI and events above the 10-year ARI, respectively. Results show a decreasing trend in the ability of all definitions to capture TC-related flood peaks with catchment area. Moreover, the 48-hour event definition captures the lowest number of events across all catchment sizes. For lower intensity flood events (e.g., between 1-year and 10-year ARI), increasing the time-period definition to 96 hours allows 10-20% more events to be captured. Differences are larger for medium size catchments between 1,000 and 100,000 km^2 (10^9 – 10^{11} m^2). When increasing the definition from 96 to 168 hours, the increase of the proportion of events captured is not significant, remaining around 5-10% throughout all catchment sizes.

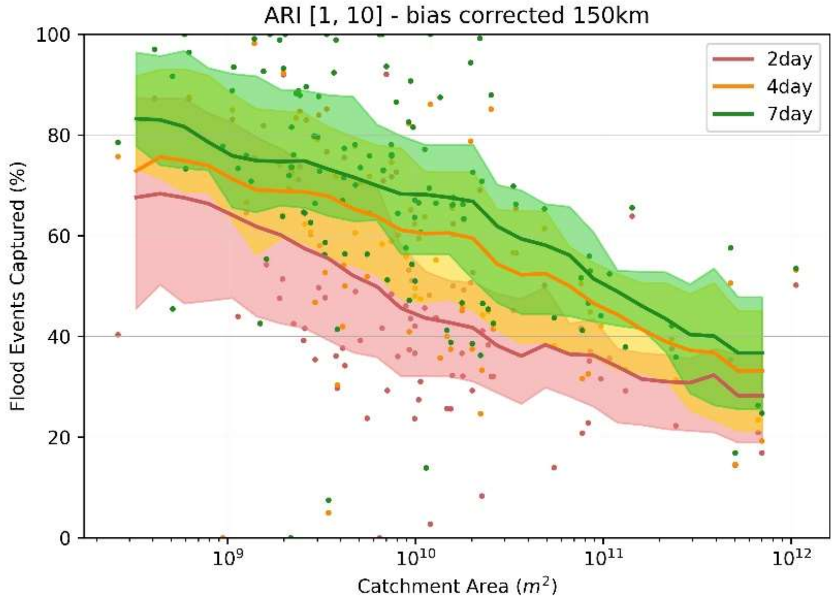


Figure 10: Scatterplot of the proportion of TC-related flood peaks captured by the 48h (red), 96h(orange) and 168h(green) event definition for events between the 1-year and 10-year ARI against catchment area in squared metres. The solid lines and shaded areas represent smooth binned median and quarters, respectively.

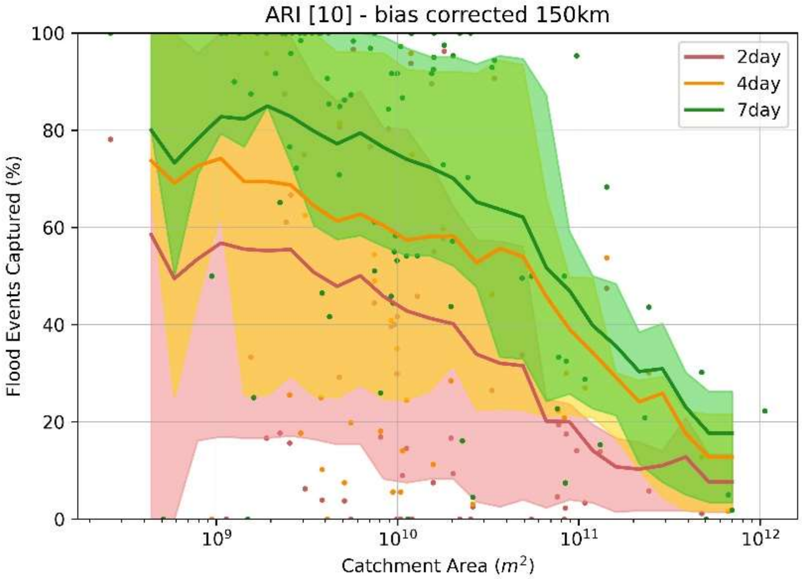


Figure 11: Same as Figure 10 for TC-related flood events above the 10-year ARI.

TC-related flood events above the 10-year ARI, the difference between the 96-hour and 168-hour definition increases significantly (Figure 11). In catchments smaller than 100,000 km², the 168-hour definition captures 70-80% of all TC -related flood events, while the 96-hour definition only captures 60% of events. For larger catchments, results suggest that there is no significant difference between the 96-hour and 168-hour definitions, while the 48-hour definition fails to capture any event .Please note that even if the 48-hour definition might be enough to capture flood events in small catchments, these events are usually not related to TCs (Figure 7).

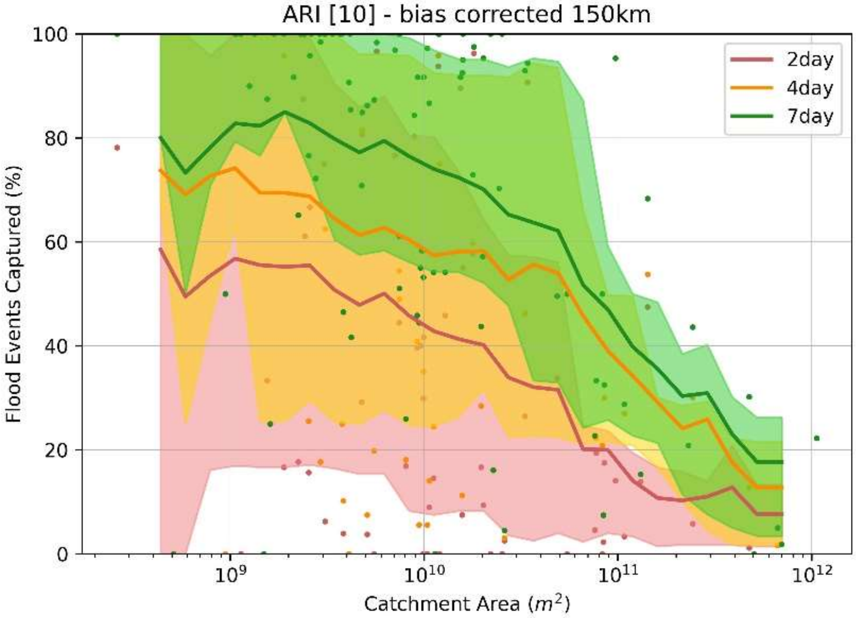


Figure 10: Scatterplot of the proportion of TC-related flood peaks captured by the 48h (red), 96h(orange) and 168h(green) event definition for events between the 1-year and 10-year ARI against catchment area in squared metres. The solid lines and shaded areas represent smooth binned median and quarters, respectively.

Eastern Basins Analysis

Figure 12 shows the total number of events impacting basins of southeast Queensland and northeast New South Wales (defined as eastern basins hereafter) during the last 44 years considering different definitions. The left panel indicates that between 5 and 15 XTCs have tracked nearby (150km) and were associated with a significant (above 90th percentile) runoff event. Larger inland catchments have seen more events due to their larger size. The second panel shows the same statistics for TC tracks that do not consider XTC transitions, as was used in the original work of 2022. We see that for most catchments south of 27°S, the number of events decreased to less than 5, while catchments to the north retain many events. This shows that when introducing extra-tropical transitions, there is an increased likelihood of an event tracking in these catchments. The two panels to the right show the number of events that caused flooding above the 2-year ARI when using a 48-hour definition and the difference when not considering XTCs. Only between 1 and 2 events with a discharge above the 2-year ARI was observed in all coastal catchments except Moreton and Stradbroke Island. In most of them, there was one less event when only considering TC tracks. We note that when only considering TC tracks, both the Brisbane River and Darling River catchments did not observe TC-related discharge events above the 2-years ARI. The change in the number of events above the 2-year ARI due to the extension of the definition period is shown in Figure 13. The 96 hours extension does not change the number of events except in the Darling River basin and small coastal basins in the north of the region. Even extending the definition to 168 hours does not increase the number of events significantly. In fact, the only additional event captured by the 168-hour definition is the flooding induced by TC Oswald in 2013, which had decayed for almost a week but still caused important flooding in the eastern basins.

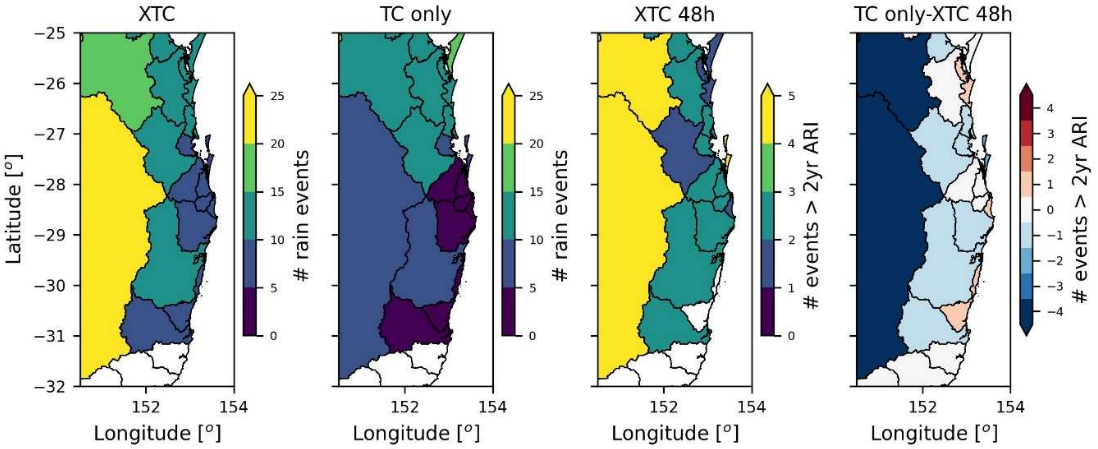


Figure 12: (left panels) Number of rainfall-inducing XTC and TC-only events from 1979 to 2022 in eastern basins. An event was considered rainfall inducing if it tracked within 150km of a given catchment and was associated with a rainfall event between the start and end of the event as defined by ARPC when considering a 168-hour definition. (Panel 3) Number of events inducing a discharge above the 2-year ARI when considering a 48-hour definition. (Panel 4) Bias of the number of events inducing a discharge above the 2-year ARI in the TC-only database used in the original work of 2022.

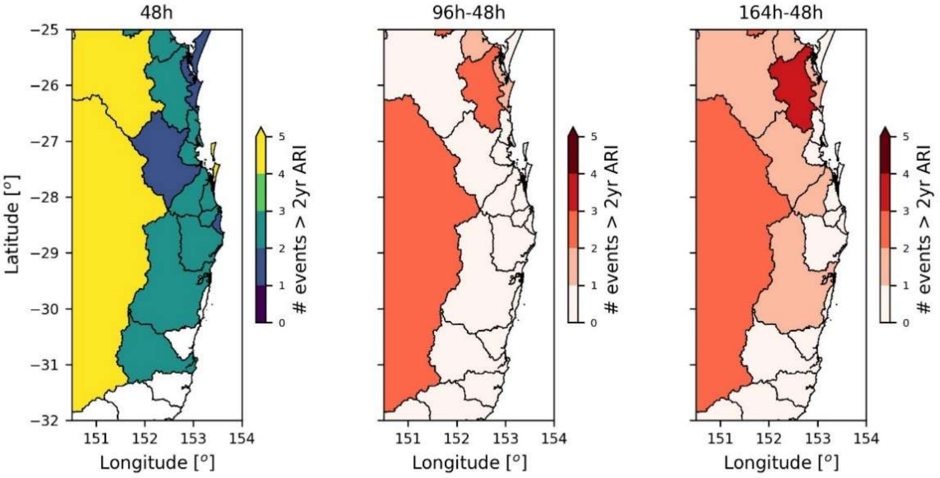


Figure 13: Number of events inducing a discharge above the 2-year ARI when considering a 48-hour definition (left) and the change associated with a 96-hour (middle) and 168-hour (right) definition

We further investigated whether despite no significant impact on the number of events, an extended definition could change the severity of events. The average ARI of events above the 2-year ARI for various definitions is shown in Figure 14. Results indicate that extending the definition of a cyclone event do not change the average ARI of events captured in catchments below 27°S. Nevertheless, there is a significant increase in average ARI when considering the 96-hour definition in the Brisbane River and Fitzroy catchments, indicating that a longer period is more adequate to capture the flood peak, rather than increase the number of events, for these moderate sized catchments. Results also show that the exclusion of XTC tracks does not decrease the severity of events either in southern catchments, but have a significant impact on catchments north of the Brisbane River basin. We note that the sharp decrease of average ARI in the Logan River basin is driven by the absence of Debbie in the TC-only database (i.e., 48-hour definition did not capture the previous modelled discharge peak), which caused significant flooding to the region as an extra-tropical cyclone.

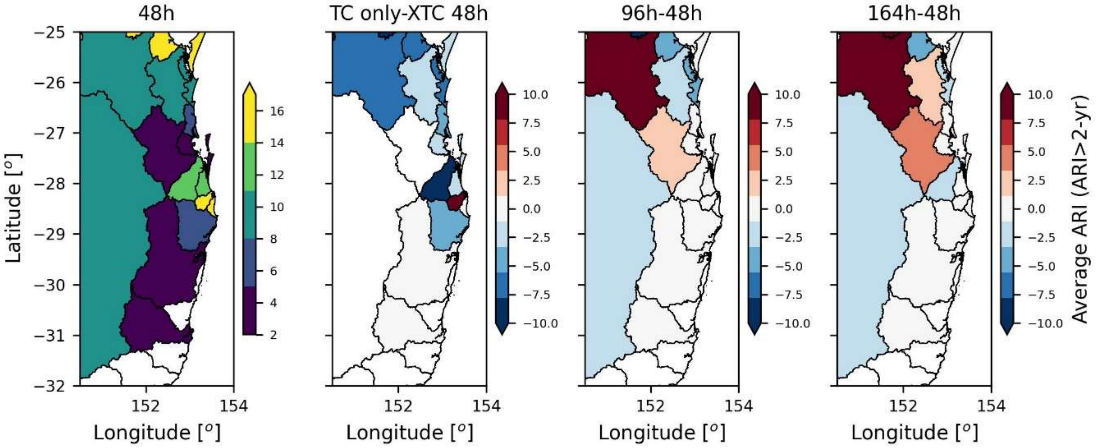


Figure 14: Same as Figure 12 and 13 for the average ARI of TC-related discharge events above the 2-year ARI.

Brisbane River Basin

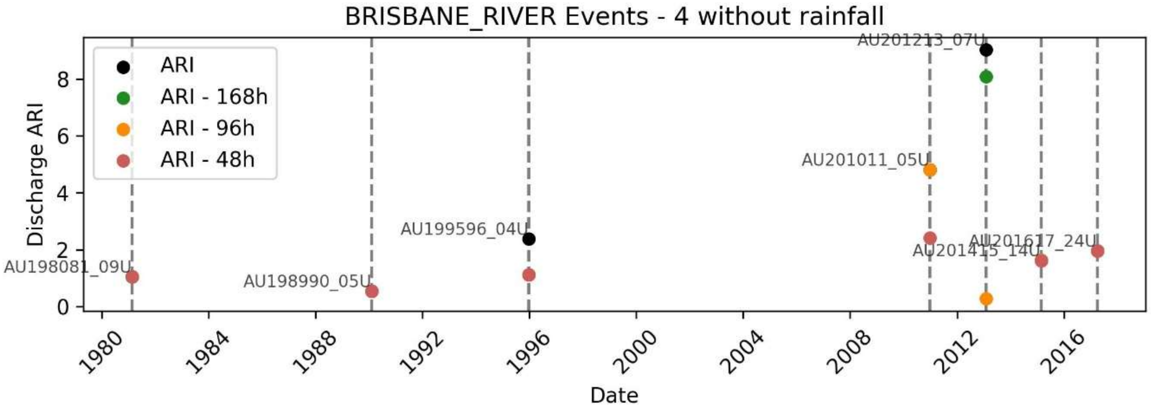


Figure 15: Timeline of TC-related discharge events' ARI since 1979 in the Brisbane River basin for various event definitions. The maximum flood ARI not considering any event definition is shown in black. Note that when different definitions captured the same ARI, their corresponding point is confounded.

Most of the 7 TC-related flood events observed in the Brisbane River catchment had a maximum ARI below 2-year (Figure 15). We note that 4 additional events were not associated with any significant rainfall (not shown). The strongest event was TC Oswald in 2013, with a modelled discharge ARI of 9-years. Results show that the 48 hours period captures the maximum ARI for most events, except for TC Tasha in 2011 and TC Oswald in 2013. Both events tracked near the Brisbane River catchment well after having decayed. The 96 hours definition was long enough to capture TC Tasha's maximum ARI, but only the 168 hours period was long enough for TC Oswald. The distribution of maximum runoff events shows good agreement between the severity of the maximum runoff (e.g., rainfall) and discharge for each TC event (Figure 16), with only Tasha and Oswald's associated maximum runoffs being over 2-year ARI. This further illustrates the ability of the discharge model to accurately represent the intensity of rainfall events in the Brisbane River catchment.

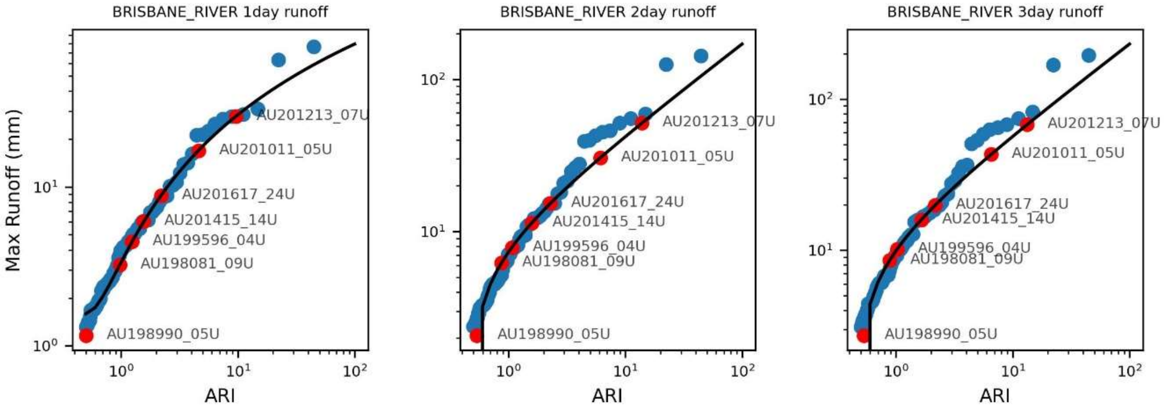


Figure 16: Exceedance probability curve of 1-day (left), 2-day(middle) and 3-day(right) maximum cumulative runoff events from 1979 to 2022 in the Brisbane River basin. The black curve shows the modelled distribution used to attribute the probability (ARI) of maximum cumulative runoff values for each TC event (red). Note that both the x-axis and y-axis are plotted on a logarithmic scale.

Richmond River Basin

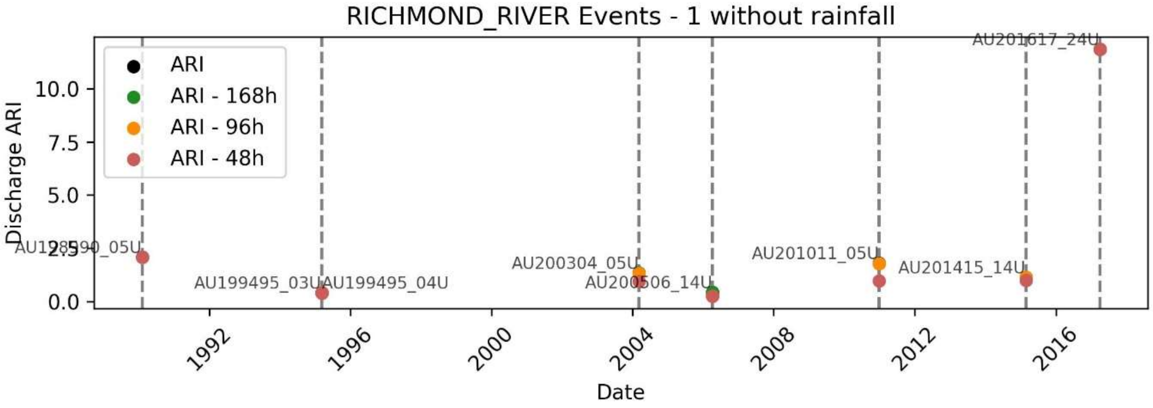


Figure 17: Same as Figure 15 for the Richmond River basin.

Similarly to the Brisbane River basin, TC-related discharge events in the Richmond River basin were mostly below the 2-year ARI, except for the flooding induced by TC Debbie in 2017, whose ARI is estimated to be ~12-year (Figure 17). In this catchment, the 48 hours period captures the maximum ARI well for all events, which might be explained by the small size of the Richmond River catchment. As was noted earlier, the flood event caused by TC Debbie was not captured by the 48-hour definition in the original work of 2022, including in the Richmond River basin. This highlights the critical importance of the model calibration, as a model delay as small as 12 hours causes the peak discharge to fall outside the 48-hour period. Note that TC Debbie decayed during the night of the 28/29 March 2017 and reached southeast Queensland in the evening of March 30th. Exceedance probability curves of maximum runoff events show that most TC-induced runoff events were also below the 2-year ARI except for TC Debbie, highlighting the good performance of the discharge model in the Richmond River basin as well (Figure 18).

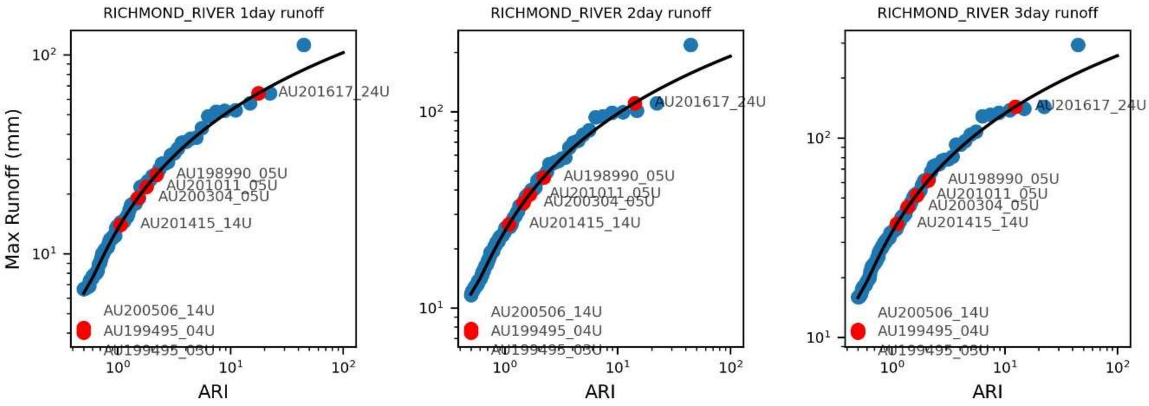


Figure 18: Same as Figure 16 for the Richmond River basin.

Long Term Trends

The comparison of results between the 1979-2000 and 2001-2022 period shows that the proportion of flood events related to TCs have significantly increased in the large inland catchments of Australia. Some smaller catchments in Western Australia and in the Northern Territory have seen less flood events caused by TCs in recent years (Figure 19). Changes in the proportion of these TC-related flood events captured by both the 48-hour and 168-hour definition show a similar pattern matching the sign of change of flood events being related to TC events. This suggests that the increase in TC-related events being captured by both definitions reflects that there were more TC-related events in later years. Please note that results were similar for the 96-hour event definition (not shown).

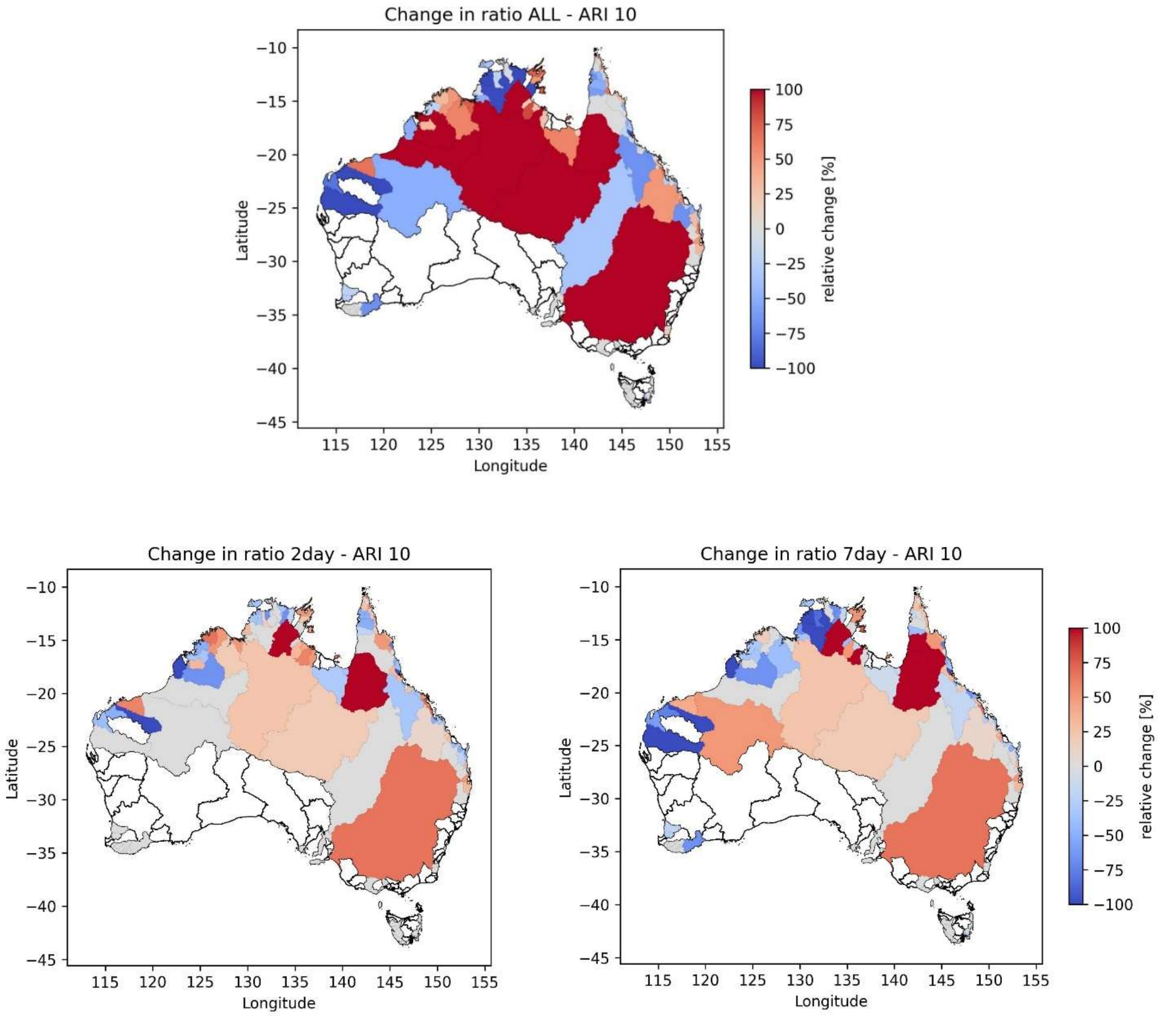


Figure 19: Change in the percentage of flood events above the 10-year ARI related to tropical cyclones (top) between the 1979-2000 and 2001-2022 period. The bottom panels show the change in the percentage of TC-related flood events above the 10-year ARI captured by the 48-hour and 168-hour event definition.

Summary & Suggestions

In this review of the TC Flooding work done in 2022, we primarily investigate the benefits of extending the ARPC TC event end definition to a 96-hour and 168-hour window after the decay of a TC. Past results suggested that a 48-hour window would not be sufficient to capture flood peaks due to TCs in medium to large scale basins. Here, we highlight the dependence of the ability of a time window to capture TC-related flood events to the size of the catchment. Nationally, a 96-hour window allows significantly more event peaks to be captured by the definition compared to a 48-hour window. Moreover, for medium to large basins, a 168-hour window is more adequate than the 96-hour window. Note that for extremely large basins, the 168-hour window is insufficient to capture extreme TC-related flood peaks. These results can be explained by the increased time it takes for flood waters to accumulate within a larger catchment.

While the validation of the model yielded satisfying results, bias correcting the timing of modelled flood peaks was critical for medium-large scale catchments. Comparisons with observations highlighted that the model does not perform well for large basins where evenly distributed rainfall is assumed. This leads to an increased uncertainty of the results for large basins. Future improvements could include a breakdown of large basins into smaller sub-basins where the SUH model might be more suitable. Additionally, where possible, streamflow observations could be used directly to extract the same statistics, although these observations remain scarce and would limit the analysis possible to a few basins.

Here, we also investigated the impacts of using a larger radius around the track to select basins impacted by a given TC track. Results suggest that extending the radius to 300 kilometres might be beneficial for smaller catchments as the rainfall footprint of a TC can extend further away than 150 kilometres. This may cause an increase in false positives in large catchments that might be affected by another rain weather system elsewhere in the catchment or at another point during the definition period. To remedy this, a spatiotemporal filter could be implemented on both the rainfall and the basin selection to avoid the case of false positives. For example, even if a part of a basin is within the 300 kilometres radius around the track, one would only consider the rainfall within this radius around the time the TC tracked near the catchment.

Despite an anticipated increase in TC-related flooding risk in catchments in southeast Queensland and northeaster New South Wales, we did not find any significant changes due to the extension of the event period definition or the use of XTC tracks in these high exposure catchments. A more detailed analysis of the results in these eastern catchments indicated that while considering XTC tracks increases the number of potential events, XTCs were not generally associated with extreme runoff. Although changes to the event definition and improved methodology prove important in some cases like TC Oswald in 2013 or TC Debbie in 2017, these types of events remain too infrequent to significantly change the risk, especially at large ARIs. We note however that there seems to be an important difference for catchments above 27°S where TC and XTC tracks are more frequent and that might be characterised by a different rainfall climatology. This might indicate the importance of estimating risk at a small enough scale to appropriately isolate signals and avoid smearing.

Finally, we briefly analysed the changes of TC-related floods and the efficiency of the three event definitions during the last 43 years. Results show that there was an increase in TC-related flooding in large inland basins, but that this was not the case in small coastal basins. This is not consistent with the hypothesis of a global slowdown of TCs when approaching the coast which should impact coastal catchments specifically. Moreover, these changes could be attributed to the variability of the system or to the uncertainty of the method used as mentioned above. A more in-depth analysis of rainfall timeseries on a longer timescale would improve of our understanding of the long-term changes of TC-induced rainfall intensity.

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