



Review and update of design rainfall-intensity-frequency-duration for eleven local government areas in South East Queensland

Report

Final

17 April 2025

Acknowledgements

The Multi-LGA IFD Review and Update Project has been funded under Work Package 3 of the Flood Risk Management Program. The Flood Risk Management Program is a jointly funded Australian and Queensland Government (50:50) 2021-22 Rainfall and Flooding - Exceptional circumstances Category C and D funding package approved under the *Disaster Recovery Funding Arrangements (DRFA)*.

The authors would like to thank the independent peer reviewers, who provided valuable feedback during this project and assisted greatly with the refinement of the analysis at key points: Don Carroll, Dörte Jakob and Rory Nathan.

The authors also thank the stakeholders and organisations that provided rainfall data that was used in the analysis: Bureau of Meteorology, Queensland Government, Seqwater and the Bundaberg Regional, North Burnett Regional, Fraser Coast Regional, South Burnett Regional, Cherbourg Aboriginal Shire, Gympie Regional, Noosa Shire, Sunshine Coast Regional and Toowoomba Regional, Somerset Regional and Scenic Rim Regional councils.

Document status

Client	Queensland Reconstruction Authority
Project	Review and update of design rainfall-intensity-frequency-duration for eleven local government areas in South East Queensland
Report title	Report
Version	Final
Authors	Ash Rasheed, Leah Traill, Declan O'Shea and Phillip Jordan
Project manager	Phillip Jordan
File name	S:\13_Projects\QRA00002\6_Deliverables\Report\QRA00002_DesignRainfallIFDUpdate_Report_Final.docx
Project number	QRA00002

Document history

Version	Date issued	Reviewed by	Approved by	Sent to	Comment
Draft A	13/06/2024	Phillip Jordan		QRA, Peer reviewers and project stakeholders	Draft for review
Version 1	19/08/2024	Don Carroll, Katrina Smith, Zein Belhout, Michel Raymond	Michel Raymond	As above	Addressing review comments
Version 2	09/09/2024	Michel Raymond	Michel Raymond	As above	Release of ARR version 4.2 (incorporating update of former draft of DCCEEW 2023 Climate Change Considerations chapter), minor revision applications of IFD data sets
Version 3	15/11/2024	Phillip Jordan	Phillip Jordan	As above	Brief commentary on comparison to LIMB IFD data set, update to project context in introduction.
Final	17/04/2025	Michel Raymond	Michel Raymond	As above	Remove QRA logo and update copyright and limitation statement

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Abbreviations and glossary

Abbreviation / term	Full term
AEP	Annual exceedance probability
ALERT	Automated Local Evaluation in Real Time: a radio-telemetry protocol commonly used for communication of data from rainfall and streamflow gauging sites
AMS	Annual maxima series
ARR	Australian Rainfall and Runoff
BoM	Bureau of Meteorology
GEV	Generalised Extreme Value distribution
HARC	Hydrology and Risk Consulting
IFD	Intensity-Frequency-Duration
Kriging	A method of spatial interpolation, governed by prior estimates of covariances in the data. Under suitable assumptions of the covariance, kriging gives the best linear unbiased prediction at unsampled grid cells.
LGA	Local government area or Local government authority
LIMB	Lockyer, Ipswich, Moreton Bay and Brisbane local government areas
L-moment	Statistics used to summarise the shape of probability distributions, calculated using linear combinations of order statistics. L-moments are more robust than conventional moments and therefore they have been widely applied in analysis of rainfall, floods and other extremes of environmental phenomena over the last few decades.
L1	First L-moment: Mean of annual maxima series
L2, L3, L4	Second L-moment, Third L-moment, Fourth L-moment
L-CV	Ratio of L2/L1
L-Skewness	Ratio of L3/L2
L-Kurtosis	Ratio of L4/L2
MAR	Mean annual rainfall
POT	Peaks-over-threshold
QA	Quality assurance
QRA	Queensland Reconstruction Authority
SEQ	South east Queensland
U/R factor	Unrestricted to restricted duration factor
Variogram	A function defining the spatial dependence of a rainfall field with distance. The variogram is the mean of the squared difference in values (design rainfall intensity in this case) between two points that are at a given distance from one another. Where a co-variate is used to define the underlying expected value (say rainfall intensity as a function of mean annual rainfall), the variogram may be used to define the residual variance in the difference between rainfall intensity for a given duration and the expected value as a function of the covariate. The variogram function is applied in kriging to undertake spatial interpolation from point to gridded values. The variance typically increases with distance (sometimes reaching a constant sill value), so that values at closer points have lower variance and are assigned more weight in the spatial interpolation process than points that are more distant.

Executive Summary

Design rainfall intensities, or design rainfall depths, are used as the basis for rainfall-based design flood estimation. The rainfall intensity, or depth, is defined for a rainfall burst duration and an exceedance probability, or frequency, of occurrence. Design rainfall depths are therefore defined by Intensity Frequency Duration (or IFD) relationships, which are normally provided in a table or chart.

Several councils in South East Queensland (SEQ) were approved for funding to develop local IFD datasets across their Local Government Areas (LGA) under Work Package 3 of the Flood Risk Management Program. QRA identified an opportunity for efficiency and combined these projects into the Multi-LGA IFD Review and Update Project. This review and update stems from the experiences of flood management professionals in SEQ over recent years, since the updated design rainfall IFD estimates that were released by the Bureau of Meteorology (BoM) in 2016 (Green *et al.*, 2015a, 2015b; Bureau of Meteorology, 2016). The BoM (2016) IFD update was undertaken in conjunction with the latest update of *Australian Rainfall and Runoff* (ARR2019) (Ball *et al.*, 2019).

The core scope, as set out in QRA's project brief, covered eight LGAs. Extensions to the project scope were approved by QRA to extend the project study area to include 11 LGAs: Bundaberg, North Burnett, Fraser Coast, South Burnett, Cherbourg, Gympie, Noosa, Sunshine Coast, Somerset, Scenic Rim and Toowoomba. Previous studies (WMAwater, 2021 and CoGC) had updated IFD estimates for five LGAs: Lockyer Valley, Ipswich, Moreton Bay, Brisbane and Gold Coast. Therefore, across these previous two projects and the current project, IFD estimates were updated for a total of 18 LGAs, covering most of the South East corner of the State, as shown in Figure ES- 1.

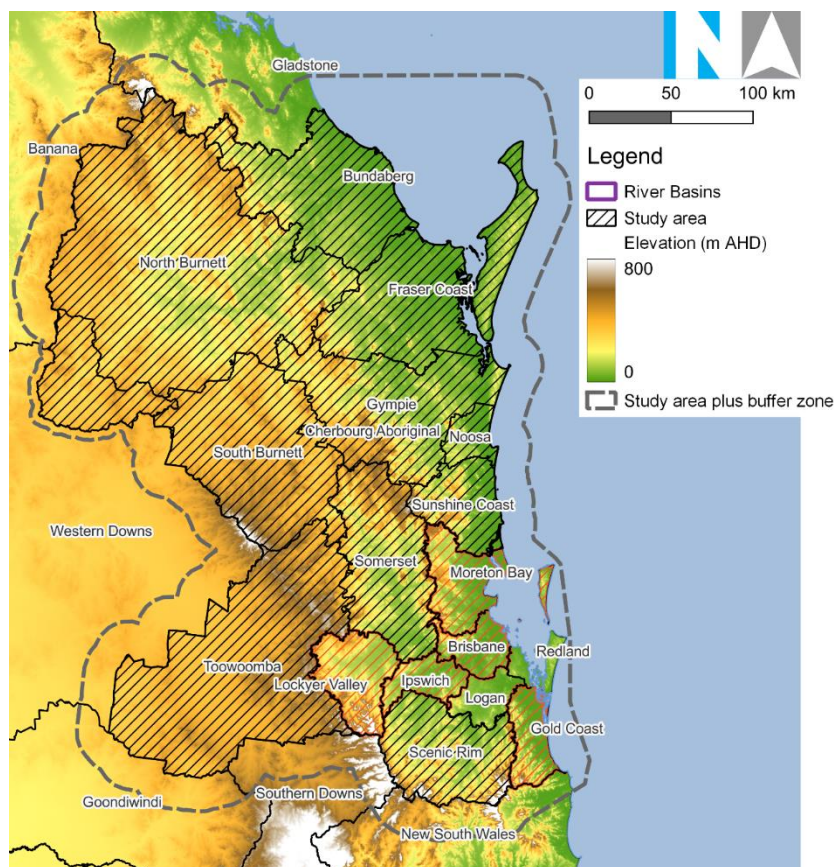


Figure ES- 1 Local government areas for current project and recent previous studies and the extent of the buffer region, where rainfall site data was collected for analysis

IFD estimates were produced for every grid cell across the study area, using two different approaches:

1. Applying regionalised L-moments to calculate GEV distributions at each 0.025° grid cell in the study area, calculating design depths for standard durations and AEP combinations at each grid cell and checking for and removing any minor remaining inconsistencies. These IFD data grids are considered the best-estimates based upon the data, for climate centred around 2010, or 0.6°C above the BoM (2016) IFD baseline for global mean temperature change.
2. At each grid cell, for each combination of standard duration and AEP, taking the maximum of:
 - Design rainfall depth from approach 1 (derived from this study) and
 - BoM (2016) IFD estimate that has been adjusted forward to the same 2010 global mean temperature, by allowing for 0.6°C increase in global mean temperature and applying the factors for sensitivity in IFD estimates with duration from Table 1.6.1 of ARR version 4.2 (Ball *et al.*, 2019; Wasko *et al.*, 2024).

These two IFD data sets, which are both aligned to 2010 global mean temperature, serve different purposes:

- The first set is based on all available QA'd data to 2023 using latest statistical techniques including advanced smoothing algorithms as per this report to derive a set of IFD tables that are minimally biased. This set is referred to as the HARC (2024) data set.
- The second set is based on an envelope approach that adopts, for all durations, the maximum of either the HARC (2024) data set and the uplifted BoM (2016) IFD data set¹. This set is referred to as the eHUB (2024) data set. This set is included as it was noted that predominantly for the shorter durations (<3 hours) the uplifted BoM (2016) data set was generally higher than the HARC (2024) data set. While this introduces bias relative to the HARC (2024) data set, it allows LGA's to retain the same level of flooding/drainage infrastructure serviceability into the future.

Rainfall data was provided by QRA, local governments, Seqwater and BoM; or obtained from the BoM or the Queensland Water Management Information Portal (QWMIP). Rainfall data was obtained from all daily and sub-daily recording rainfall sites that were contained within the buffer region shown by the dashed in Figure ES- 1.

After implementing the QA process, valid annual maxima data was obtained from 810 sub-daily and 567 daily gauges, a total of 1,236 gauges. Figure ES- 2 shows the number of gauges across the study region and the number of valid water year maxima identified at each gauge. Densities of gauges are highest in the south-east of the study region, between Noosa and the Gold Coast, and extending west into Ipswich and the eastern parts of Lockyer Valley, Somerset and Scenic Rim.

As shown in Figure ES- 3, the number of rainfall gauges recording valid annual maxima increases across the period of record. This was particularly true for sub-daily gauges, with very few gauges available prior to about 1960 and then substantial increases over the decade between 2005 and 2015.

¹ The uplifted BoM (2016) data incorporates a climate change adjustment (ARR 2024) that uplifts the IFD's to present day climate conditions. This does **not** introduce a conservative bias into the tables.

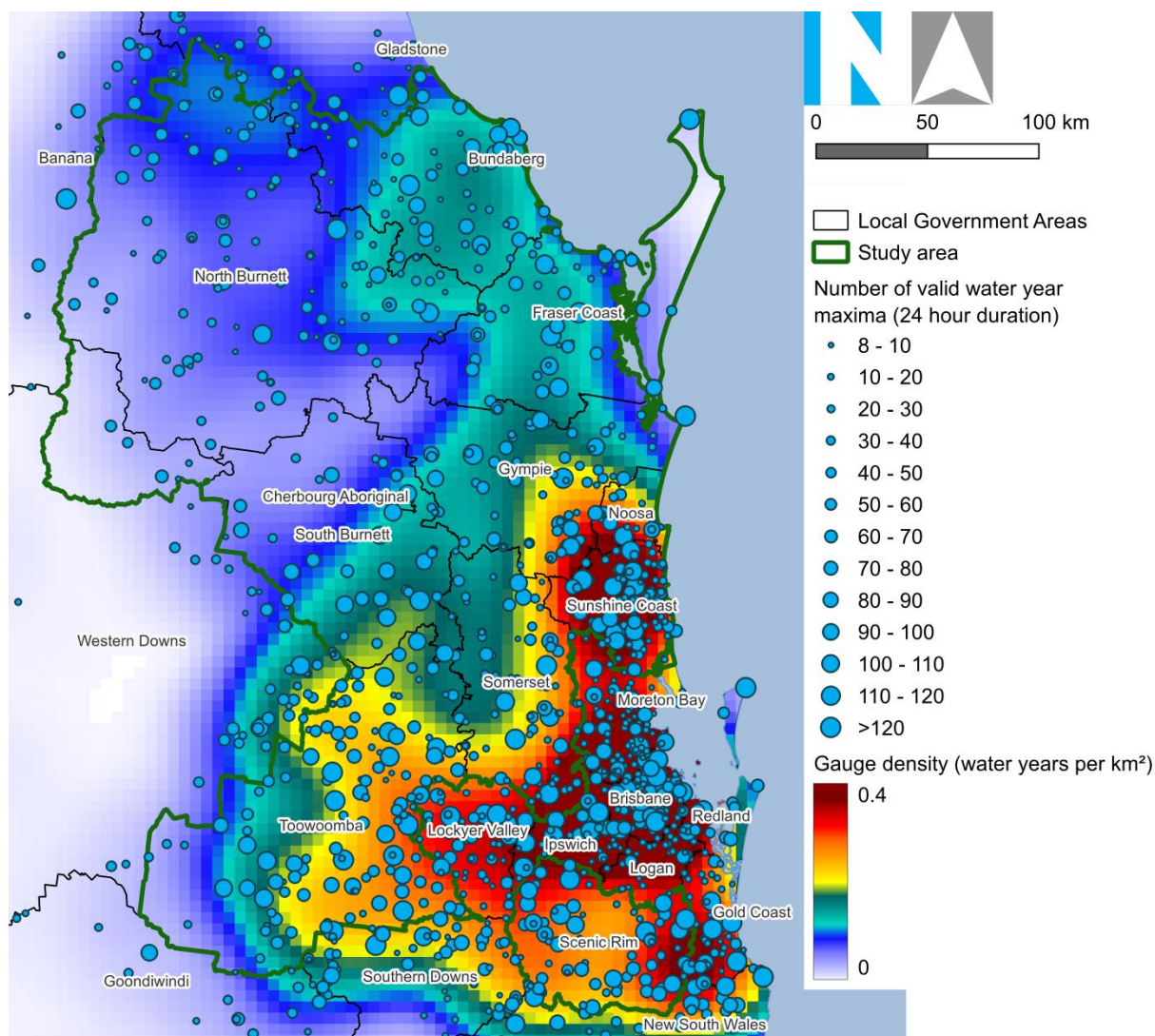


Figure ES- 2 Density of coverage of daily and sub-daily gauges across the study region, showing number of valid water year maxima at each site for the 24 h duration and density of gauges (number of water year maxima per km²)

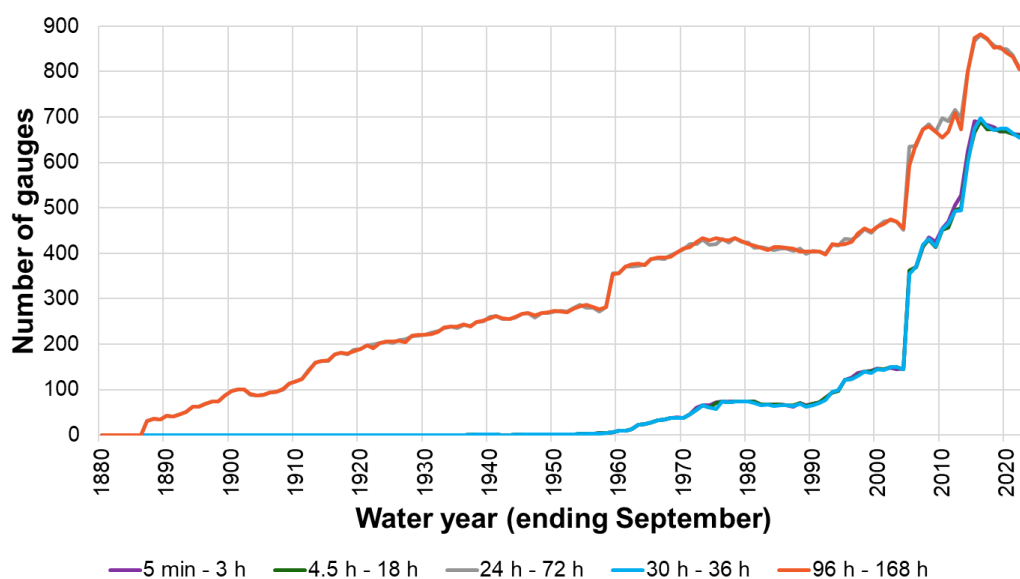


Figure ES- 3 Number of gauges reporting valid maxima by water year and duration

Figure ES- 4 shows that the mid-point of the data adopted for the BoM (2016) IFD update was in the mid-1970's and, on average, global average temperatures had only risen by 0.3°C above pre-industrial by that time. For the current study the L-moments were normalised to be representative of data centred on the year 2010, using a scaling approach (Wasko *et al.*, 2023a). By this point in time, Figure ES- 4 shows that global average temperatures had risen to 0.9°C above pre-industrial. The IFD data for the current study were derived from statistical analysis on data representing 2010 global average temperatures. This period is characterised by average global temperatures 0.6°C warmer than the 1961-1990 period that characterizes the BoM 2016 IFDs (0.9°C above a 1850-1900 baseline).

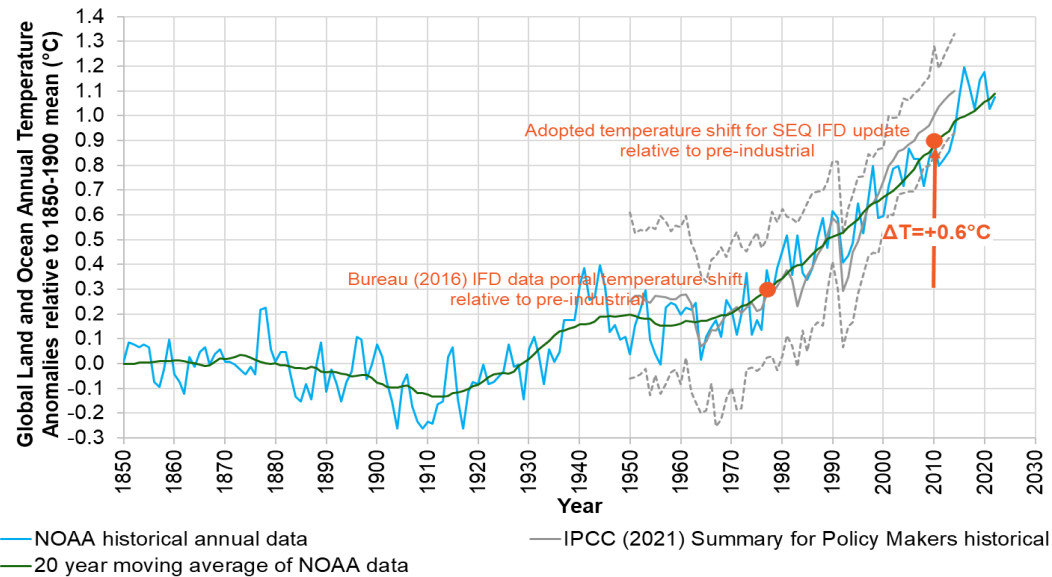


Figure ES- 4 Global average air temperature, 1850-2023 and representative temperatures adopted for IFD estimation

The IFD data sets presented here represent 2010 global average temperatures (defined by the 20-year average). Table 1.6.2 of the updated climate change considerations chapter of ARR (version 4.2) provides global mean surface temperature projections relative to the BoM (2016) IFD estimates. However, when using the either of the two IFD data sets provided with this study, this table should be replaced by Table ES- 1.

Table ES- 1 IPCC Sixth Assessment Report global mean surface temperature projections for four socio-economic pathways relative to the baseline temperature for the updated IFD estimates for the SEQ region (HARC, 2024). The 90% uncertainty interval is provided in parenthesis*

Projection scenario	SSP1-2.6	SSP2-4.5	SSP3-7.0	SSP5-8.5
Current and near-term (2021-2040)	0.6 (0.3-0.9)	0.6 (0.3-0.9)	0.6 (0.3-0.9)	0.7 (0.4-1.0)
Medium term (2041-2060)	0.8 (0.4-1.3)	1.1 (0.7-1.6)	1.2 (0.8-1.7)	1.5 (1.0-2.1)
Long-term (2081-2100)	0.9 (0.4-1.5)	1.8 (1.2-2.6)	2.7 (1.9-3.7)	3.5 (2.4-4.8)

* Projections obtained from the Summary for Policymakers of the Working Group I Contribution to the IPCC Sixth Assessment Report (AR6)

Table ES- 2 lists the total number of QA'd water year maxima across the study region. The size of the sub-daily rainfall set used for the current study in this region was more than three times greater, both in terms of the number of rainfall gauges and the number of water year maxima, than the data set of sub-daily rainfall gauges that was used by the BoM (2016) IFD analysis. Figure ES- 5 demonstrates the substantial difference in coverage of sub-daily gauges across the study region between the current

study and those that were used by the BoM (2016). This substantial increase in the size of the rainfall data record was sufficiently large to adopt different approaches to statistical analysis of the rainfall data across the region than were used by the BoM (2016), which applied techniques that could be applied on an Australia-wide basis, including regions with sparser rainfall gauge coverage.

Table ES- 2 Total number of water year maxima by gauge type and rainfall burst duration

Duration range	Sub-daily gauges	Daily gauges	Total
5 min - 3 h	14,071	0	14,071
4.5 h - 18 h	13,926	0	13,926
24 h, 48 h, 72 h	16,955	29,439	46,394
30 h - 36 h	13,912	0	13,912
96 h - 168 h	16,832	29,481	46,313

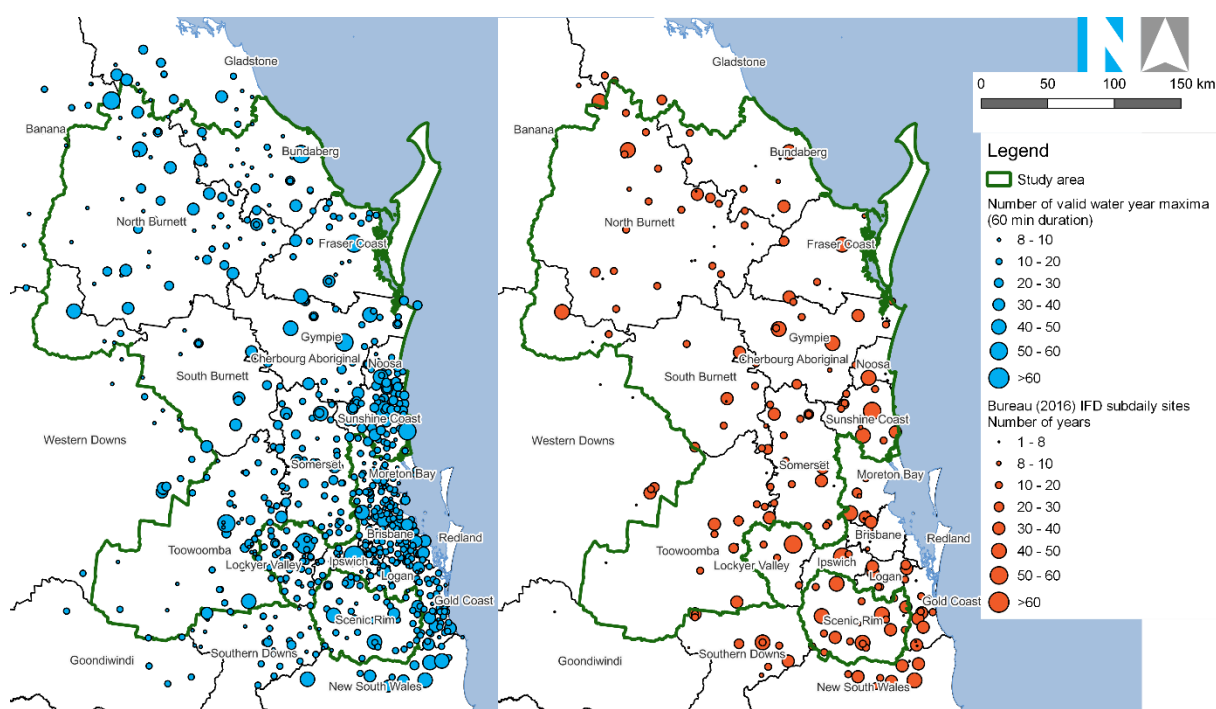


Figure ES- 5 Comparison between number of valid water year maxima adopted for the 60 minute duration from sub-daily gauges between the current study (left) and used by the BoM (2016) IFD analysis (right)

A water year of 1 October to 30 September was adopted for the analysis, as the lowest number of annual maxima are recorded in the months of July to September of each year. Factors to adjust the daily rainfall (restricted from 9am to 9am) to 24 hour rainfall that is not fixed to a set time window (unrestricted rainfall) were assessed from the data after QA screening of valid data. The analysis was repeated for durations from 2 day to 7 day totals. The 1 day mean factor of 1.15 for the current study was identical to that derived by the BoM (2016) (Jakob *et al.*, 2009) and Dwyer & Reed (1995), despite the different data sets and methods employed.

Updated design Intensity Frequency Duration (IFD) depths were produced for all combinations of 24 durations (from 5 minutes to 168 hours) and 13 annual exceedance probabilities (63.2% to 1 in 2,000 AEP and 2 and 5 year average recurrence intervals) for an area covering 11 local government areas in south-eastern Queensland and the surrounding region. This update represents a significant

increase in available rainfall data, with an additional 11 years (2013-2023) of gauge records available compared the BoM 2016 IFDs.

For an individual rainfall station with a relatively short record, there is considerable uncertainty in estimating L-moments due to sampling variability. To control the potential impact of shorter record lengths, a regionalisation approach was adopted where higher order L-moment ratios L-CV and L-skewness were estimated using a Region of Influence (ROI) approach (Burn, 1990). Similar methods were also applied by the BoM (2016) and LIMB study (WMAwater, 2021), although with slightly different approaches adopted for spatial interpolation and pooling of data. These differences are outlined in Section 13.1.

The methodology for producing the IFD curves using regionalisation of L-moments has also been tailored to suit the high density of rainfall gauges in SEQ. In particular, the method makes use of a hybrid approach for the regionalisation of L-CV and L-skewness, which uses regional wide averages for short durations (≤ 2 hours) and a region of influence approach for long durations (≥ 48 hours) to account for systematic difference in daily and sub-daily gauge data. The method applied for the current study was as follows:

- For each rainfall event duration, the L1 value was spatially interpolated from all rainfall sites with at-least 8 years (for sub-daily gauges) or 30 years (for daily gauges) of water year maxima values. Spatial interpolation was undertaken via kriging, with mean annual rainfall as the explanatory co-variate. Mean annual rainfall was selected as the covariate, as it provided the highest Coefficient of Determination (R^2) for all durations considered compared to other covariates that were considered (elevation, slope, standard deviation of elevation and distance to coast).
- For each rainfall event durations of less than 2 hours, the L-CV and L-Skewness values were adopted from the regional average of L-CV and L-Skewness across the entire study region, calculated from all sub-daily sites with at least 18 years of water year maxima.
- A minimum threshold of 0.17 was set for L-skewness, which ensured that the fitted GEV distribution's shape parameter was negative and hence the GEV quantile function had an infinite upper bound. The threshold generally was applied to durations of 1 hour and shorter. In conjunction with this, the L-CV values for durations where L-skewness was thresholded to 0.17 were set to the value of the shortest duration with L-skewness above 0.17.
- For each rainfall event duration of 48 hours and longer, the L-CV and L-Skewness values were calculated by pooling together the nearest rainfall gauge sites that had at least 18 years of water year maxima (for sub-daily gauges, and at least 30 water year maxima for daily gauges), until 500 water years of data had been accumulated. The pooled value of L-CV and L-Skewness were then calculated using the weighted average by the number of years of annual maxima at each rainfall site.
- Smoothing was undertaken, at every grid cell, to ensure that there was a monotonic increase in L-CV and L-Skewness with duration. These adjustments were relatively small but were required to ensure that the design rainfall depth increases monotonically with increasing duration at every grid cell.
- The parameters of the GEV distribution were calculated from the smoothed L-moment values at every grid cell, for every duration across the study area.
- Design rainfall depths were calculated from the GEV parameters at every grid cell (0.005° and 0.025° resolution), for every duration and for each AEP between 63.2% and 0.05% across the study area.

Figure ES- 6 shows the gridded design rainfall estimates across the study region for the 1% AEPs, for eight selected durations between 5 minutes and 168 hours. There was a clear signal of design rainfall depths being greater in areas of higher mean annual rainfall, which were typically closer to the coast or in higher elevation areas. Maps of gridded IFD estimates for other durations and AEPs are provided in the full report.

As a check on the calculation and interpolation process, the design rainfall depths from the gridded values for each AEP and duration were compared with the design rainfall depths that would be produced by directly estimating these from the L-moments calculated at each individual rainfall gauge in the study region for each duration. Figure ES- 7 show comparisons, across every sub-daily and daily gauge in the study region respectively, between the gridded design rainfall depths and the at-site estimates, across a range of AEPs and durations. The average differences between these values are close to 0%, across all AEPs and durations. Differences are relatively small, typically within $\pm 20\%$ for the 63% AEP (1 in 2 year). Larger spreads of differences between the at-site and gridded values are seen for rarer AEPs. This increase in spread is expected because the parameters of the GEV distribution and hence rarer AEPs estimates fitted to data from an individual rainfall site become less reliable. The interpolation and pooling process was designed to smooth out this process and produce statistically robust estimates of the rarer AEP design depths that vary smoothly across durations and spatially across the study region.

Figure ES- 8 shows maps of percentage differences across the study region between the current study and the BoM (2016) design rainfall estimates, for the 1% AEP respectively. The revised IFD analyses produce median changes for durations of 12 hours and longer and for AEPs between 50% and 1% across the SEQ region that are within $\pm 5\%$. However, percentage increases in IFD estimates are larger than this (often between +10% and +50%) in the parts of SEQ that have higher mean annual rainfall. Decreases in IFD estimates are typically seen in the western parts of the study region for durations of 12 hours and longer, and across the entire study region for durations of 1 hour or shorter. The current study has made greater use of locally sourced rainfall data, particularly from sub-daily rainfall gauges. The BoM (2016) adopted a scaling approach to produce design rainfall estimates for durations shorter than 1 hour, and applied on an Australia-wide basis. This approach produced conservatively high design intensities for these short durations. The analysis for the current study fitted sub-hourly IFDs to the data observed at sub-daily rainfall gauges in the region, which resulted in lower IFD estimates. On average, the most significant decreases were for durations shorter than 6 hours in the western and northern parts of the study region.

The IFD data and this report have undergone independent peer review. The peer reviewer's statement is included in Appendix M.

These IFD data sets will be made available on the ARR data hub.

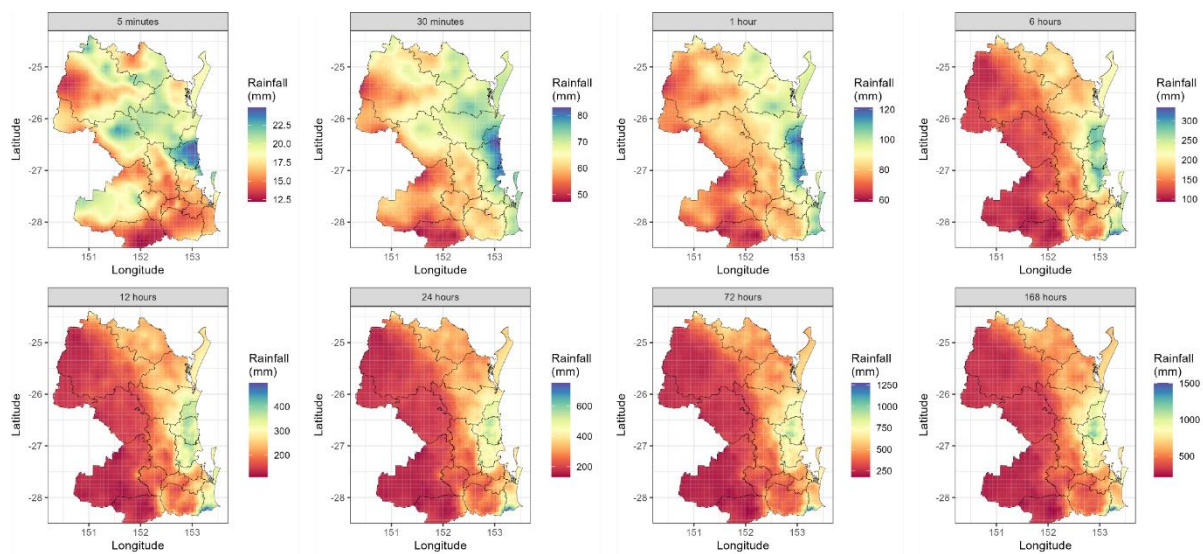


Figure ES- 6 1% AEP IFDs

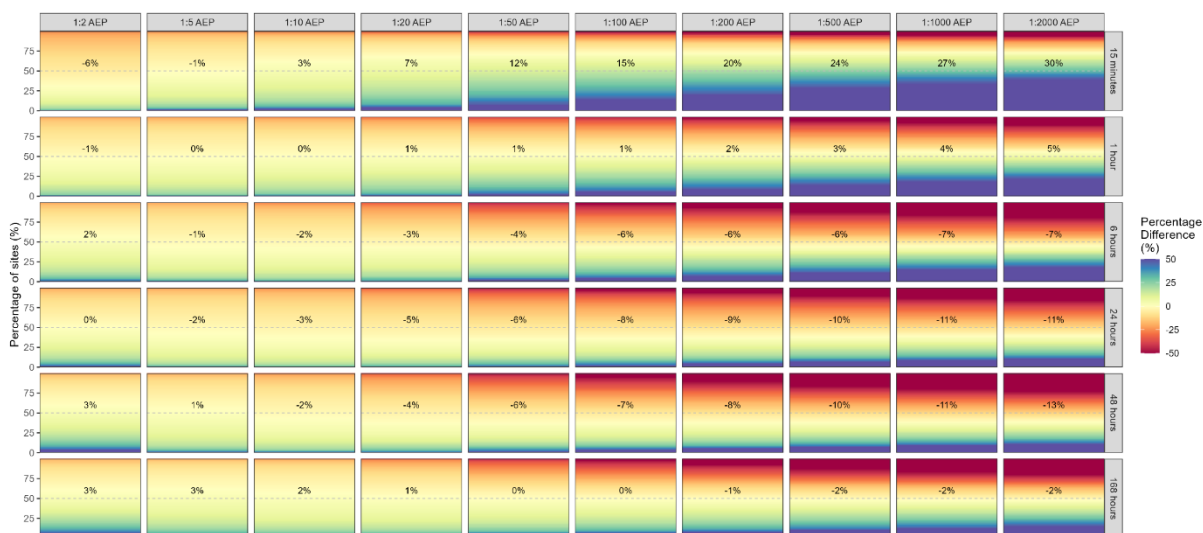


Figure ES- 7 Percentage difference in the at-site and gridded IFDs for different AEPs and durations

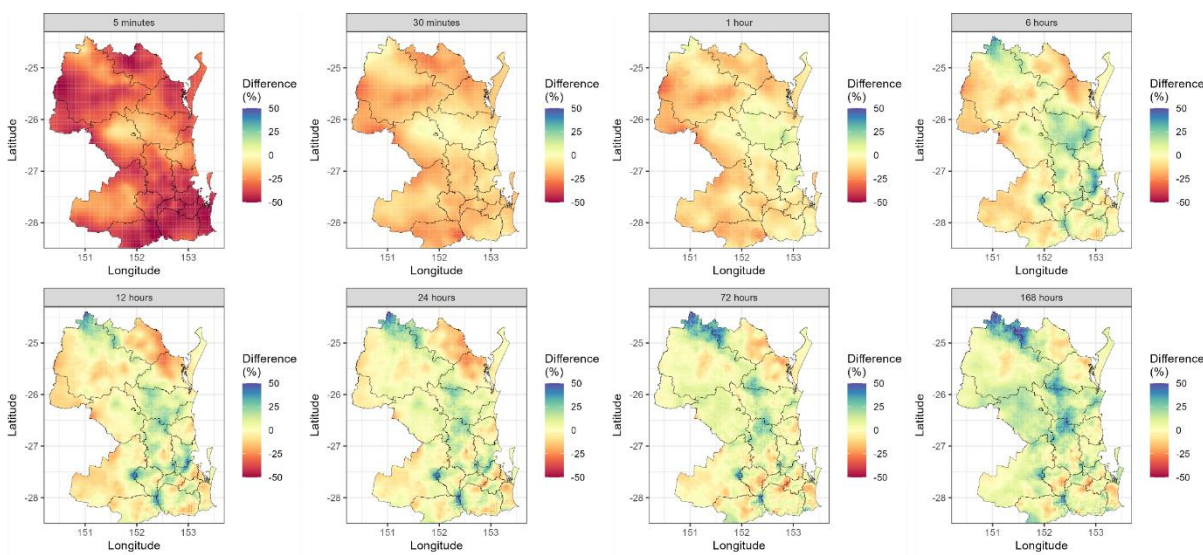


Figure ES- 8 1 Percentage difference between 1% AEP BoM IFDs (ARR, 2016) and IFDs from this study (HARC, 2024)

1. Introduction

1.1 Purpose of this study

Design rainfall intensities, or design rainfall depths, are used as the basis for rainfall-based design flood estimation. The rainfall intensity, or depth, is defined for a rainfall burst duration and a frequency, or probability, of occurrence. Design rainfall depths are therefore defined by Intensity Frequency Duration (or IFD) relationships, which are normally provided in a table or chart.

Several councils in South East Queensland (SEQ) were approved for funding to develop local IFD datasets across their Local Government Areas (LGA) under Work Package 3 of the Flood Risk Management Program. QRA identified an opportunity for efficiency and combined these projects into the Multi-LGA IFD Review and Update Project.

This review and update stems from the experiences of flood management professionals in SEQ over recent years, since the updated design rainfall IFD estimates that were released by the Bureau of Meteorology (BoM) in 2016 (Green *et al.*, 2015a, 2015b; Bureau of Meteorology, 2016). The BoM (2016) IFD update was undertaken in conjunction with the latest update of *Australian Rainfall and Runoff* (ARR2019) (Ball *et al.*, 2019) and applied analysis methods that were suited to continental-wide application. Broadly, the reasons for the concerns of flood management professionals are:

- 1) The BoM (2016) analysis was conducted using rainfall data that was collected up to 2012. More than a decade has elapsed since compiling the rainfall data for the ARR2019 update meaning an additional 10 years of rainfall data were available. In particular, the length of record at many sub-daily rainfall sites will have increased significantly since 2012.
- 2) The last decade included several strong La Niña years resulting in large rainfall and flood events in SEQ. This has included tropical cyclones Oswald (2013), Marcia (2015), Debbie (2017), Trevor (2019), Tiffany and Seth (2022). Significant monsoon and severe thunderstorm events also occurred over this period. By comparison, the 2000-2009 period was drier and had fewer large rainfall events, which could skew IFD statistics using pre-2012 data, particularly for sub-daily sites with shorter periods of record.
- 3) The BoM (2016) may not have used all the data from local rainfall gauges in Queensland, particularly the ALERT (Automated Local Evaluation Real Time rainfall gauges used for flood monitoring and warning), due to difficulties at the time in accessing the data from local agencies, concerns about data quality and/or relatively short periods of record that were available at some of those sites in 2012. The BoM (2016) method was suited to Australia-wide application and therefore used regression relationships to provide synthetic estimates of the parameters of probability distributions for durations shorter than 24 hours at daily gauges, which were then regionalised across Australia. This approach was well suited for large regions of the continent, where the density of sub-daily rainfall gauges is much lower than the density of daily rain gauges. For regions with high sub-daily rainfall gauge density, such as SEQ, application of the regression estimate approach may result in too little weight on information from the sub-daily gauges.
- 4) The spatial interpolation approach adopted by the BoM (2016) to derive gridded values from point estimates applied spline interpolation, with elevation used as the only co-variate. There was limited testing undertaken to demonstrate that the interpolation approach was optimal (or near optimal). Subsequent studies (for some areas in the SEQ region – see below and parts of coastal NSW) have demonstrated that use of kriging, testing additional covariates and alternative

weighting factors can provide improved spatial interpolation of IFD estimates, at least in regions with larger variations in terrain and stronger orographic gradients in rainfall.

Local studies were undertaken in the Coffs Harbour and Wollongong regions of New South Wales (NSW) (WMAwater, 2018), for the Lockyer, Ipswich, Moreton Bay and Brisbane (LIMB) Local Government Areas (LGAs) (WMAwater, 2021). These studies have identified that local rainfall data can be analysed to produce IFD estimates that provide improved fits to local rainfall data. The above five factors were investigated for the LIMB and NSW coastal region studies (WMAwater, 2018, 2021).

An IFD update undertaken for the City of Gold Coast (CoGC) LGA by the Bureau of Meteorology in 2021 concluded that additional rainfall data collected did not appear to provide sufficient basis to justify the adoption of the re-analysed design rainfalls. A subsequent peer review recommended an envelope approach viz. maximum of BoM 2016 and updated IFD Tables.

1.2 Report structure

This report has been prepared to summarise the outcomes of the project. The report addresses the following aspects of the project:

- **Section 3:** Collation of rainfall data, in a wide variety of data formats, from many agencies that collect rainfall data across SEQ
- **Section 4:** Quality Assurance (QA) checks on the rainfall data, to provide a set of annual maxima estimates at each gauge, for each of the standard rainfall burst durations between 5 minutes and 168 hours (7 days) that are typically used in design flood estimation
- **Sections 2 and 6:** Review of the density of data across the study area, to provide additional evidence that further steps should be undertaken to update the IFD data for the region
- **Section 5:** Development and recommendation of unrestricted to restricted conversion factors, which are required to allow data collected at daily gauges (typically recorded at 9 am on each day) to be integrated with the IFD analysis applied to sub-daily gauges
- **Section 6:** Summation of the spatial and temporal coverage of annual maxima across the study region
- **Section 7:** Assessment of potential non-stationarity in the rainfall data, due to climate change
- **Section 8:** Fitting of L-moments to data at each rainfall site
- **Section 9:** Checks that were undertaken to confirm that the GEV distribution represented an appropriate choice for estimation of design rainfall frequency curves in the study area
- **Section 10:** Explanation of the approach to spatial interpolation and regionalisation of L-moments and GEV distribution parameters from individual gauges to a gridded data set across the study area
- **Section 11:** Mapping of revised IFD grids
- **Section 12:** Comparison of IFD estimates from the revised grids to estimates derived from the data at each individual rainfall site
- **Section 13:** Comparison of the gridded IFD results with previous studies of IFD for the region from the BoM (2016) and the LIMB project (2021)
- **Section 14:** Conclusions and recommendations

2. Extent of study area

The core scope, as set out in QRA's project brief, covered eight LGAs: Bundaberg, North Burnett, Fraser Coast, South Burnett, Gympie, Noosa, Sunshine Coast and Toowoomba. Cherbourg Aboriginal Shire (31.8 km²) is completely surrounded by South Burnett Regional Council, so it made logical sense to update IFD estimates for Cherbourg, along with the other eight LGAs. Extensions to the project scope were approved by QRA to extend the project study area to include the Somerset and Scenic Rim LGAs. This took the total extent of the study area to 11 LGAs.

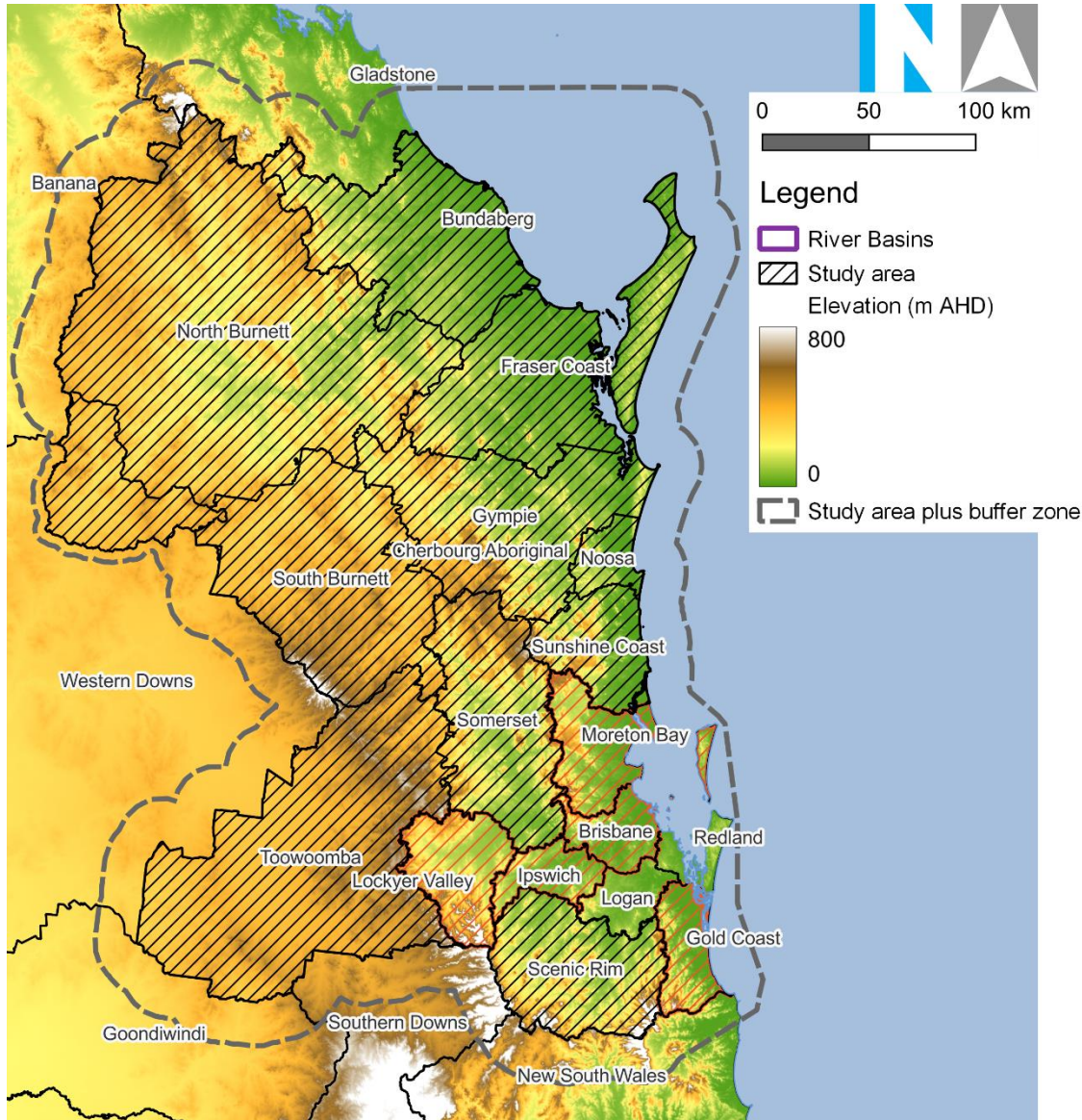


Figure 2-1 Local government areas for current project and recent previous studies and the extent of the buffer region, where rainfall site data was collected for analysis

As noted earlier, previous studies (WMAwater, 2021 and CoGC) had updated IFD estimates for five LGAs: Lockyer Valley, Ipswich, Moreton Bay, Brisbane and Gold Coast. Therefore, across these previous two projects and the current project, IFD estimates were updated for a total of 16 LGAs, covering most of the South East corner of the State. These study regions are shown in Figure 2-1.

The study area was extended slightly, so that the whole of the Burnett River catchment was included (see Figure 2-2). The study area therefore completely covered the land area of the 11 LGAs listed in Table 2-1 and small portions of three others, to cover the extent of the Burnett River catchment. The overall study area extended to 77,215 km². Rainfall data was collected from sites that were within the buffer region, also shown on Figure 2-1 and Figure 2-2, which extended for approximately 20 km beyond the boundaries of the LGAs in the study region.

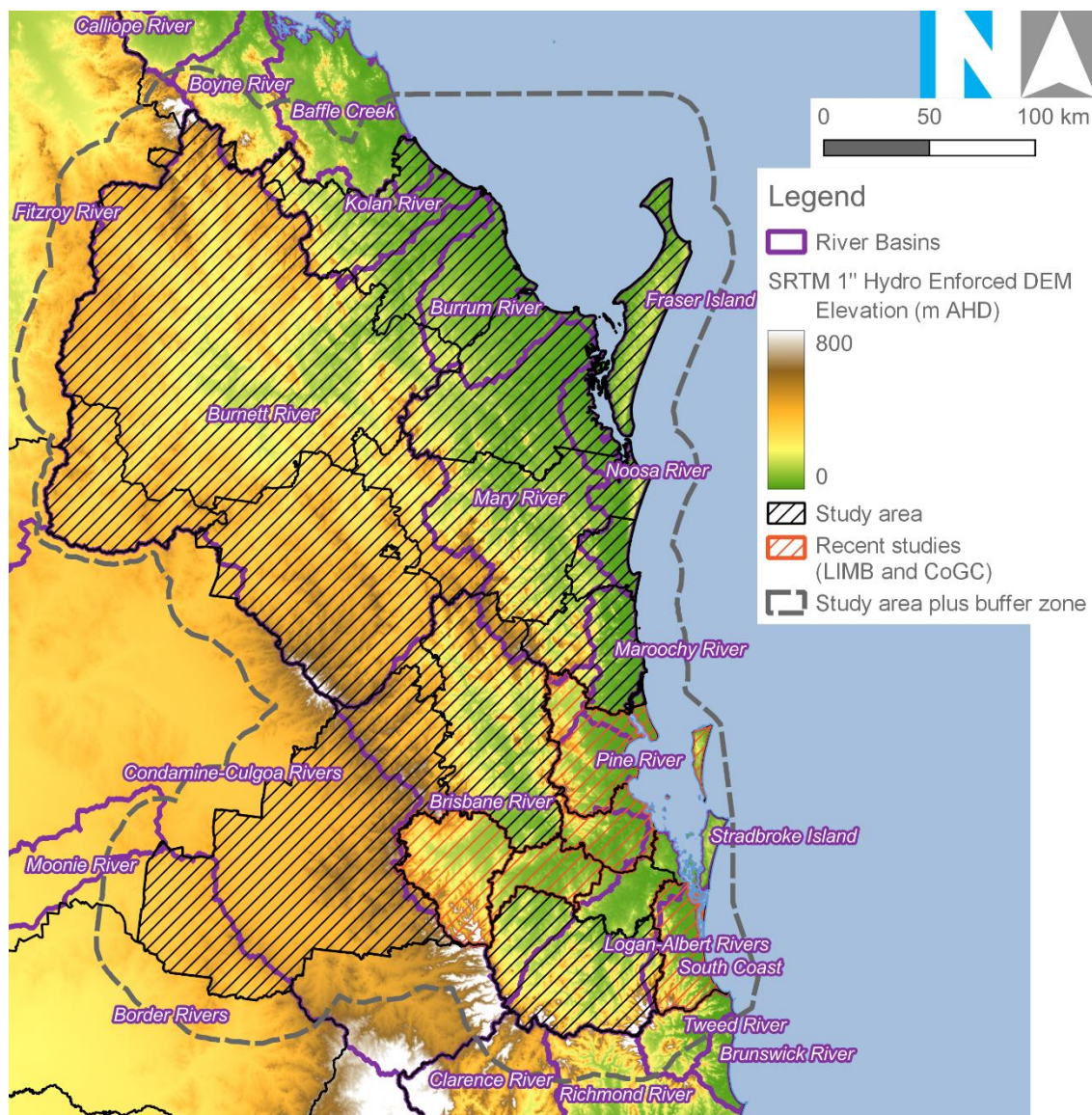


Figure 2-2 Local government areas for current project and river basins in the region

Table 2-1 Local Government Areas included in this study

Name	Land area included in study (km ²)
Bundaberg Regional	6,431.11
Cherbourg Aboriginal Shire	31.77
Fraser Coast Regional	7,094.89
Gympie Regional	6,885.74
Noosa Shire	868.56
North Burnett Regional	19,670.52
Scenic Rim Regional	4,240.76
Somerset Regional	5,373.64
South Burnett Regional	8,378.59
Sunshine Coast Regional	2,264.31
Toowoomba Regional	12,976.31
Western Downs Regional (part in Burnett River catchment)	2,964.50
Banana Shire (part in Burnett River catchment)	30.84
Gladstone Regional (part in Burnett River catchment)	4.00
Total	77,215.52

3. Rainfall data received

Rainfall data was provided by QRA, local governments, Seqwater and the BoM; or obtained from the BoM or the Queensland Water Management Information Portal (QWMIP). Rainfall data was provided in multiple different formats, as listed in Table 3-1. For analysis purposes, it was more convenient to convert the data into a common time series class object (in C# code).

Specifications for the common time series object were as follows:

- Regular time step, for sub-daily data, of 5 minutes
- Regular time step, for daily data, of 1 day (nominally starting at 9 am of each day)
- Dates always nominated as the end of the time step (as per convention used by Bureau of Meteorology for daily rainfall data, which are always for the day ending at 9 am on the nominated date)
- Times use Queensland local time zone (including application of daylight saving, for those relatively few years when daylight saving was applied)
- Rainfall depths in each time step are in mm
- Missing or low-quality data flagged as a nominated missing data value

Specific issues with parsing some of the raw data were:

- Where flags or quality codes were provided with the data, a standard approach was applied to designating data to be acceptable for use (OK) or not acceptable for use. The initial approach to using quality codes and flags, for each data type, are explained below.
- Regularised BoM pluviograph data format is on a 6 minute time step. Other data is on an irregular time steps:
 - If the 6 minute or irregular interval crosses the end of a regular 5 minute period, it was assumed that the rainfall rate was uniform within the original 6 minute or irregular period.
 - For Bureau of Meteorology pluviograph format data (6 minute time step), when data is shown as accumulated, over a period, it was assumed that the rainfall has fallen at a constant rate for that period.
 - Irregular period data may have long gaps between reported values, which normally reflects a period of no rain, followed by the commencement of rainfall, rather than a much longer period of drizzle at low rainfall rates. It was therefore be assumed that where the gap between the time of irregular period reports is longer than 30 minutes, all of the rainfall fell in the 30 minute period prior to the reported time and no rainfall fell prior to the start of that 30 minute period.

Details of each of the raw data formats that were provided for the project are provided in Appendix K.

Table 3-1 List of data formats provided, location on HARC network and numbering and naming convention for sites used by data provider

Data provider	Data type	Timestep	Numbering and naming convention used by data provider
Bureau of Meteorology (SILO)	Daily rainfall gauges	1 day	All gauges numbered and named, using standard BoM numbers
Bureau of Meteorology	Sub-daily rainfall gauges	6 minutes	All gauges numbered and named, using standard BoM numbers
Bureau of Meteorology	One-minute AWS data	1 minute	All gauges numbered and named, using standard BoM numbers
Bureau of Meteorology	Flood warning event data	Irregular (some daily)	All gauges numbered and named, using standard BoM numbers
Bureau of Meteorology	Flood warning accumulated data	Irregular	All gauges numbered and named, using standard BoM numbers
QWMIP, Department of Regional Development, Mines and Water (RDMW)	Stand alone or with stream gauge rainfall gauge	Irregular	AWRC 6 digit numbering, with an appended alpha code (A, B, C etc.) for site location. Standalone pluviometers use AWRC basin number, then P, then a three digit code
Scenic Rim Regional Council	One big CSV file, containing data for all sites	5 minutes	Gauges named and numbered using ALERT identification code numbers
Seqwater	Network Common Data Form (NetCDF) files of raw and processed point rainfall gauge data	15 minutes	All gauges numbered and named, using standard BoM numbers
South Burnett Regional Council	Daily gauges: Bureau of Meteorology daily rainfall format	Daily	All gauges numbered and named, using standard BoM numbers
South Burnett Regional Council	Sub-daily gauges: Bureau of Meteorology One-minute AWS data format	1 minute	All gauges numbered and named, using standard BoM numbers
Sunshine Coast Council	One big CSV file, containing data for all sites	5 minutes	All gauges numbered and named, using standard BoM numbers
Toowoomba Regional Council	Toowoomba Regional Council csv export format	5 minutes	CSV files for each site only have site name. Within each of the CSV files, the 3 rd value on each row is a site ID number (2, 3 or 4 digit integer value)
Gympie Regional Council	Gympie spreadsheets	1 day (usually 6 am but some days have time of observation noted)	CSV files have site name only, no numbering

4. Quality assurance of rainfall data

4.1 Quality assurance methods

Problems can be introduced in the process of measuring rainfall, accurately and precisely recording it and transmitting the data from remote sites to central data repositories. In some cases, QA had already been undertaken by the organisations providing the data. Even with these checks in place, it is possible that errors can be contained within the rainfall data sets provided. An advantage of undertaking a region-wide study, such as this, is that QA could be implemented simultaneously across the daily and sub-daily rainfall data provided by all agencies.

For design IFD estimation, the focus is on the larger recorded rainfall events, i.e. events that are sufficiently large that they would only be exceeded once or twice in a year. The overall process was as follows:

- Raw rainfall data, which was provided in multiple different formats, was converted to a common time-series data format
- A single catalogue of rainfall stations was produced, with unique station numbers, standardised station naming, location (latitude, longitude, easting and northing) and elevation above Australian Height Datum (AHD)
- A peak over threshold (POT) analysis was undertaken to extract the largest rainfall bursts, in each water year:
 - From the rainfall data at each sub-daily site, rainfall totals for independent rainfall bursts were calculated for periods of 5, 10, 15, 20, 25, 30, 60 and 90 minutes, 2, 3, 4.5, 6, 9, 12, 18, 24, 30 and 36 hours and 2, 3, 4, 5, 6 and 7 days and
 - From the rainfall data at each daily site, rainfall totals for independent rainfall bursts were calculated for periods of 1, 2, 3, 4, 5, 6 and 7 days.
- For event maxima extracted from daily rainfall gauges, equivalent unrestricted burst totals were calculated by applying a conversion factor to the restricted duration totals to calculate unrestricted duration totals (see Section 5)
- Annual maxima data were combined for co-located rainfall gauge sites, where co-located sites were defined as having the same latitude and longitude, rounded to three decimal places (an accuracy of approximately 10 m)
- Annual maxima were checked for consistency against the same event or water year at surrounding rainfall sites and/or against gridded rainfall data
- A consolidated data set of QA'd annual maxima for each rainfall gauge or group of co-located gauges was produced
- Summary statistics were produced of the number of rainfall gauges, station years of QA'd annual maxima at gauges across the study area and summarised by LGA.

4.2 Quality assurance of names, numbers and spatial locations of rainfall data sites

Rainfall data was provided or obtained from several different organisations. There were several different systems used by these organisations for numbering, naming and providing the locations of these rainfall gauge sites. In some cases, gauge names were provided in all capitals, whilst other organisations used a mix of upper and lower case letters. There was inconsistent use of common

abbreviations, such as AL (for Automated Local Evaluation in Real Time, ALERT), TM (for Telemetry), St for Street, Rd for Road, Dve for Drive etc.

A standardisation process was undertaken for naming of all rainfall gauges, whereby:

- Each site was assigned a unique site number
- The site name was converted to conventional title case, capitalising the first letter of each word and standardising commonly used abbreviations
 - For locations containing a public thoroughfare type, abbreviations were standardised as per the Australian Government Metadata Online Registry (METEOR), <https://meteor.aihw.gov.au/content/270020> and the Australian Government Style Manual <https://www.stylemanual.gov.au/grammar-punctuation-and-conventions/names-and-terms/australian-place-names>
 - Other standard acceptable abbreviations were standardised, as per Table 4-1
 - In general, other terms were spelt out in full, rather than abbreviated
- Commas and apostrophes were removed from site names, to avoid future issues with writing out names to csv file format (just use spaces, instead)
- Latitude and longitude coordinates for each site were assigned, so that co-located sites had identical coordinates
- Easting and Northing coordinates were assigned, in Map Grid of Australia 2020, Zone 56, from the site latitude and longitude
- Ground elevation was assigned from the Shuttle Radar Terrain Mission (SRTM) 1 arc-second Digital Terrain Model (DTM)
- Where provided with the original data, site elevation was checked that it was within a few metres in height of the SRTM ground elevation. Sites with large differences were manually checked and the most likely accurate estimate of site elevation, i.e. SRTM or as provided with the data, was adopted. (Note that many sites either had no elevation provided or the elevation provided was 0 m AHD, which was effectively a missing elevation data flag).
- A catalogue was maintained that mapped the data provider organisation, original site name provided by the organisation (in the same case), original site number, original location coordinates (if provided), original site elevation (if provided) and original source of the rainfall data provided.
- Groups of sites were identified, where it was likely that the same rainfall gauge had data provided in two or more instances from different organisations and/or in different formats. This was done to assist later quality assurance (QA) stages of removing duplicate event or annual maxima.

Table 4-1 Standard abbreviations retained in cleaned up site names

Abbreviation	Term
Aero	Aerodrome
ALERT	Automated Local Evaluation in Real Time
AWS	Automated Weather Station
BCC	Brisbane City Council
BoM	Bureau of Meteorology
CSIRO	Commonwealth Scientific and Industrial Research Organisation
DNRM	Department of Natural Resources and Mines
DPI	Department of Primary Industries
Mt	Mount
RSL	Returned and Services League
SFR	State Forest Reserve
SPS	Sewage Pump Station
St	Saint or Street
STP	Sewage Treatment Plant
TM	Telemetered
TRC	Toowoomba Regional Council
WTP	Water Treatment Plant
WWTP	Waste Water Treatment Plant

4.3 Extraction of independent event maxima from each October-September water year, for multiple durations

Identification of extremes requires the use of an independency criterion that is consistent with the assumption made in application of the extreme value theorem to distribution fitting ensuring that the extremes are totally statistically independent (Ntegeka and Willems, 2008).

For Annual Maxima Series (AMS) analysis, the standard water year applied in this study was 1 October to 30 September. This period is commonly applied for annual frequency analysis of rainfall and streamflow data in Queensland. The driest period of the year in Queensland is typically August to October, so it was reasonable to assume that annual maxima burst rainfall depths observed in one water year would be uncorrelated with annual maxima in the next. However, this assumption assumes the absence of multi-year or multi-decadal drivers in the AMS and the absence of trends in the AMS. The use of the October-September water year should be sufficient to minimise year to year autocorrelation in the AMS. Use of an alternative water year definition (e.g. the January to December calendar year) would risk introducing spurious year-to-year autocorrelation in the AMS series, via events occurring late in one year that are correlated with those in the next.

Checks on the water year definition (see Section 6.3) subsequently confirmed that the 1 October to 30 September water year did produce the lowest number of annual maxima in July, August and September, which made it an appropriate choice for the definition of the water year.

In all subsequent analyses for this project, a convention was adopted to label the water year as the year ending 30 September. This meant that AMS events occurring in the wettest months of the year in

SEQ (typically January to March) would be labelled with the same water year and calendar year numbers. Events recorded in October, November and December would be labelled with a water year from the following calendar year.

Automated code was run on the:

- sub-daily rainfall data, for each site, to calculate rainfall totals for every overlapping time window in the record, for periods of 5, 10, 15, 20, 25, 30, 60 and 90 minutes, 2, 3, 4.5, 6, 9, 12, 18, 24, 30 and 36 hours and 2, 3, 4, 5, 6 and 7 days and
- daily rainfall data, for each site, to calculate rainfall totals for every overlapping time window in the record, for periods of 1, 2, 3, 4, 5, 6 and 7 days.

A Peaks Over Threshold (POT) analysis was used to extract the largest events in the record, at each site and for each duration. For sites with continuous records (or near to continuous records, with relatively infrequent periods of missing data), the POT was applied to extract the largest 30 annual maxima in each water year.

Ntegeka & Willems (2008) notes that there is not a consistent approach in the adoption of independence criteria for POT series. O'Shea et al. (2023) adopted a minimum period of 5 days between the end of one event and the start of the next one, for extracting event maxima from daily rainfall data. For analysis of short duration (10 minute) rainfall intensities, Ntegeka & Willems (2008) adopted a minimum 12 hour separation between events. Rahman et al. (2001) applied a more complicated approach to identification of independent "storm core" events, which involved comparison of the burst totals for different periods within the event to the 2 year ARI point design rainfall intensity. The period that produced the largest ratio of depth to the 2 year ARI design intensity was designated as the "storm core" for that event. The storm events that were input to this process were first identified by requiring at least 6 completely dry hours between events. This would result in separation of at least 6 hours between bursts, although the independent period between bursts would often be considerably longer, as the storm core identification process would focus on the most extreme period of each event. For the initial analysis of POT series in the current project, intervals for independence criteria were adopted, as shown in Table 4-2.

Table 4-2 Independence criteria adopted for extraction of POT series from sub-daily and daily recorded data sets

Sub-daily data		Daily data	
Burst duration (min)	Minimum separation between bursts in POT series (min)	Burst duration (days)	Minimum separation between bursts in POT series (days)
5	1440		
10	1440		
15	1440		
20	1440		
25	1440		
30	1440		
60	1440		
90	1440		
120	1440		
180	1440		
270	1440		
360	1440		
540	1440		
720	1440		
1080	1440		
1440	1440	1	1
1800	1800		
2160	2160		
2880	2880	2	2
4320	4320	3	3
5760	5760	4	4
7200	7200	5	5
8640	8640	6	6
10080	10080	7	7

An AMS analysis was undertaken to extract the largest events in the record, for each October-September water year and for each duration. AMS values were extracted from every water year with at least some valid data, at every site and for every duration. The later steps of the QA process were used to identify AMS values from water years where it was unlikely that the true water year maxima were captured at the site, as it was likely that another event in the same water year(s) exceeded those value(s) at the site but there was no valid data available for the larger event(s).

4.4 Preliminary checks

To ensure the maxima extraction was working as intended, a few maxima series from each data source was manually inspected. This process revealed a consistent flaw in the BoM's flood warning accumulated data sourced from ALERT gauges. Specifically, records frequently had 'blips' where the accumulated total rainfall would increase or decrease dramatically before returning to a more consistent reading (Figure 4-1). These blips caused unrealistically high annual maxima.

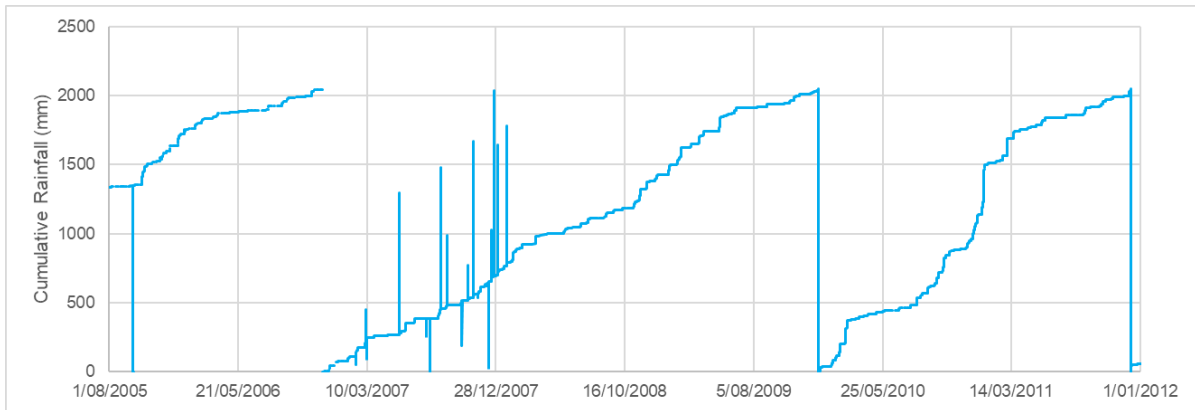


Figure 4-1 An example of the blips in the BoM's flood warning accumulated dataset.

In an attempt to rectify these flaws, the data reader was modified so that if a reading returned to the same value from two readings ago, the previous reading was ignored. However, this only fixed a minority of the blips, as there were many variations to how these flaws occurred. Some blips had multiple readings before returning to a previous value, while for example some blips did not return to the previous value but increased by a few millimetres.

Therefore, a subset of the accumulated gauges located in areas with sparse sub-daily information was chosen for manual clean-up. 67 out of 442 accumulated gauges were located more than 5 km away from a non-accumulated sub-daily gauge. The data for these 67 gauges was inspected and corrected manually and then re-processed and annual maxima re-derived.

Another observation made during these preliminary checks was that many gauges recorded very low annual maxima. This was due to large gaps in the raw data, or the record beginning/ending close to the end/start of the water year. This was addressed later in the QA process in Section 5.

4.5 Combining annual maxima from gauges at the same location

After maxima from daily rainfall gauges were converted from restricted to unrestricted totals (see Section 5), an AMS for each individual gauge was then available for robust QA checks to be undertaken. However, to avoid checking the same maxima twice, the annual maxima data was first combined for co-located gauges.

Co-located gauges were defined as having the same latitude and longitude, rounded to three decimal places (an accuracy of approximately 10 m). Out of 2,076 individual gauges, 917 were co-located with another gauge. At these sites, there was an average of 2.36 gauges per site and a maximum of 6 gauges per site.

Gauges at the same site did not necessarily record the same annual maxima. This occurred for several reasons including: differing data resolutions (e.g., daily vs sub-daily), differing periods of missing data and errors in the common site datasets. To create an AMS for each unique site, the largest maximum was selected for each water year (see Table 4-2). For daily durations, all gauge maxima were considered, whereas for sub-daily durations (including 30 and 36 hours), only sub-daily gauges were used.

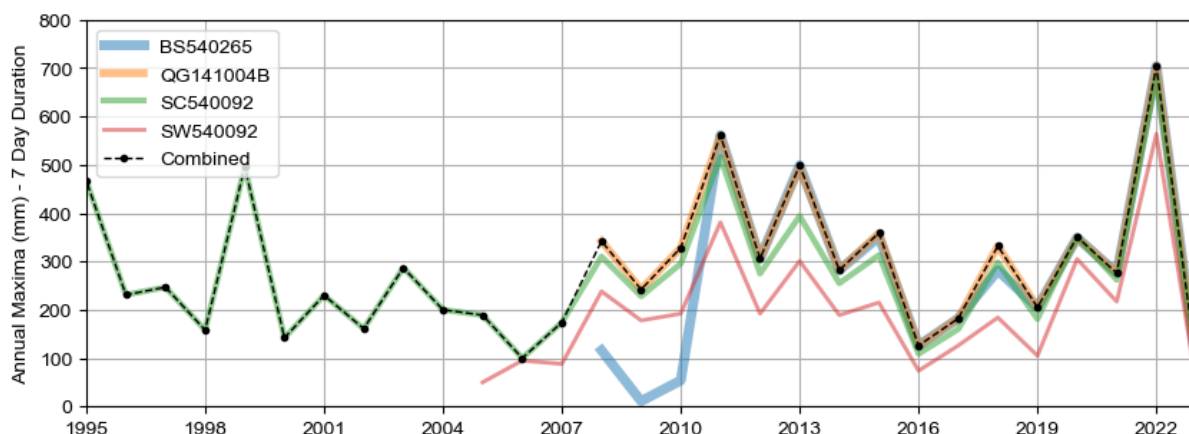


Figure 4-2 An example of how annual maxima was combined for co-located gauges.

4.6 Filtering of data based on length of record available

To make the QA process more efficient, minimum record length criteria were applied because fitting L-moments and probability distributions to series with only a few years of record would produce unreliable statistical fits at those sites. The same record length criteria were applied as those described in Chapter 3 of Book 2 of Australian Rainfall and Runoff (Green *et al.*, 2019), see Table 4-3.

As referred to earlier, some AMS contained very low annual maxima due to gaps in the data. Years where the annual maxima was less than or equal to 10 mm for the 1 day duration were excluded.

Table 4-3 Minimum record length criteria

Gauge Type	Record length criteria
Daily	≥ 30 years*
Sub-daily	> 8 years*
Combined	Total record ≥ 30 years* or combined sub-daily record > 8 years*

* Excluding years where the annual maxima was ≤ 10 mm for the 1 day duration

4.7 Identification of erroneous event maxima and missing water year maxima

After the preprocessing took place, robust QA processes were applied to:

3. Identify AMS values, for unique sites and durations, that are much smaller or larger than would be likely, given values recorded at nearby sites or from gridded independent rainfall data sets and
4. Identify water years where it was unlikely that the true water year maxima value was identified in the original AMS values, for that site and duration

Specifically, two daily durations (7 days and 1 day), and two sub-daily durations (12 hours and 1 hour) were checked (Table 4-4). For the daily durations, an AMS using gridded daily rainfall data from the Australian Water Availability Project (AWAP) (Raupach *et al.*, 2009, 2012) was generated for each unique site. The difference between the gauge annual maxima and AWAP annual maxima was calculated. Events were flagged for further checking based on this difference, as follows:

- If the gauge annual maximum was greater than the corresponding AWAP annual maximum by more than 100 mm for the 1 day duration, or 200 mm for the 7 day duration, the gauge annual maximum event was flagged
- If the gauge annual maximum was less than the corresponding AWAP annual maximum by more than 50 mm for the 1 day duration, or 100 mm for the 7 day duration, the AWAP annual maximum event was flagged

The flagged events were rounded to 9 am, before being grouped together. This resulted in 2,108 flagged gauge annual maxima being grouped into 482 events for the 1 day duration, and 2,052 flagged gauge annual maxima being grouped into 308 events for the 7 day duration.

For each event, a map showing both the gridded AWAP event totals and gauge event totals was produced, with flagged gauges labelled (see Figure 4-3). Each map was visually inspected for erroneous data, and unreliable annual maxima were identified for exclusion.

One disadvantage of using events to check maxima is that the event window may exclude the peak rainfall. This was a problem especially for the 1 day checks, where spurious spikes in recorded rainfall resulted in much higher annual maxima than AWAP, but due to the event window chosen, the gauge total seemed reliable. To combat this, checks on other durations were used to verify the 1 day checks, and exclude unreliable annual maxima.

For the sub-daily durations (12 hours and 1 hour), a different QA approach was implemented. Instead of comparing maxima to a gridded data set and extracting events to check, the annual maxima for all sub-daily gauges were mapped for every water year.

For each water year, the annual maxima were compared to surrounding gauges, with gauges that were previously marked for exclusion during the 1-day checks shown using different symbology (triangles vs circles) (see Figure 4-4). Again, unreliable annual maxima were identified for exclusion.

Table 4-4 Summary of durations checked.

Sequence of checks	Duration	# maps checked	Notes
1 st	1 day	482	One map per flagged rainfall event
2 nd	7 days	308	One map per flagged rainfall event
3 rd	12 hours	88	One map per water year (1937-2023)
4 th	1 hour	88	One map per water year (1937-2023)

All maps used for the checks were provided in the data package, provided with this report.

Data files of all annual maxima that passed the QA checks were also provided in the data package.

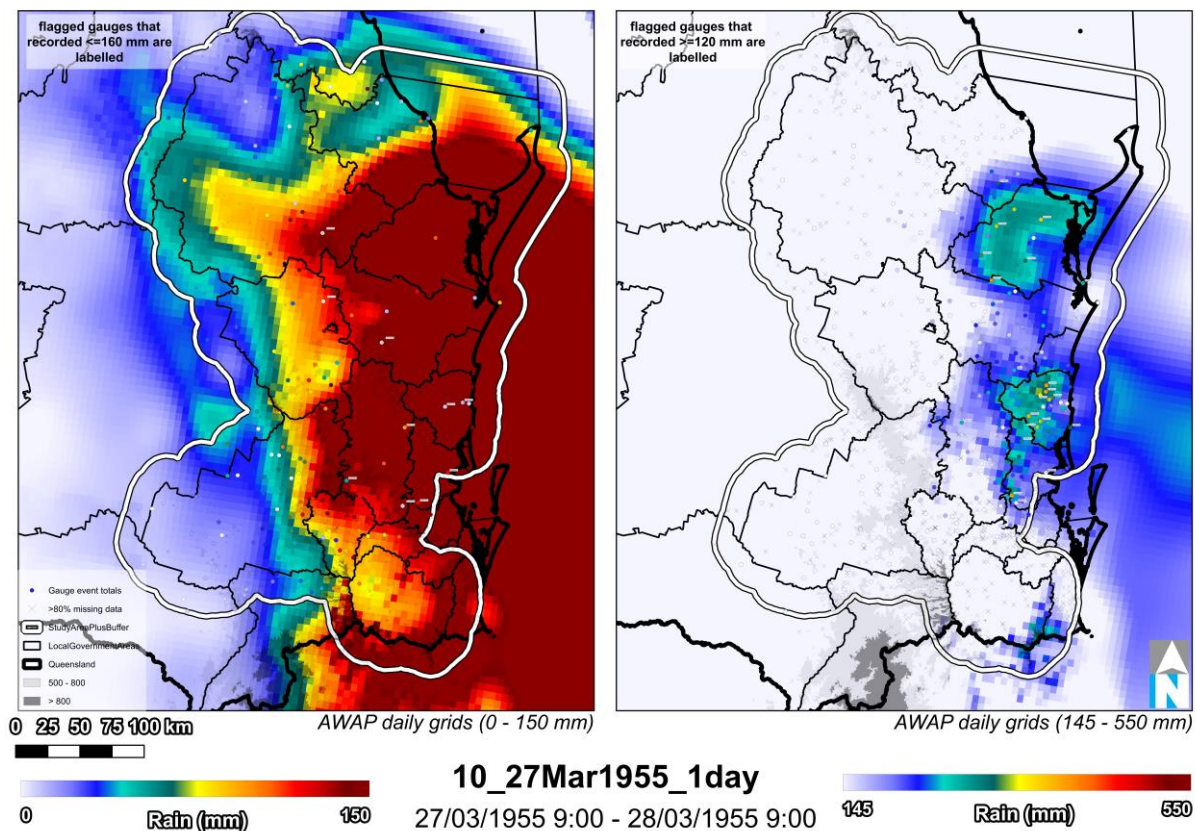


Figure 4-3 An example map used to check the 1 day duration. Similar maps were generated to check the 7 day duration.

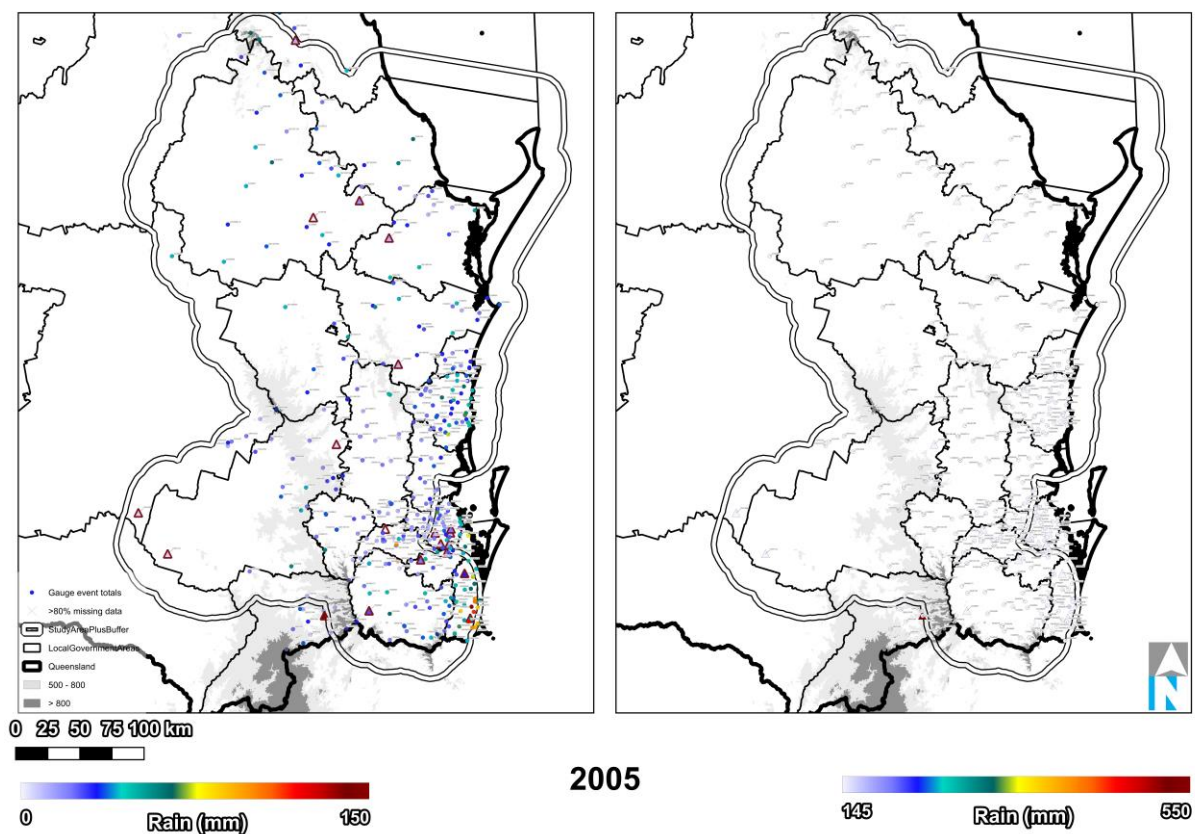


Figure 4-4 An example map used to check the 1 hour duration. Similar maps were generated to check the 12 hour duration.

Of approximately 55,500 daily annual maxima, nearly 9,500 (17%) annual maxima were excluded due to excluding low annual maxima and the visual checks of the mapped data. 95% of the annual maxima excluded for the 1-day duration were also excluded for the 7-day duration.

Of approximately 19,000 sub-daily annual maxima, around 800 (4%) annual maxima were excluded. 81% of the annual maxima excluded for the 1-hour day duration were also excluded for the 12-hour duration.

The QA checks for these 4 durations were extended to longer and shorter durations as shown in Table 4-5. For combined gauges, the 1-day AMS can be made up of both daily and sub-daily gauges, whereas the 30- and 36-hour (i.e., 1800 and 2160 minute) AMS were derived only from sub-daily gauges. Thus, the 12-hour checks were considered more applicable to the 30- and 36-hour durations for combined gauges.

Table 4-5 How checks were extended to longer and shorter durations.

Duration (mins)	Individual gauges	Combined gauges
5	1 hour	1 hour
10		
15		
20		
25		
30		
60		
90		
120		
180		
270	12 hours	12 hours
360		
540		
720		
1080		
1440		1 day
1800	1 day	12 hours
2160		
2880		1 day
4320		
5760		
7200	7 days	7 days
8640		
10080		

5. Unrestricted to restricted duration conversion factors

5.1 Purpose of U/R conversion factors

Rainfall sites recording at daily resolution for longer periods, exceeding several decades, are more abundant than sites recording at sub-daily resolution. The daily rainfall sites record the accumulated rainfall once per day, typically reported for the period up to 9 am local time at the rainfall gauge site. To utilise the data from the daily rainfall sites for frequency analysis, the data recorded for the 'restricted' or 'fixed' period: 9 am to 9 am must be converted to an 'unrestricted' or 'sliding' period that can commence or end at any time during the day. This is accomplished by the calculation of unrestricted to restricted (U/R) conversion factors, which are applied to durations of 1, 2, 3, 4, 5, 6 and 7 days.

The U/R conversion factors are calculated from sub-daily rainfall gauges, which report at high resolution (typically a few minutes) to infer the restricted daily or multi-day rainfall totals that would have been derived from a daily rainfall gauge that would have been reporting at 9 am on each day. The U/R conversion factors calculated from analysis of data at sub-daily rainfall gauges across a region are then applied to the restricted totals recorded at daily gauges before frequency analysis is undertaken on water year maxima recorded at those daily gauges.

A worked example of the calculation of U/R factors for 4 rainfall events at one sub-daily rainfall gauge (QG143108A, Warrill Creek at Amberley) is presented here. Figure 5-1 shows cumulative rainfall depths recorded over 2 days of each event, with the cumulative totals always starting at 9 am local time on the first day. The maximum unrestricted bursts of 24-hour duration were calculated from each of the four events, as shown in the top 2 rows of Table 5-1. Figure 5-2 shows the cumulative totals that would have been recorded for the same periods, had that gauge only reported at 9 am local time on each day. Rows 3 to 6 of Table 5-1 show the calculation of the maximum restricted 1 day burst for the same 4 events. The U/R factor for 1 day for each event was calculated by dividing the maximum unrestricted burst total by the restricted burst total, as shown in the bottom row of Table 5-1.

Table 5-1 Worked example calculation of burst-specific 24 hour/1 day U/R conversion factors for 4 events (see Figure 5-1 and Figure 5-2) recorded at gauge QG143108A, Warrill Creek at Amberley

Burst	29 Mar 2017	25 Feb 2022	19 May 2009	27 Jan 2013
24 hour unrestricted burst start time	29/03/2017 21:45	25/02/2022 11:40	19/05/2009 22:35	27/01/2013 9:20
24 hour unrestricted burst depth (mm)	232.0	202.5	163.3	152.0
Day 1 9 am start time	28/03/2017 9:00	25/02/2022 9:00	18/05/2009 9:00	25/01/2013 9:00
9 am day 1 rainfall depth (mm)	79.0	139.0	39.1	89.6
9 am day 2 rainfall depth (mm)	153.0	141.0	135.0	135.4
Maximum 9 am rainfall depth	153.0	141.0	135.0	135.4
Event-specific factor = Unrestricted depth / restricted depth	1.52	1.44	1.21	1.12

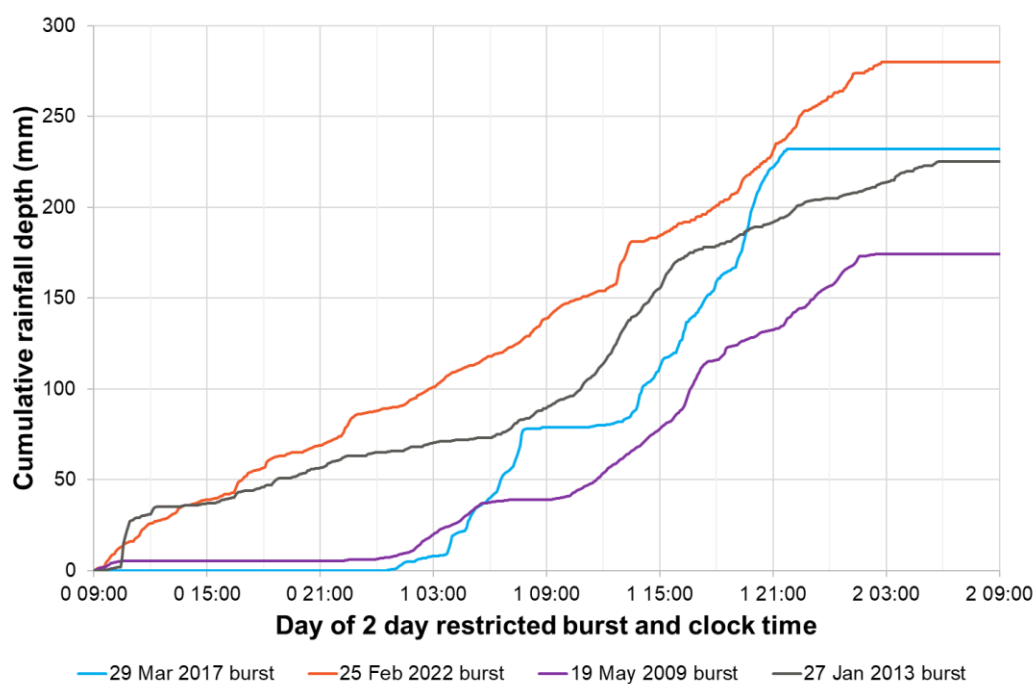


Figure 5-1 Cumulative rainfall depths from the 2 calendar day peak burst, with bursts always starting at 9 am local time on the first day, for 4 large rainfall events recorded at gauge QG143108A, Warrill Creek at Amberley

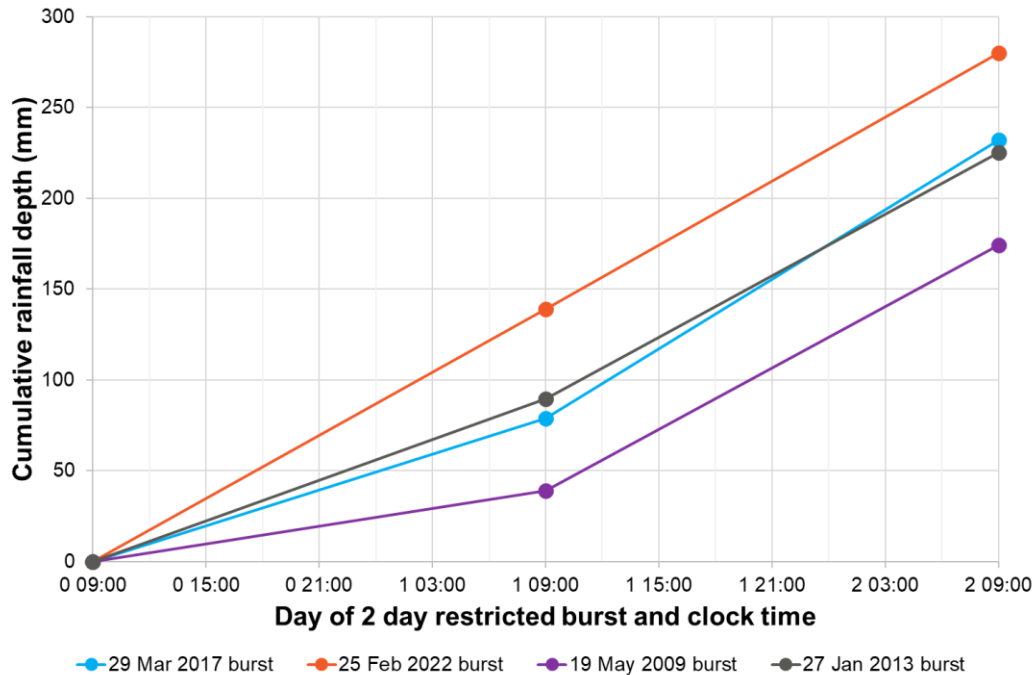


Figure 5-2 Cumulative rainfall depths from the same 4 large rainfall events shown in Figure 5-1, recorded at gauge QG143108A, Warrill Creek at Amberley, but with depths converted to daily totals restricted to always start and end at 9 am local time

5.2 U/R factors adopted by previous investigations

The history of U/R factors derived from various Australian and international studies between the 1960's and early 2000's is provided in Boughton & Jakob (2008).

The BoM adopted U/R factors shown in Table 5-2. The method of derivation of these factors, (concentrating on the 1 day to 24 hour factor) is provided in Section 4.1 of Jakob et al. (2005). The BoM's U/R factors were derived by applying the method developed by Dwyer & Reed (1995). The analyses undertaken by the Bureau and by Dwyer & Reed (1995) utilise several short periods of record, 16384 hours in duration (just short of 2 years), from a sub-daily rainfall gauge. Figure 5-3 shows the 5 periods (labelled A to E) that were used by both the Bureau and Dwyer & Reed. The approaches applied by the Bureau exploited the fractal scaling behaviour of rainfall to extract relationships between U/R factors computed for durations between 1 and 32 hours to fit the U/R factor for 24 hours or 1 day. In this way, the Bureau and Dwyer & Reed (1995) 'mined' as much information content as they could from relatively short periods of record at a handful of rainfall sites.

Jakob et al. (2005) found that the mean U/R factor for 1 day for Brisbane was 1.15, with factors for each of the 5 periods analysed ranging between 1.146 and 1.153 (see Figure 6 of Jakob et al., 2005). The 1 day U/R factor adopted by the Bureau (2016) of 1.15 was the same as the mean value that they identified for Brisbane. Dwyer & Reed (1995) found that the U/R factor for Brisbane was 1.147. Boughton & Jakob (2008) analysed U/R factors for durations between 1 and 24 hours. Although there was some similarity in the approach adopted with Jakob et al. (2005), Boughton & Jakob (2008) did not smooth the U/R factors fitted across durations. This lack of smoothing resulted in a 24 hour/1 day U/R factor derived by Boughton & Jakob (2008) that was considerably lower (1.081 derived from analysis of annual maxima for Brisbane and 1.127 for the average of seven Australian capital cities)

than those that were adopted by the Bureau for *Australian Rainfall and Runoff* (2019), Dwyer & Reed (1995) and Jakob et al. (2005). Boughton & Jakob (2008) found higher factors for shorter duration bursts, so the low values for the 24 hour duration from that study may have been due to not smoothing across durations.

WMA Water (2021) derived U/R factors for the Lockyer, Ipswich, Moreton Bay and Brisbane (LIMB) study region, which are shown in Table 5-2. The LIMB study derived U/R factors by directly extracting unrestricted duration annual maxima and the restricted duration annual maxima (for an overlapping period) from the full record of data at all the gauges across the LIMB study region. U/R factors were then presented as box plots (see Figure 5-4), showing the median values, interquartile ranges and outliers for durations between 1 and 7 days. Although not explicitly stated in the report, it appears as though WMA Water (2021) adopted the median value for each duration as the U/R factor. For reasons explained below, the median value approach that was most likely adopted by WMA Water (2021) is systematically less than the estimates based on averaged U/R factors (refer Figure 5-4) and is at variance with previous estimates.

Table 5-2 U/R factors adopted by previous studies

Duration (days)	Dwyer & Reed (1995) Brisbane	Jakob et al. (2005, Fig. 6) Brisbane	Boughton & Jakob (2008) Brisbane	Bureau (2016) (<i>Australian Rainfall and Runoff</i> , 2019, Table 2.3.4)	LIMB study (WMA Water, 2021)
1	1.147	1.15	1.081*	1.15	1.0994
2				1.11	1.0204
3				1.07	1.0083
4				1.05	1.0036
5				1.04	1.0015
6				1.03	1.0009
7				1.02	1.0000

* See Table 1 of (Boughton and Jakob, 2008), which analysed data only from Brisbane annual maxima events. They found a mean factor for all Brisbane events of 1.112.

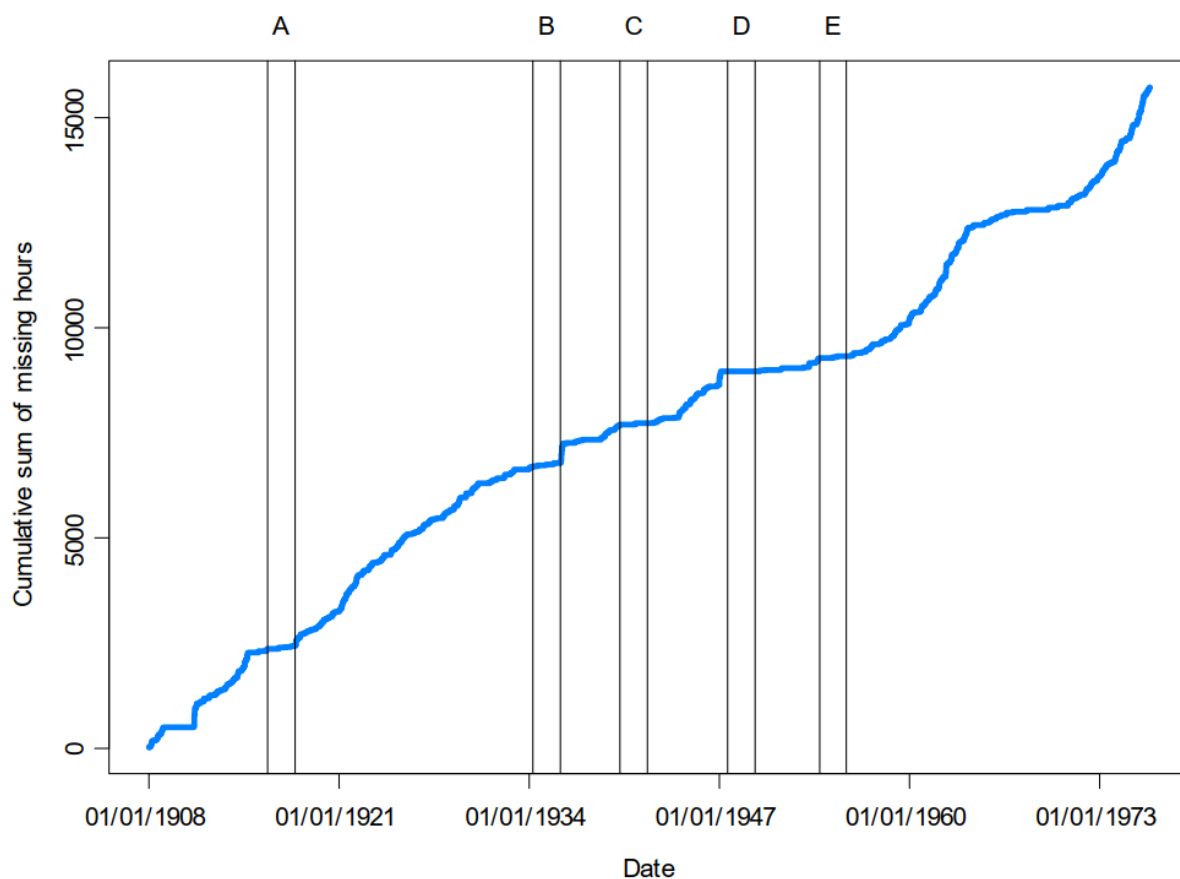


Figure 5-3 Periods (labelled A to E) selected for analysis of U/R factors by both the Bureau (Jakob et al., 2005) and Dwyer & Reed (1995) from the sub-daily rainfall data recorded at Brisbane Regional Office gauge, showing that there was complete or near-complete sub-daily rainfall records over each of those periods (reproduced from Figure 4 of Jakob et al., 2005)

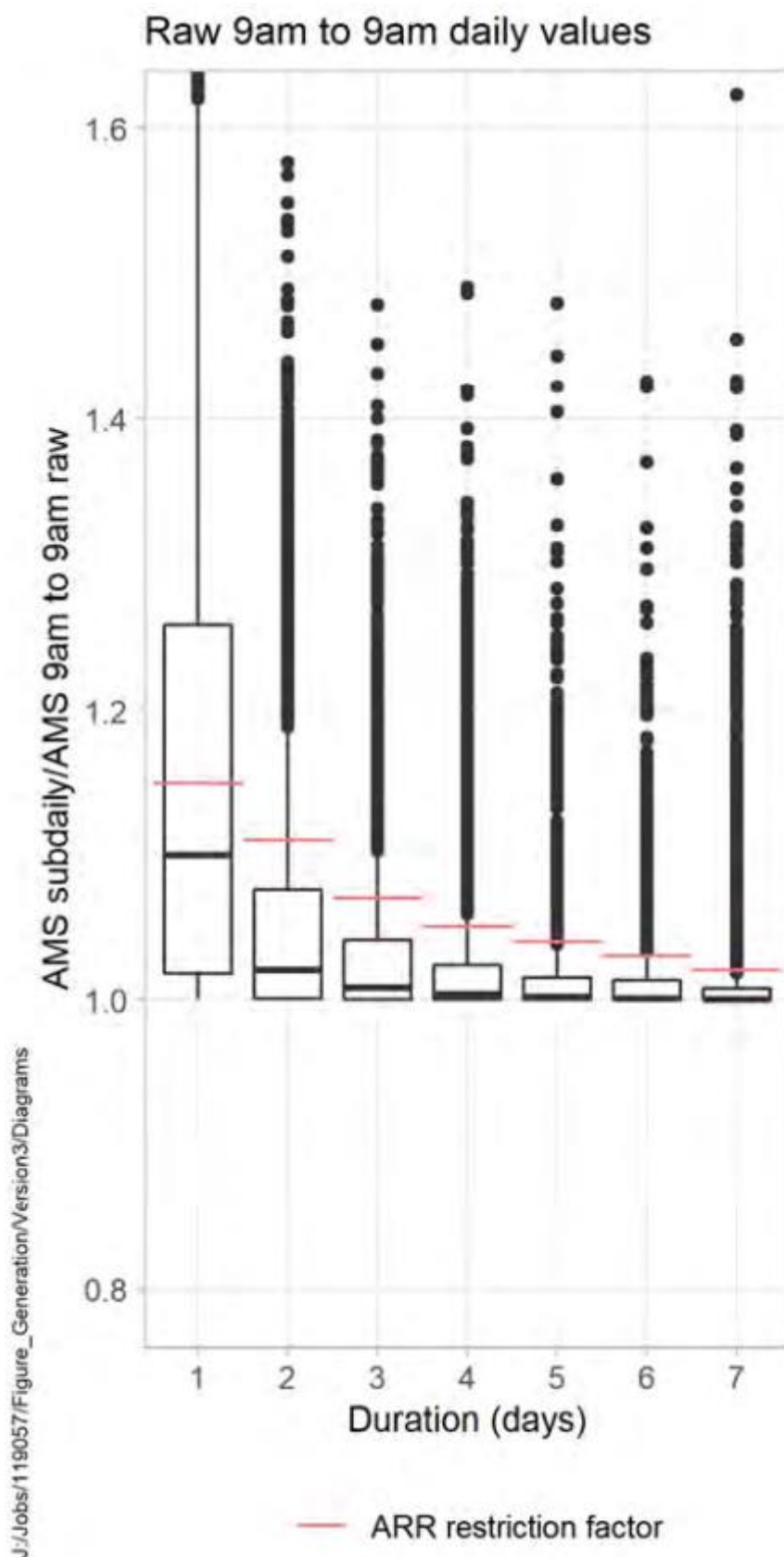


Figure 5-4 Box plots of annual maxima series event totals derived from unrestricted periods to those derived from data restricted to 9 am start times derived for the LIMB study area (reproduced from Diagram 3, page 10 of WMA Water, 2021)

5.3 Method of analysis

Water year maxima events were extracted, for both unrestricted and restricted durations, from all of the sub-daily rainfall sites across the study area that had sufficiently long and reliable rainfall records. Water year maxima were therefore extracted from a total of 132 sub-daily rainfall sites, as listed in Appendix L and with locations of the sites shown on Figure 5-14 and Figure 5-15. For the 1 day duration, this resulted in the analysis of 3,285 bursts of 1 day/24 hours, or an average of almost 25 water year maxima per site. This approach of extracting all the water year maxima from reliable sub-daily rainfall sites across the region was the same as that taken by the LIMB study (WMAwater, 2021). However, the approach taken for the current study differs from LIMB in the statistical analysis that was then undertaken on U/R factors after the water year maxima were extracted. LIMB adopted the median value as the U/R factor, whereas the current study used a different statistical approach, due to the strong skew in the U/R factors, which makes the median a low biased estimate of the representative U/R factor.

Figure 5-5 shows that there were many more sub-daily rainfall sites available for analysis in the last 30 years, since around 1992, than were available prior to that time. The analysis conducted for this study should reflect the hydro-meteorological factors that have been prevalent in the region over the last three decades, which could influence the U/R factor calculations. Figure 5-6 shows that the water year maxima were dominated by bursts occurring over January to March, with a lower prevalence over October to December and fewer maxima extracted over April to September. This reflects the seasonality of large rainfall events in South East Queensland (SEQ).

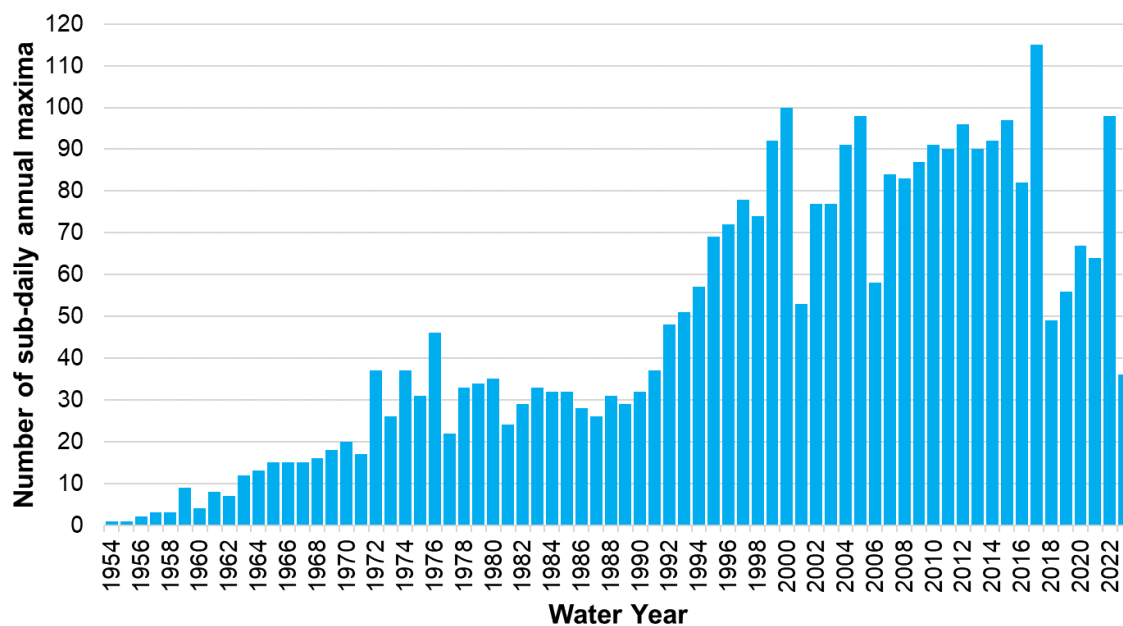


Figure 5-5 Number of 24 hour sub-daily annual maxima, by water year, utilised for unrestricted to restricted factor analysis

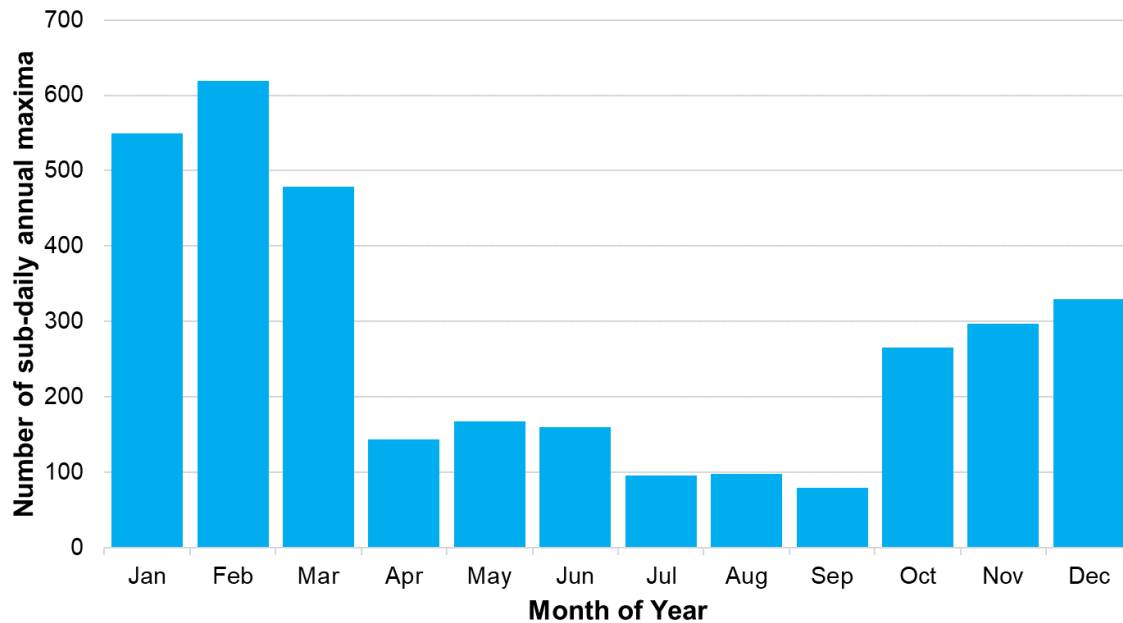


Figure 5-6 Number of 24 hour sub-daily annual maxima, by month of year, utilised for unrestricted to restricted factor analysis

Probability distributions were fitted to the U/R factors for the bursts. It was found that the U/R factors were well fitted by a beta distribution, given by:

$$\frac{U}{R} \sim B(\alpha, \beta) + 1$$

where α and β are parameters of the fitted distribution. The parameters α and β were fitted to optimise the fit of the distribution to the cumulative density function of the observed data.

The sensitivity of the distributions of U/R factors was tested due to variations in:

- Burst duration: 1, 2, 3, 4, 5, 6 and 7 days
- Seasonality: Dec-Feb, Mar-May, Jun-Aug and Sep-Nov and
- Burst intensity: categorised according to the ratio of the unrestricted burst depth to the mean of the unrestricted burst depth for all bursts of the same duration at that site.

5.4 U/R factor results for 1 day duration

Figure 5-7 shows the histogram of U/R factors for 1 day duration, for all burst events. The distribution is strongly skewed, with many bursts (almost 30%) having a U/R factor between 1 and 1.02. However, there are a relatively small number of bursts where the U/R factor is between 1.5 and 2. For those bursts, the 24 hour rainfall total was distributed almost equally across two days, before and after the 9 am daily recording cut-off.

Figure 5-8 shows that a beta distribution (with $\alpha = 0.4735$ and $\beta = 2.692$) provided an excellent fit to the U/R factors for the 1 day duration. The mean value of the fitted beta distribution was 1.150 and the median value of the fitted beta distribution was 1.080. The mean and median values of the raw data for 1 day U/R factors were 1.149 and 1.083, respectively.

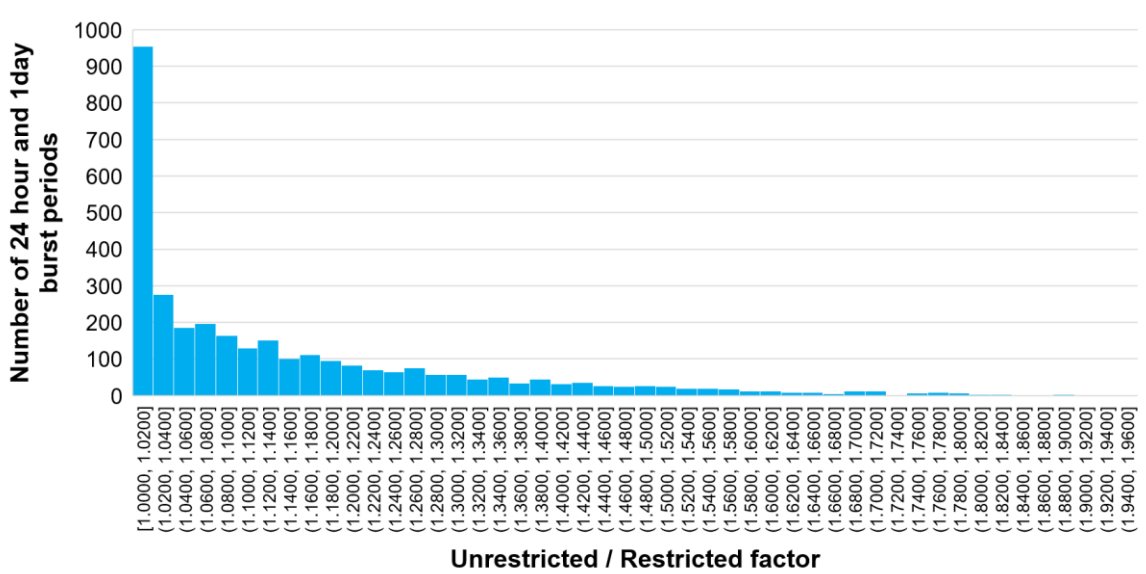


Figure 5-7 Histogram of U/R factors for 24 hour/1 day duration, all data (N = 3,285)

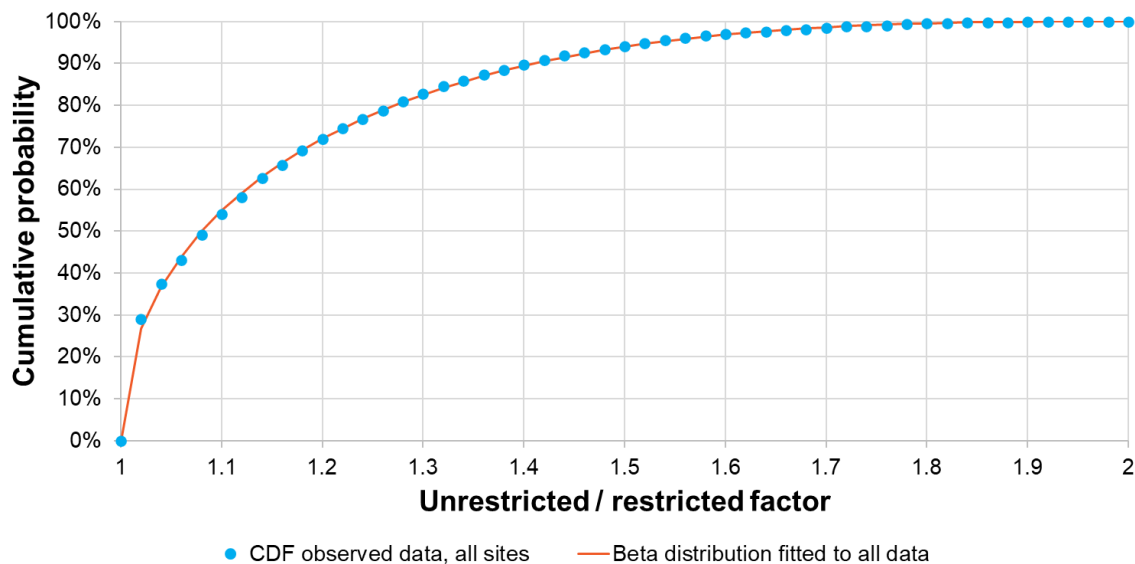


Figure 5-8 Cumulative distribution of U/R factors for 24 hour/1 day duration, all data (N = 3,285)

Figure 5-9 shows that there was some relationship between seasonality and U/R factor. U/R factors were slightly lower in September-November and slightly higher in June-August than in December-May. Lower U/R factors in September-November were probably associated with greater relative prevalence of diurnal thunderstorm events, which would be more likely to have most of their rainfall contained within a single 9 am to 9 am day. Higher U/R factors in Jun-Aug were probably associated with greater relative prevalence of longer duration synoptic events, which are typically more uniformly distributed across the hours of the day. Similar relationships between U/R factors and changes in dominant storm types across seasons have been observed in previous studies overseas (Dwyer and Reed, 1994, 1995; Llabrés-Brustenga *et al.*, 2020). U/R factor distributions for Dec-May, which contain about 70% of the total number of 1 day annual maxima, were similar to the U/R factor distributions derived from all of the data.

Table 5-3 shows that the mean U/R factors for 1 day duration were close to the annual mean of 1.150 for Dec-Feb (1.148) and Mar-May (1.158). The mean U/R factor was higher in Jun-Aug (1.168) but lower in Sep-Nov (1.132).

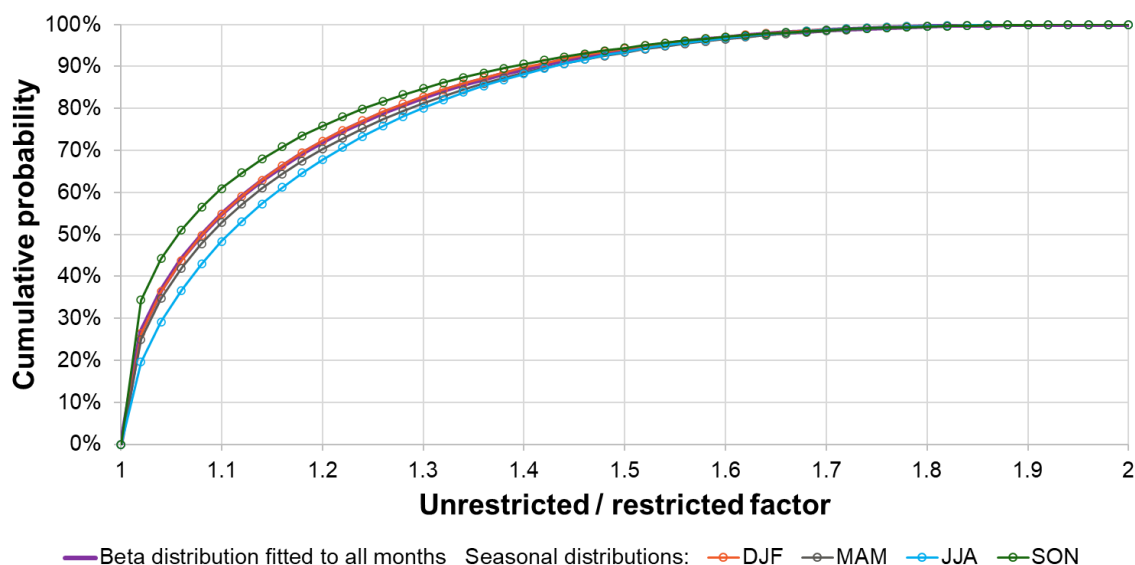


Figure 5-9 Cumulative distribution of U/R factors for 24 hour/1 day duration by season

Table 5-3 Seasonality of beta distributions fitted to U/R factors for 24 hour/1 day duration

Season	Number of bursts	α	β	Mean	Median
Dec-Feb	1,499	0.4838	2.777	1.148	1.081
Mar-May	791	0.4933	2.636	1.158	1.088
Jun-Aug	354	0.5974	2.962	1.168	1.107
Sep-Nov	641	0.3751	2.464	1.132	1.056
All months	3,285	0.4735	2.692	1.150	1.080

Figure 5-10 shows the scatter of 1 day U/R factors and relative burst intensity. It is difficult to visually interpret any relationship from this plot because there are many more bursts of relatively moderate intensity (unrestricted depth between about 0.4 and 1.4 times the mean annual unrestricted burst depth at the site) than rarer and more intense events. To further explore this, beta distributions were fitted to the U/R factors for each of the quartiles of event severity factor, as shown in Figure 5-11. This shows that more intense 1 day bursts, in the upper quartile, tend to have larger U/R factors than bursts in the lower three quartiles.

The mean U/R factor for the largest 25% of 1 day bursts was 1.183, compared with 1.150 for all 1 day bursts (see Table 5-4). The mean U/R factor for the lowest three quartiles by relative intensity was 1.138. Separate relationships were also fitted, with the event severity separated into 10 bins instead of 4 (deciles instead of quartiles), as shown in Table 5-5. The finer subdivision in burst intensity merely results in small and apparently random variations in distributions and mean values between adjacent decile bins, after allowing for the overall trend observed that the highest quartile has higher U/R factors than the others. For example, the eighth, ninth and tenth deciles had mean fitted U/R factors of 1.169, 1.195 and 1.180 respectively, varying randomly around the upper quartile mean value of 1.183. In summary, the upper quartile of events, with a 1 day unrestricted burst depths greater than 1.2 times

the mean annual maxima at the site, had a mean U/R factor of 1.183 but there was no evidence within this band that much rarer events had different U/R factors to less rare events.



Figure 5-10 Relationship between U/R factor for 24 hour/1 day duration and burst intensity (ratio of unrestricted burst maxima at the site to mean annual 24 hour burst maxima at the site)

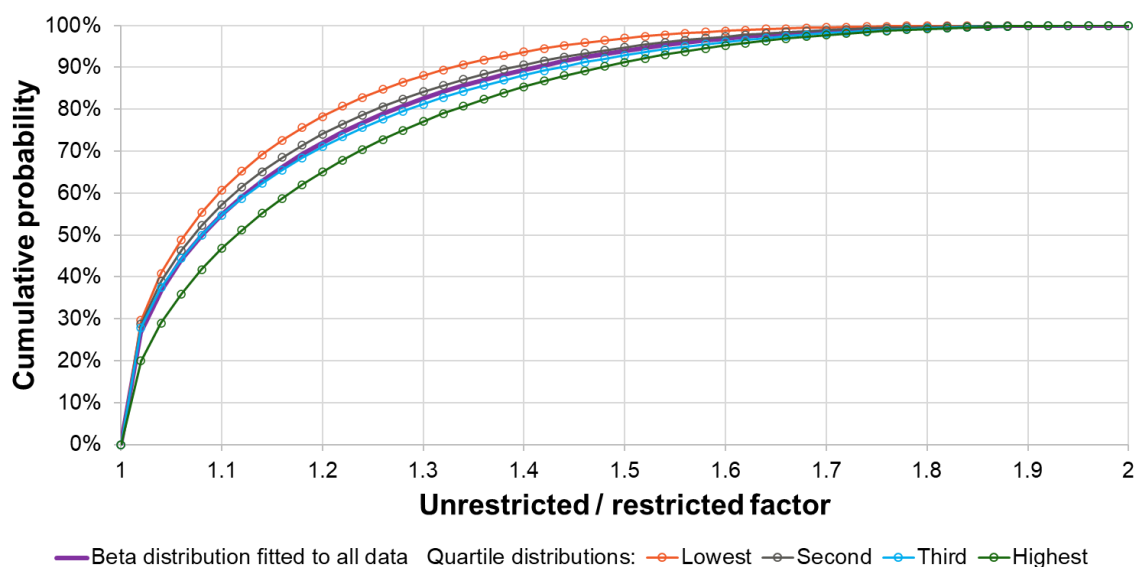


Figure 5-11 Cumulative distribution of U/R factors for 24 hour/1 day duration by burst intensity (relative to mean annual unrestricted burst depth at each site)

Table 5-4 Relationship between beta distributions fitted to U/R factors for 24 hour/1 day duration and relative burst intensity (by quartiles)

Quartile	Number of bursts	α	β	Mean	Median
Lowest	821	0.4860	3.553	1.120	1.063
Second	821	0.4560	2.807	1.140	1.072
Third	821	0.4405	2.392	1.156	1.080
1 st , 2 nd & 3 rd	2,463	0.4537	2.825	1.138	1.071
Highest	822	0.5553	2.475	1.183	1.114
All data	3,285	0.4735	2.692	1.150	1.080

Table 5-5 Relationship between beta distributions fitted to U/R factors for 24 hour/1 day duration and relative burst intensity (by deciles)

Decile	Number of bursts	α	β	Mean	Median
Lowest	329	0.5497	3.951	1.122	1.070
Second	328	0.4667	3.376	1.121	1.062
Third	329	0.3878	2.607	1.129	1.057
Fourth	328	0.4509	2.733	1.142	1.072
Fifth	328	0.5151	3.284	1.136	1.076
Sixth	329	0.4527	2.486	1.154	1.081
Seventh	328	0.4161	2.391	1.148	1.072
Eighth	329	0.5141	2.520	1.169	1.099
Ninth	328	0.5513	2.278	1.195	1.123
Highest	329	0.5609	2.547	1.180	1.113
All data	3,285	0.4735	2.692	1.150	1.080

5.5 Impact of random variations in U/R conversion factors on rainfall quantiles

The analysis in Section 5.4 above demonstrated that U/R conversion factors for 24 hours/1 day duration were well fitted by a Beta distribution. There was weak evidence of seasonality in the U/R factor distribution for SEQ but this was not sufficiently large to be explicitly concerned with in fitting frequency distributions to rainfall data. There was stronger evidence that relatively larger events, those for which the unrestricted maxima were greater than 1.2 times the mean annual maxima (also for unrestricted events), had larger U/R factors. Given this, it is possible that U/R conversion factors could differ with event AEP.

To test this, a numerical simulation was undertaken. The numerical simulation generated 500 random samples of unrestricted duration 24 hour annual maxima, from the same underlying GEV distribution, with each of the 500 samples containing 30 randomly generated water year maxima². Each of those unrestricted duration annual maxima were then assigned a randomly sampled U/R factor, generated from the Beta distributions described above (varying by relative event intensity). L-moments and GEV distribution parameters were then fitted to each of the 500 samples (each 30 years) of unrestricted

² The parameters used to randomly generate the GEV distributions for unrestricted 24 hour duration annual maxima are shown in the top row of Table 5-6, which were fitted to 30 years of unrestricted duration water year maxima at gauge QG143108A, Warrill Creek at Amberley

24 hour annual maxima and each of the 500 samples (each 30 years) of restricted 1 day annual maxima. The ratio of the 50%, 20%, 10%, 5%, 2%, 1%, 0.5% and 0.2% AEP design rainfall estimates were then calculated from each of the 500 matching samples of unrestricted and restricted duration data. Confidence limits were then calculated for the U/R factors of the 50%, 20%, 10%, 5%, 2%, 1%, 0.5% and 0.2% AEP design rainfall estimates.

Figure 5-12 shows that the mean U/R factors are relatively consistent with AEP. The mean U/R factor for any given AEP (between 50% and 0.2%) sits well within the inter-quartile range for all other AEPs. The variability in U/R factors from the fitted distributions increases with AEP, which is a consequence of the uncertainty in estimating design rainfall quantiles for rarer AEPs from relatively short records, as each generated sample only contained 30 years of record. Figure 5-12 shows that the distributions of U/R factors are skewed, with the mean greater than the median value and the upper tail (5% and 25% confidence limits) further from the median value than the lower tail (75% and 95% confidence limits). The skewed shape of the U/R factor distributions for the fitted rainfall quantiles are a consequence of the strongly skewed Beta distributions in U/R factors that were used to generate the data.

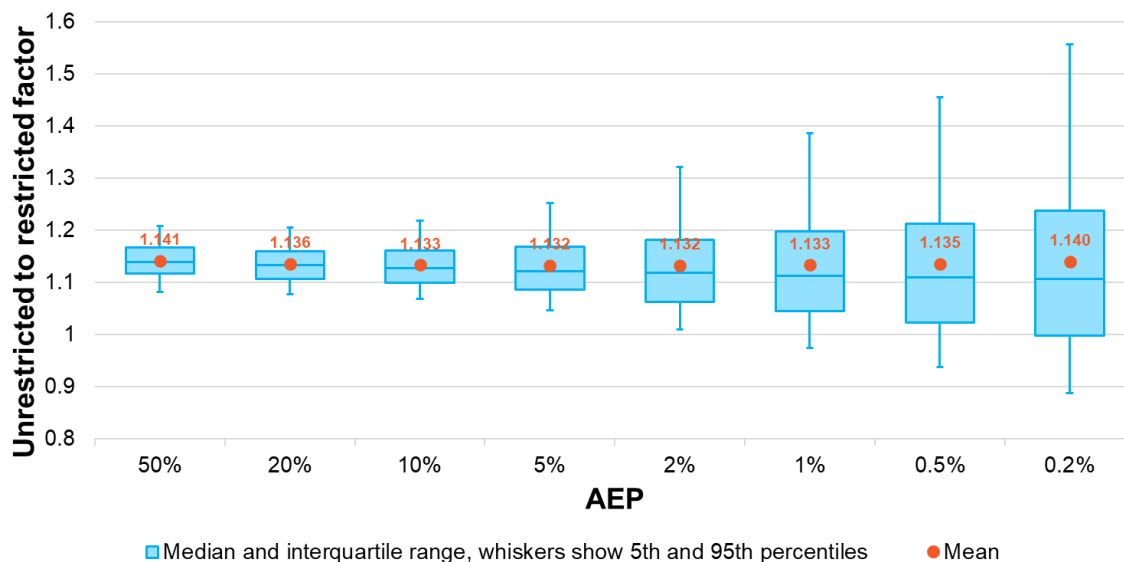


Figure 5-12 Box plots of 24 hour/1 day U/R factors calculated from a numerical simulation experiment, involving generation of 500 samples each containing 30 values of water year maxima, with random generation of U/R factors for each individual event from the Beta distributions described by parameters given for each of the quantiles in Table 5-8

Table 5-6 and Table 5-7 show that the mean values of the first and second L-moments (L1 and L2) and the mean values of the scale and location parameters of the GEV distributions fitted to the 500 samples of unrestricted data were also about 1.14 times the corresponding values for the restricted data. The mean of values of the shape parameter (Table 5-6) and the L-skew and L-kurtosis (Table 5-7) from the distributions fitted to restricted data were virtually identical to those fitted to unrestricted duration data. In summary, scaling the all the restricted duration maxima by the mean factor would have the same effect as a much more complicated approach of randomly sampling U/R factors from a Beta distribution on the L-moments and the parameters of the fitted GEV distribution.

Figure 5-13 shows that there is no difference in the spread of L-skew and L-kurtosis parameters between data generated across the 500 samples for unrestricted 24 hour duration (left) and restricted 1 day duration (right). Therefore, there is equivalent information content in L-moment parameters fitted to daily and sub-daily recording rainfall sites, given the same length of record at each site.

Table 5-6 Parameters of GEV distributions in Monte Carlo numerical simulation experiment

Simulation case	κ (shape)	α (scale)	ξ (location)
Values used to generate random unrestricted samples	-0.063	33.09	81.23
Mean of 500 randomly generated unrestricted 24 hour samples	-0.055	32.72	81.15
Mean of 500 randomly generated restricted 1 day samples	-0.055	29.11	71.00
Ratio of U/R values	0.999	1.124	1.143

Table 5-7 L-moments generated in Monte Carlo numerical simulation experiment

Simulation case	L1	L2	L3	L4	L-skew	L-kurtosis
Values used to generate random unrestricted samples	102.54	24.41	5.11	4.09	0.209	0.167
Mean of 500 randomly generated unrestricted 24 hour samples	102.37	24.48	5.31	4.29	0.208	0.172
Mean of 500 randomly generated restricted 1 day samples	89.97	21.85	4.79	3.87	0.208	0.172
Ratio of U/R values	1.138	1.120	1.109	1.110	0.999	0.998

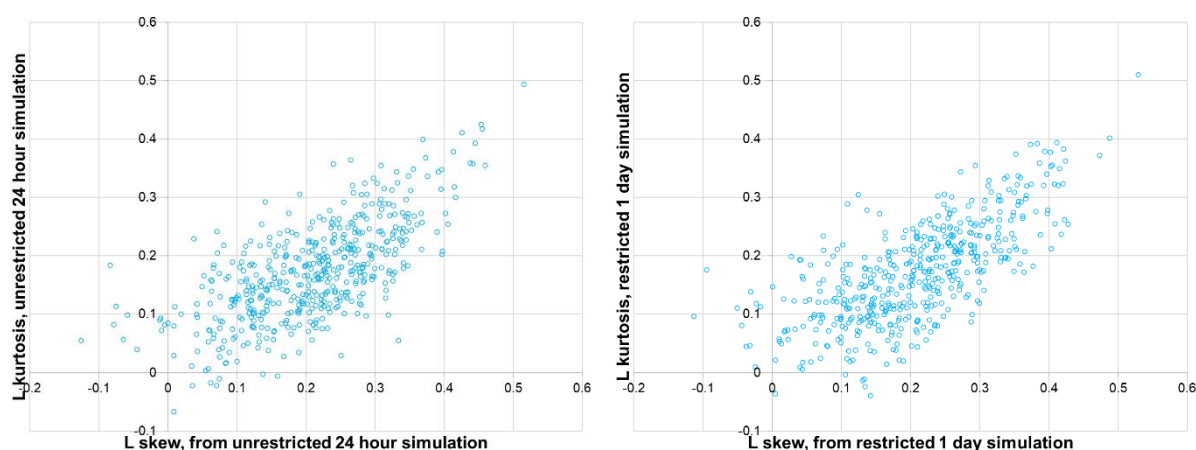


Figure 5-13 L-skew and L-kurtosis scatter plots generated from 500 samples each containing 30 values of water year maxima, for unrestricted 24 hour duration (left) and restricted 1 day duration (right) with random generation of U/R factors for each individual event from the Beta distributions described by parameters given for each of the quartiles in Table 5-8

5.6 Discussion of factors for 1 day duration

Bureau (Jakob *et al.*, 2005) and Dwyer & Reed (1995) used only a relatively small amount of data (less than 10 years of rainfall record, at the Brisbane rainfall site) to calculate U/R factors. In addition, the data used from the Brisbane rainfall site by Bureau (Jakob *et al.*, 2005) and Dwyer & Reed (1995) was relatively old, collected between 1916 and 1954.

The advantage of the approach taken in the current study and LIMB (WMAwater, 2021) was that a much more extensive database of sub-daily rainfall data was analysed, with the data extracted from

hundreds of rainfall sites, spread across the study region. Most of the data was also obtained over recent years and possible shifts in hydro-meteorological factors causing large rainfall events, that could influence the U/R factors, would be represented in this recent data.

Even given the much larger data set that was analysed for the current study and the use of more recent data, the current study has identified a mean 1 day duration U/R factor of 1.150, which is identical to that used by the Bureau (2016) and the factors fitted to Brisbane data by the Bureau (Jakob *et al.*, 2005) and Dwyer & Reed (1995). The LIMB study (WMAwater, 2021) adopted 1.0994 for the 1 day duration but this was because the median value was used. As demonstrated above, the strongly skewed nature of the U/R factor distribution results in biased estimates of design rainfall quantiles if the median factor is chosen for correcting daily restricted rainfall depths to unrestricted duration depths.

Seasonality affected the U/R factors for 24 hours/1 day duration but the influence of seasonality was relatively weak for the SEQ region. As the largest annual maxima occur between December and May in this region and the U/R factors for that season were similar to the mean for the whole year, it was not warranted to adjust U/R factors by season.

A numerical simulation experiment was undertaken, which demonstrated that scaling all the restricted duration maxima by a single mean factor would have the same effect on the U/R factors for rainfall frequency quantiles (between 50% and 0.2% AEP) as a much more complicated approach of randomly sampling U/R factors from a Beta distribution on the L-moments and the parameters of the fitted GEV distribution.

The consistency between the analysis conducted for the current study, Bureau (2016) and Dwyer & Reed (1995), despite the different data sets and methods employed, provides considerable confidence that 1.150 was an appropriate mean to adopt as the 24 hour/1 day U/R factor across the study region. However, the more extensive data set that was analysed for the current study reveals that 24 hour/1 day U/R factors should be applied to daily rainfall totals in the following circumstances:

- 1.150 for all 1 day restricted duration (9 am to 9 am rainfall bursts)
- However, for specific events, a bespoke U/R factor should be applied, where there was sufficient numbers and spatial coverage of sub-daily rainfall sites for the event to make a reasonable estimate of the U/R factor that should be applied to daily rainfall sites in the study area and the U/R factor from those sites would be appreciable greater than the standard value. This was identified as being warranted in specific cases:
 - For the March 2017 event, the mean 1 day U/R factor across the study region was 1.534, with the mean factor derived from 435 sub-daily rainfall gauges. The U/R factor values for this event were consistently high across the region but it was difficult to discern a specific spatial pattern of U/R 1 day factors within the event (see Figure 5-14). Therefore, the mean value of 1.534 was applied to 1 day maxima recorded at daily gauge sites in March 2017.
 - For the January 2011 event, 1 day U/R factors that were close to 2 were identified in the northern and western parts of Ipswich City Council (WMA Water 2021, section 3.9.1), which is also near the south-eastern boundary of Somerset Regional Council (see Figure 5-15). The average factor derived for that event was 1.245, not significantly different from the overall average of 1.150. However, 42 gauges in two regions showed distinctly higher 1 day U/R factors (Figure 5-15). These U/R factors had a mean value of 1.597, which was applied to 1 day maxima at daily gauge sites in Jan 2011 within the region shown on Figure 5-15.

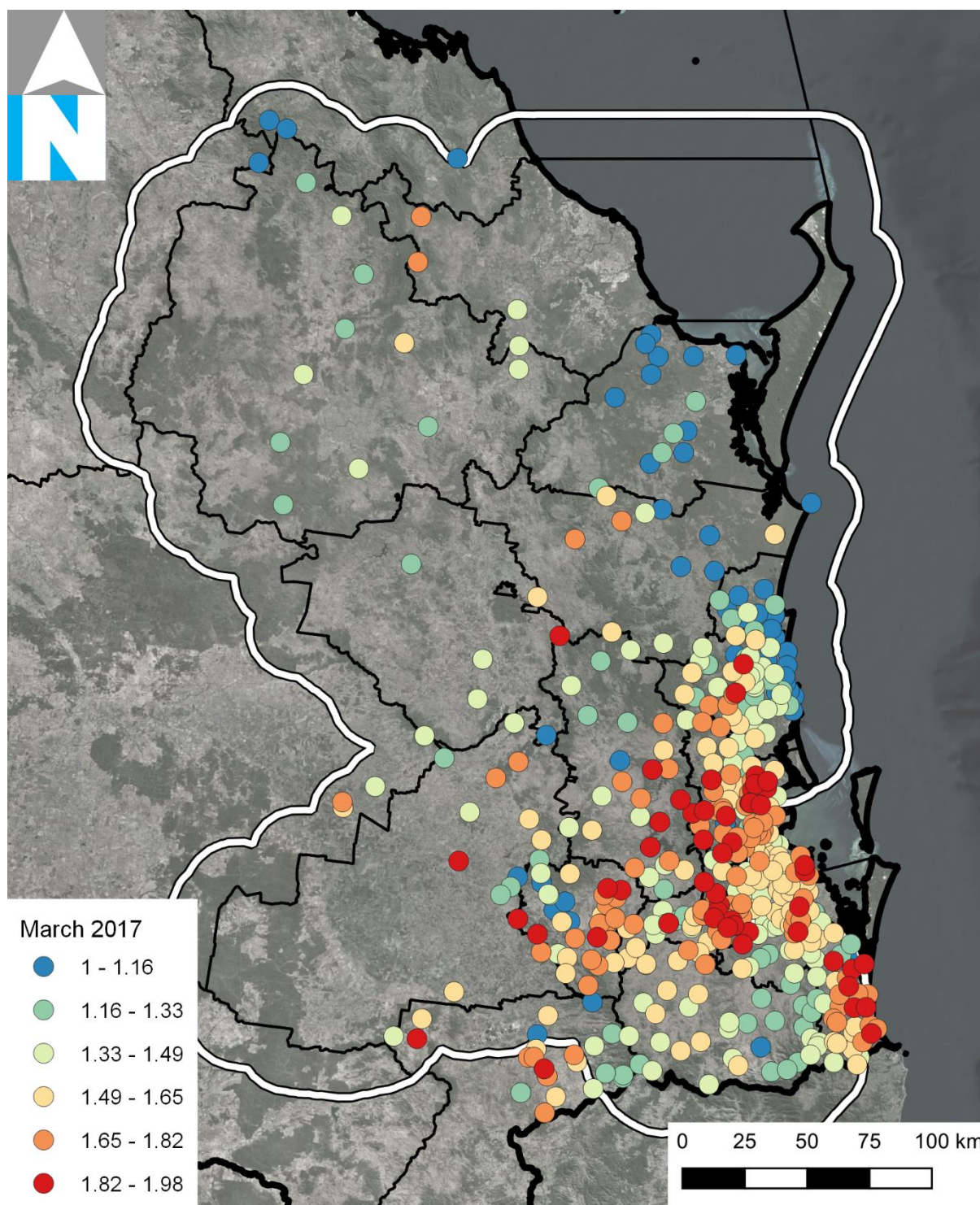


Figure 5-14 Map of 24 hour/1 day U/R factors for the March 2017 event

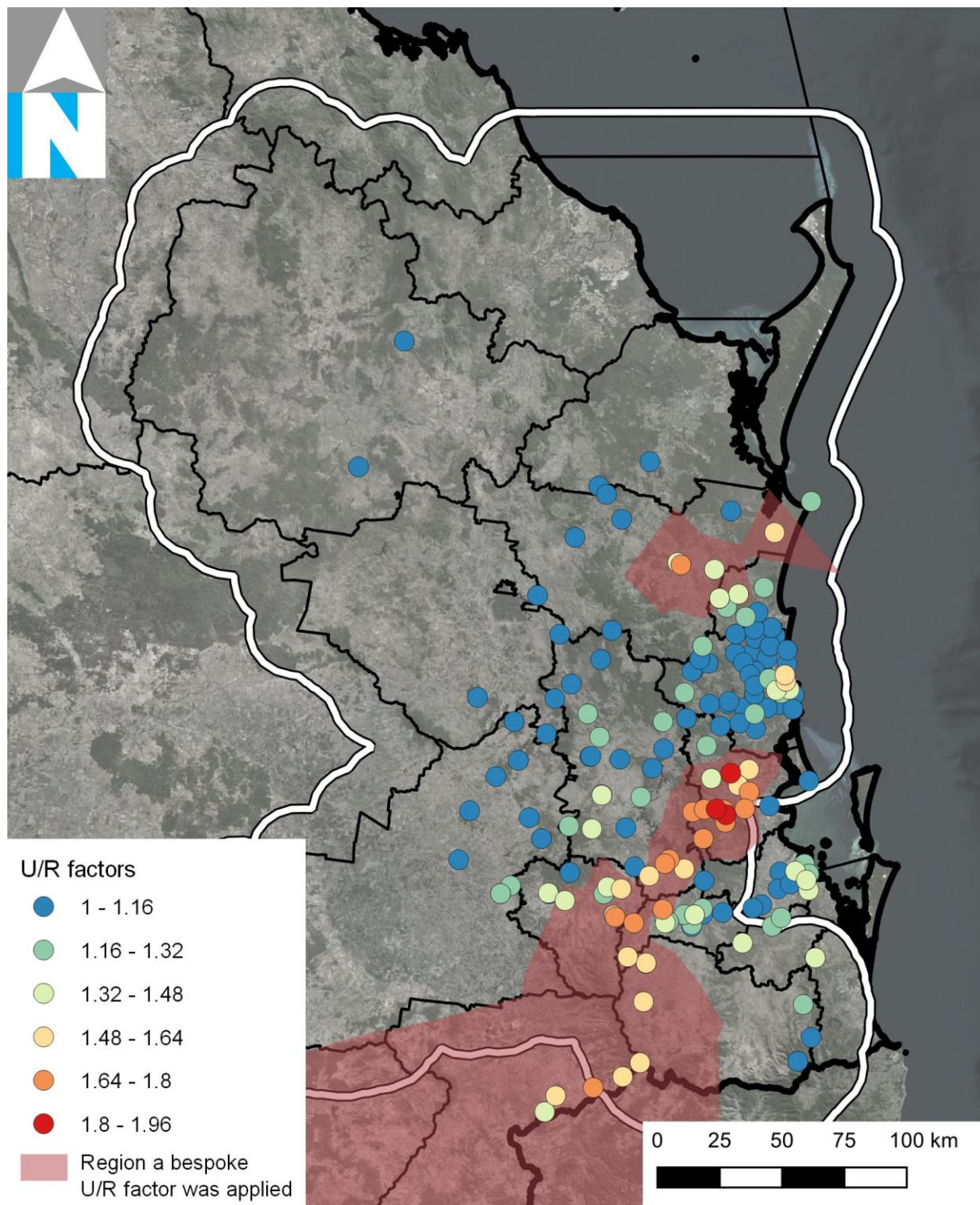


Figure 5-15 Map of 24 hour/1 day U/R factors for the January 2011 event, with the region where specific U/R factors were applied shaded

5.7 U/R factors for 2 to 7 day durations

The same analysis as was conducted for 1 day U/R factors was repeated for the 2 day duration. For 2 day duration, the mean U/R factor across all bursts was 1.059 (see Table 5-8). The histogram of the observed data for 2 day duration is shown in Figure 5-16 and the fitted cumulative distribution function for U/R factors is shown in Figure 5-17.

As the event duration increased from 1 to 2 days, the sensitivity of U/R factors to seasonality reduced to the point where it was insignificant and could be ignored (see Figure 5-18). For the 2 day duration, the sensitivity of U/R factors to relative burst intensity also reduced considerably, as shown in Figure 5-19 and Table 5-8. The highest quartile of events for the 2 day duration, by relative intensity, had a mean U/R factor of 1.069, which was 0.01 greater than the U/R factor for all events. A 1% difference in U/R factors was considered immaterial and the mean U/R adjustment factor of 1.059 for the 48 hour/2 day duration was adopted for all events, regardless of relative intensity or season.

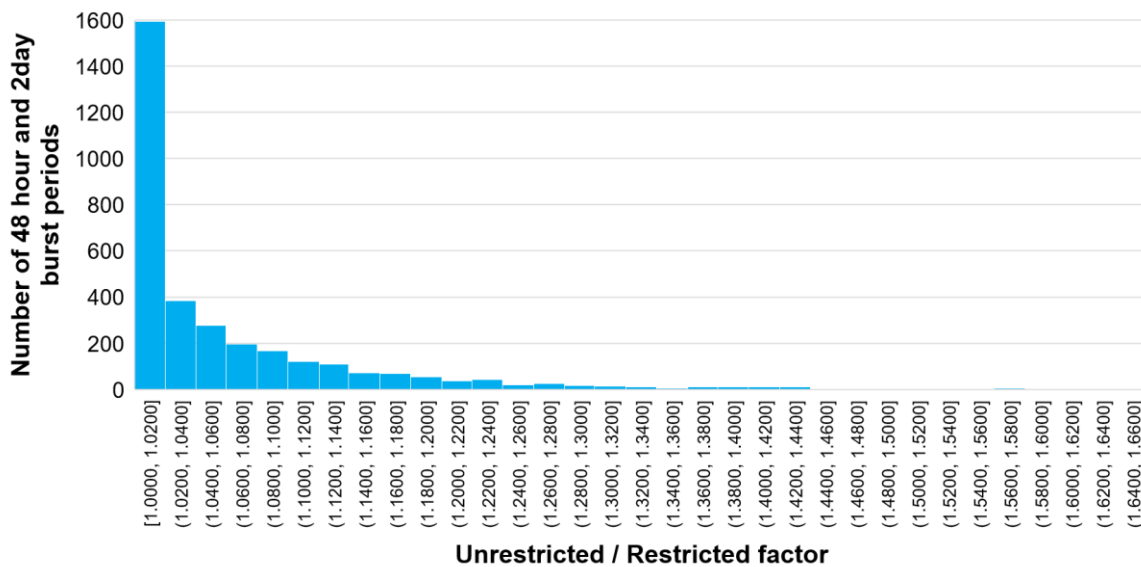


Figure 5-16 Histogram of U/R factors for 48 hour/2 day duration, all data (N = 3,291)

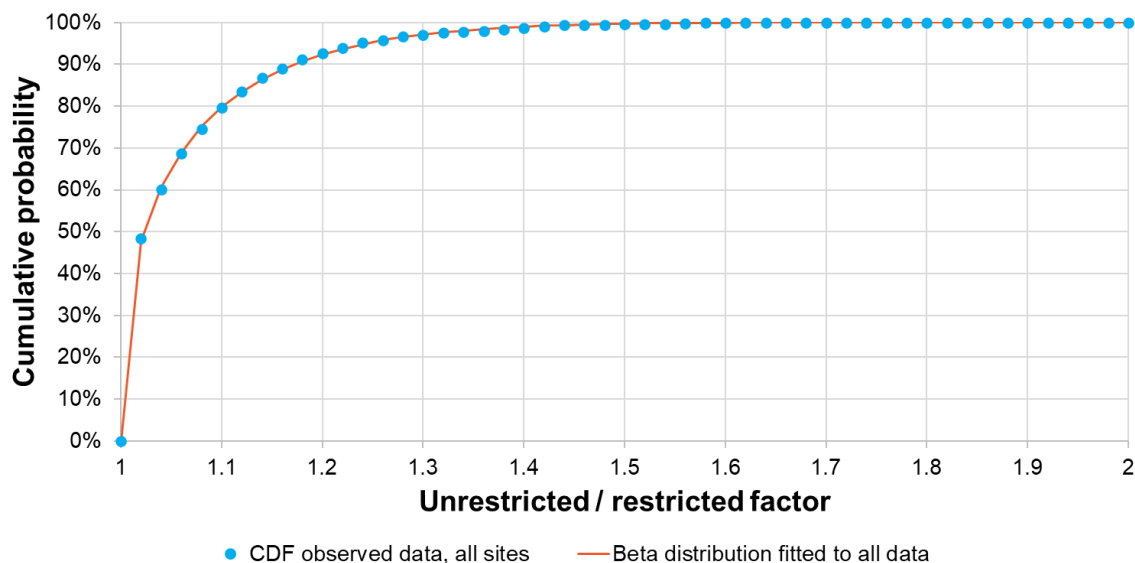


Figure 5-17 Cumulative distribution of U/R factors for 48 hour/2 day duration, all data (N = 3,291)

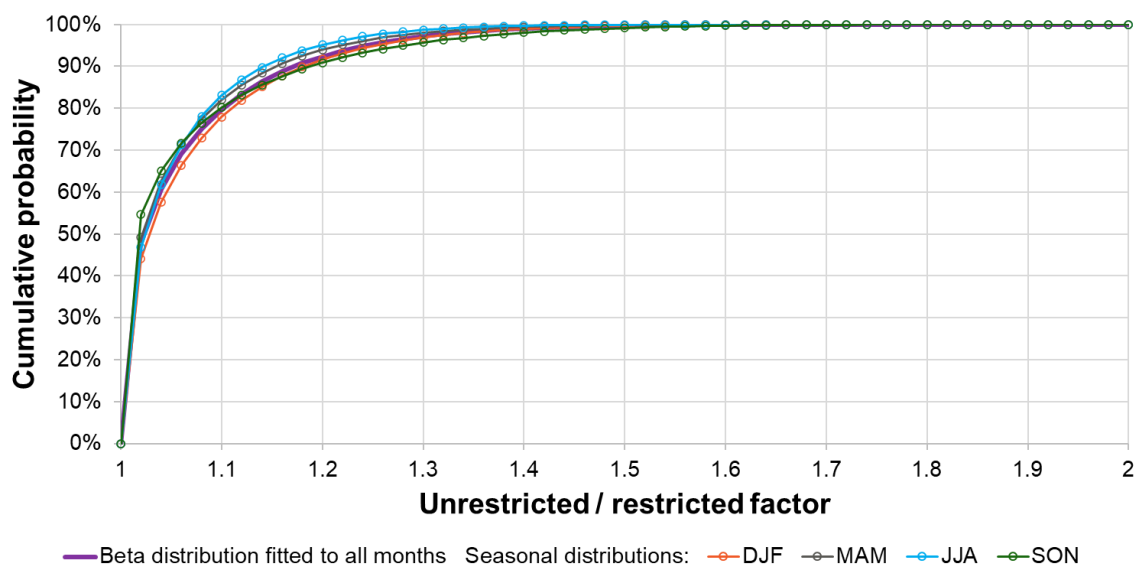


Figure 5-18 Cumulative distribution of U/R factors for 48 hour/2 day duration by season

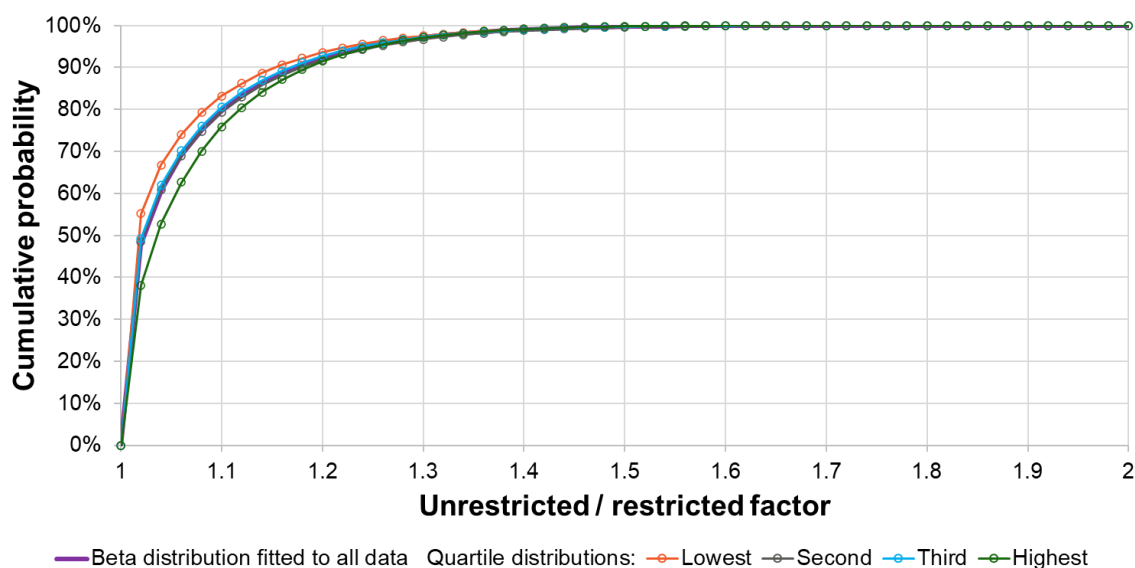


Figure 5-19 Cumulative distribution of U/R factors for 48 hour/2 day duration by burst intensity (relative to mean annual unrestricted burst depth at each site)

Table 5-8 Relationship between beta distributions fitted to U/R factors for 24 hour/1 day duration and relative burst intensity (by quartiles)

Quartile	Number of bursts	α	β	Mean	Median
Lowest	823	0.3074	5.782	1.050	1.014
Second	822	0.3636	5.612	1.061	1.022
Third	822	0.3696	6.068	1.057	1.021
1 st , 2 nd & 3 rd	2,468	0.3454	5.794	1.056	1.019
Highest	823	0.5267	7.141	1.069	1.036
All data	3,291	0.3856	6.105	1.059	1.023

Table 5-9 lists the U/R factors that were adopted for this study, for all daily durations between 1 and 7 days. As discussed in section 5.6, the 1 day mean factor of 1.15 for the current study was identical to that derived by the Bureau (2016) (Jakob *et al.*, 2009) and Dwyer & Reed (1995), despite the different data sets and methods employed.

The adopted values of U/R factors for durations between 2 and 6 days were a few percent lower than those adopted by the Bureau (2016) (see Table 5-9). The HRS10 report (Jakob *et al.*, 2009) only discusses the derivation of the 1 day U/R factor, although presumably the same method was then employed for the other durations. It is therefore uncertain as to why the 1 day mean U/R factors adopted for the current study and the Bureau (2016) would be the same but there would be differences at the longer durations.

The adopted values of U/R factors for all durations were larger than those adopted for the LIMB study (WMAwater, 2021) (see Table 5-9). As noted earlier, it is most likely that the LIMB study adopted median values as the basis for U/R factors. This is supported by the similar values of median U/R factors from this study and the LIMB factors (c.f. third and fifth columns of Table 5-9). As noted above, the strongly skewed nature of the U/R factor distributions makes the median a biased choice for U/R factors. The difference in adopted U/R factors could result in differences of around 5% in 24 hour and 4% in 48 hour annual maxima in the overlapping zones between the LIMB and the current study region. However, these differences only apply to design rainfall estimates derived using daily rainfall stations, as analysis of data from sub-daily rainfall stations does not use U/R factors and the pooling and gridding process of daily and sub-daily data probably would have smoothed out some of the differences that could have been introduced by differences in U/R factors.

Table 5-9 U/R factors adopted for this study and comparison to previous studies

Duration (days)	Adopted for this study	Median for this study (not adopted)	Bureau (2016) (<i>Australian Rainfall and Runoff</i> , 2019, Table 2.3.4)	LIMB study (WMA Water, 2021)
1	1.150*	1.080	1.15	1.0994 [£]
2	1.059	1.023	1.11	1.0204
3	1.036	1.007	1.07	1.0083
4	1.027	1.002	1.05	1.0036
5	1.021	1.000	1.04	1.0015
6	1.020	1.000	1.03	1.0009
7	1.0195	1.000	1.02	1.0000

Notes: * Specific factors to be adopted for March 2017 event and specific areas for the January 2011 event (see Section 5.6)

[£] Specific factors were applied in northern and western parts of Ipswich City for January 2011 event

6. Temporal and spatial coverage of annual maxima data

6.1 Spatial coverage of annual maxima data

After implementing the QA process, valid annual maxima data were obtained from 794 sub-daily and 442 daily gauges, a total of 1,236 gauges. The number of gauges within each LGA are listed in Table 6-1. The number of water year maxima obtained from gauges within each LGA are listed in Table 6-2. Data was obtained from some gauges that were outside the core study area but that fell within the buffer zone, which extended for approximately 20 km around the core study area.

The overall list of daily and sub-daily gauge sites, with numbers of water year maxima for the 24 hour durations are provided in Table 6-1.

Table 6-1 Number of gauges with valid annual maxima by LGA

LGA	Number of subdaily gauges	Number of daily gauges	Total number of gauges
Bundaberg	30	34	64
Cherbourg	0	0	0
Fraser Coast	21	22	43
Gympie	31	41	72
Noosa	14	5	19
North Burnett	56	49	105
Scenic Rim	41	38	79
Somerset	61	23	84
South Burnett	21	28	49
Sunshine Coast	70	30	100
Toowoomba	47	84	131
Banana	15	9	24
Brisbane	57	39	96
Gladstone	16	9	25
Gold Coast	47	11	58
Goondiwindi	14	6	20
Ipswich	39	12	51
Lockyer Valley	45	19	64
Logan	31	2	33
Moreton Bay	77	15	92
Redland	5	8	13
Southern Downs	36	36	72
Western Downs	23	28	51
*New South Wales	13	19	32
Totals	810	567	1377

Table 6-2 Number of valid annual maxima by LGA

LGA	Number of 24h water year maxima from sub-daily gauges	Number of 24h water year maxima from daily gauges	Number of 24h water year maxima from all gauges
Bundaberg	538	2,387	2,925
Cherbourg	0	0	0
Fraser Coast	557	1,688	2,245
Gympie	1,007	2,453	3,460
Noosa	376	368	744
North Burnett	1,240	2,941	4,181
Scenic Rim	1,259	2,521	3,780
Somerset	1,350	1,645	2,995
South Burnett	691	1,875	2,566
Sunshine Coast	1,777	2,142	3,919
Toowoomba	1,032	5,828	6,860
Banana	283	628	911
Brisbane	1,297	3,171	4,468
Gladstone	322	623	945
Gold Coast	1,010	926	1,936
Goondiwindi	336	366	702
Ipswich	721	972	1,693
Lockyer Valley	785	1,393	2,178
Logan	517	186	703
Moreton Bay	1,339	1,137	2,476
Redland	206	578	784
Southern Downs	756	2,133	2,889
Western Downs	592	1,456	2,048
*New South Wales	648	1,324	1,972
Totals	18,639	38,741	57,380

As a region-wide study, it is important to note that data was pooled from rainfall gauges across the entire study area. In other words, data from rainfall gauges within one LGA were used to inform the statistical analysis for IFDs in other parts of the study region. Figure 6-1 and Figure 6-2 illustrate the number of gauges across the study region and the number of valid water year maxima identified at each gauge. The gauge density colouration shows the indicative number of water years per km² of area, calculated using a 40 km radius circle at each location. A density of 0.4 water years/km² (the deepest brown colour) would represent about 2,000 water year maxima within a 40 km radius circle. By comparison, a density of 0.1 water years/km² (the deep blue colour) would represent about 500 water year maxima within a 40 km radius circle. Densities of gauges are highest in the south-east of the study region, between Noosa and the Gold Coast, and extending west into Ipswich and the eastern parts of Lockyer Valley, Somerset and Scenic Rim.

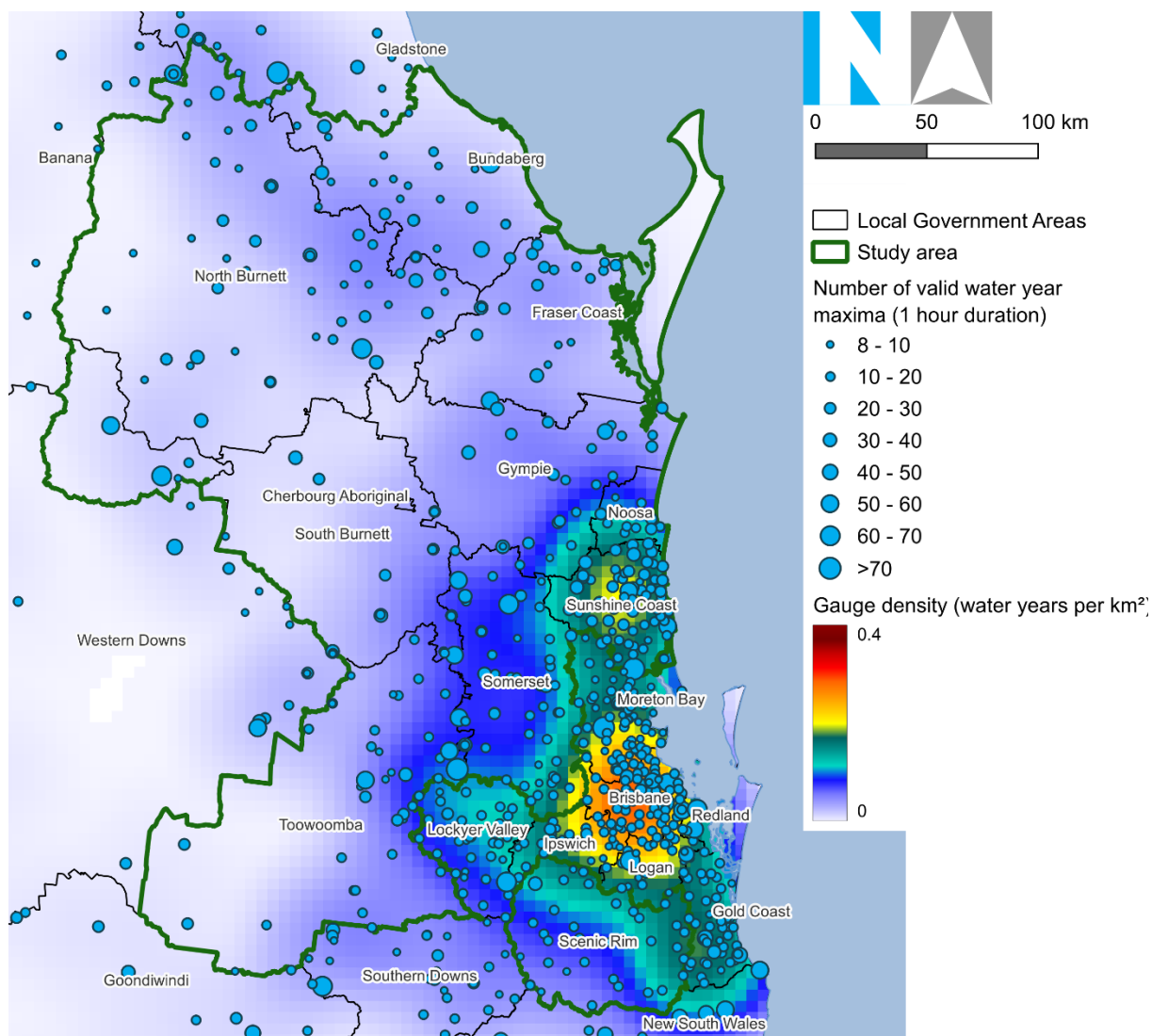


Figure 6-1 Density of coverage of sub-daily gauges across the study region, showing number of valid annual maxima at each site for the 60 minute duration and density of gauges (number of annual maxima per km²)

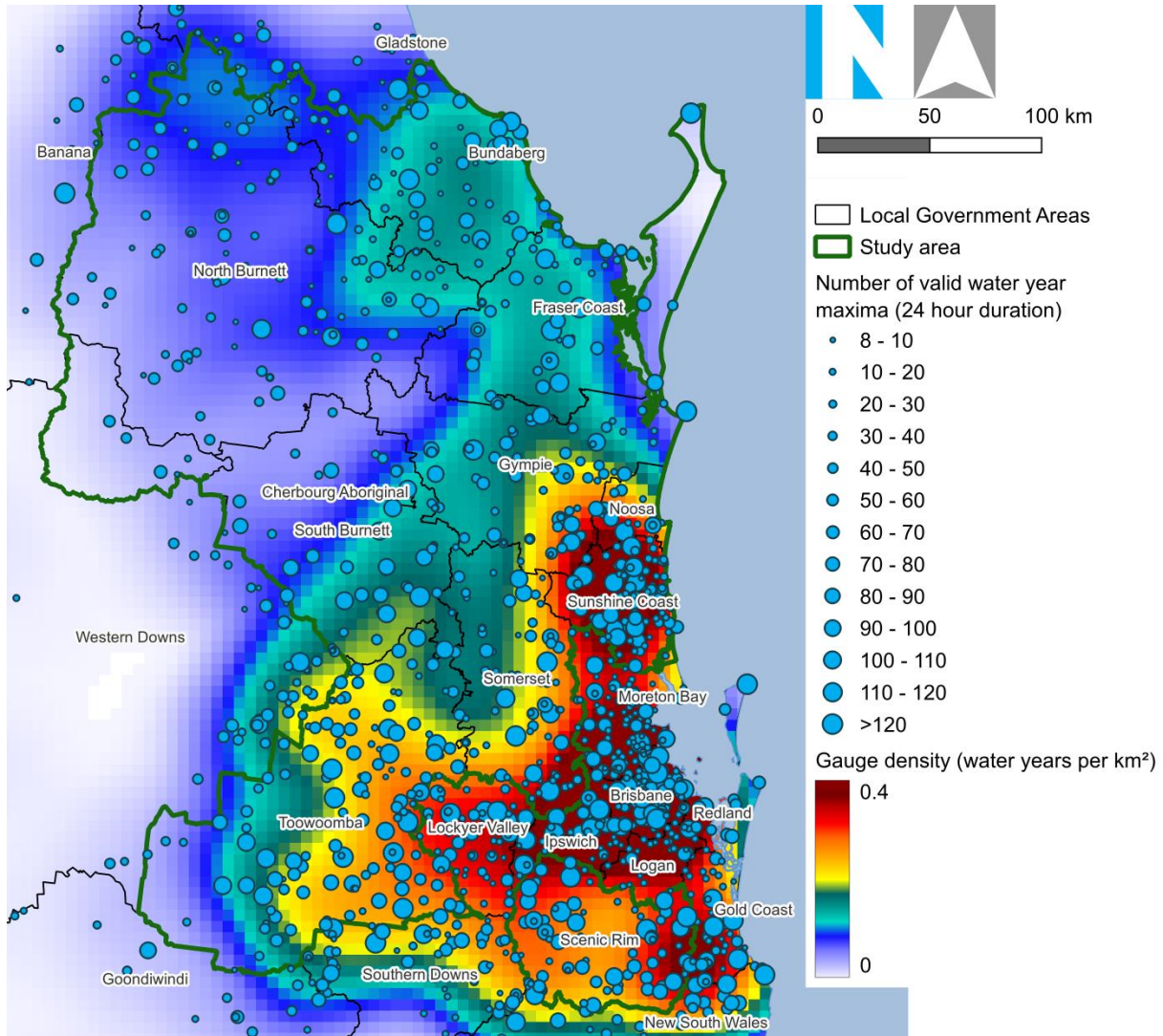


Figure 6-2 Density of coverage of daily and sub-daily gauges across the study region, showing number of valid annual maxima at each site for the 24 h duration and density of gauges (number of annual maxima per km²)

Figure 6-3 and Figure 6-4 show histograms of the number of water years of valid annual maxima across the study region for sub-daily and daily gauges respectively. Figure 6-3 shows that the bulk of the sub-daily gauges have between 8 and 19 years of valid annual maxima, with a smaller number of gauges having much longer records of between 20 and 67 years. Figure 6-4 shows that a little under half of the combined daily and sub-daily gauges had between 5 and 19 years of valid 24 hour water year maxima. 647 gauges, or about 53% of the total, returned 20 years or more of valid 24 hour water year maxima. Six gauges across the study region had 137 years of valid annual maxima.

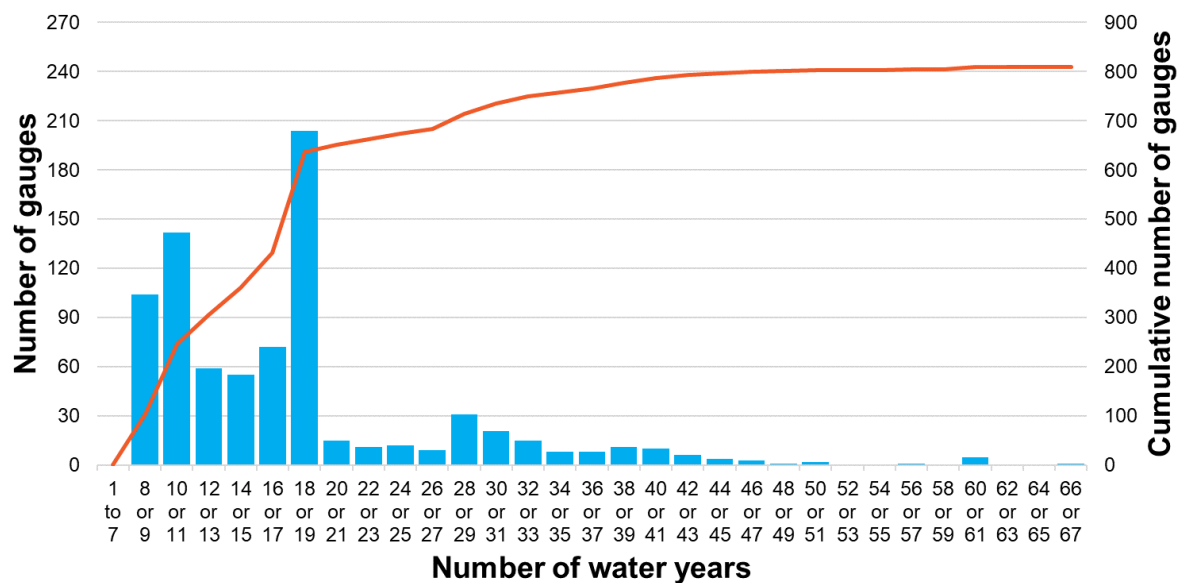


Figure 6-3 Histogram of number of water years with valid annual maxima for 60 min duration, from sub-daily gauges

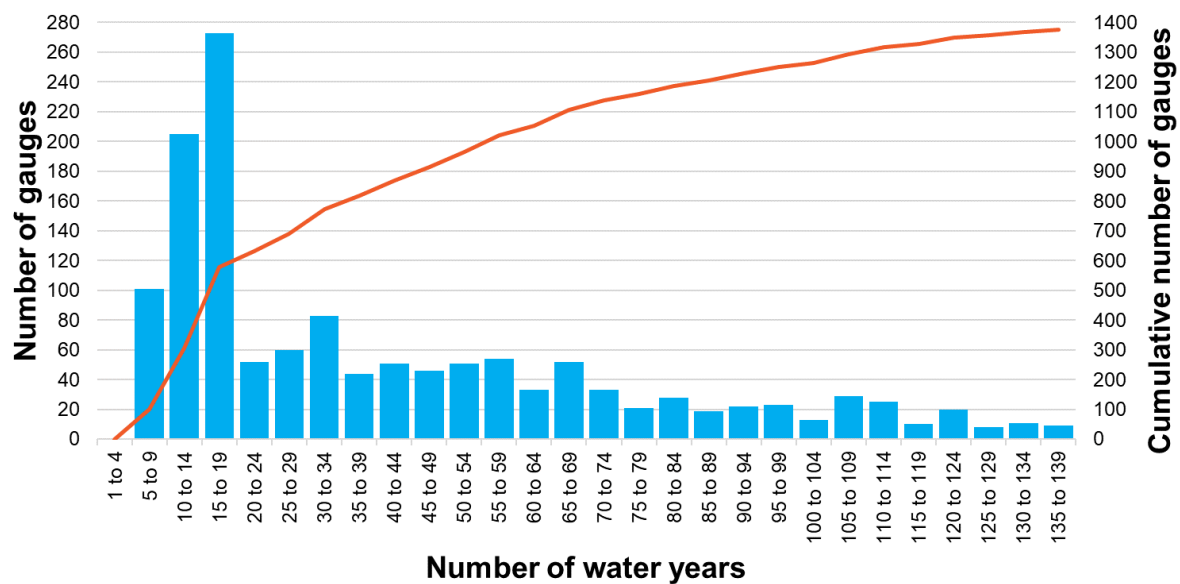


Figure 6-4 Histogram of number of water years with valid annual maxima for 24 h duration, from daily and sub-daily gauges

6.2 Temporal coverage of annual maxima

After implementing the QA process, the water year maxima data consisted of the number of values shown in Table 6-3. Note that the numbers shown in this table are for each duration listed, e.g. there were 14,071 valid water year maxima identified for each duration between 5 minutes and 3 hours, i.e. 5 min, 10 min, 15 min, ... 180 min. There were almost double the number of valid water year maxima from daily gauges as from sub-daily gauges. In some cases, combining co-located gauges resulted in combined sites that were comprised of a mix of sub-daily and daily gauge data. They were classified as sub-daily gauges, since they contained some sub-daily data, which explains the increase of about 3,000 water year maxima for durations of 24-72 hours and 96-168 hours compared to the 18, 30 and 36 h durations.

Table 6-3 Total number of water year maxima by gauge type and rainfall burst duration

Duration range	Sub-daily gauges	Daily gauges	Total water years
5 min - 3 h	14,071	0	14,071
4.5 h - 18 h	13,926	0	13,926
24 h, 48 h, 72 h	18,157	38,693	56,850
30 h - 36 h	13,912	0	13,912
96 h - 168 h	18,021	38,694	56,715

The first gauges for which records are available recorded data in the water year ending September 1887. As shown in Figure 6-5, the number of rainfall gauges recording valid annual maxima increases across the period of record. This was particularly true for sub-daily gauges, with very few gauges available prior to about 1960 and then substantial increases over the decade between 2005 and 2015.

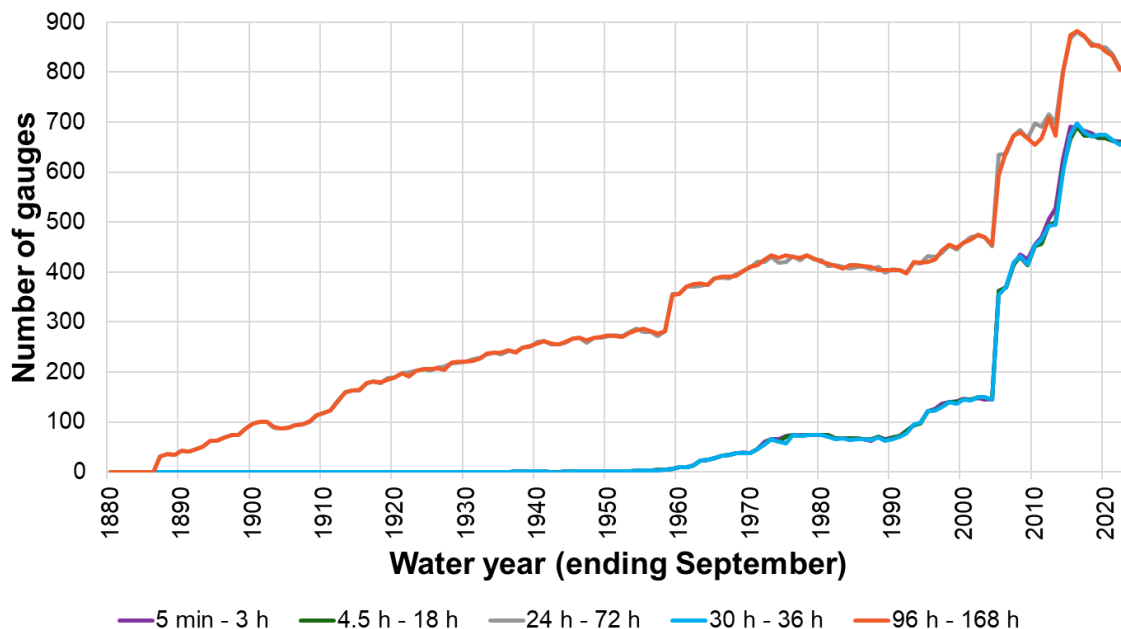


Figure 6-5 Number of gauges reporting valid maxima by water year and duration

6.3 Review of water year for analysis

A water year of 1 October to 30 September was adopted for the analysis. Figure 6-6 and Figure 6-7 confirm that this was an appropriate choice, with the lowest number of annual maxima being recorded in July to September of each year.

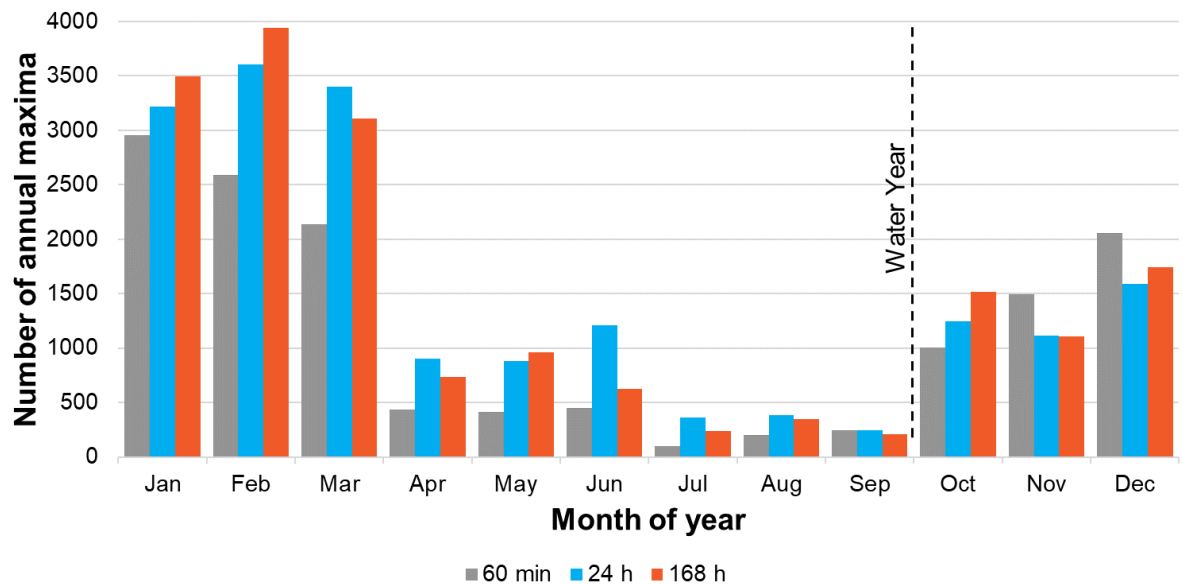


Figure 6-6 Number of valid water year maxima by month of year from sub-daily gauges

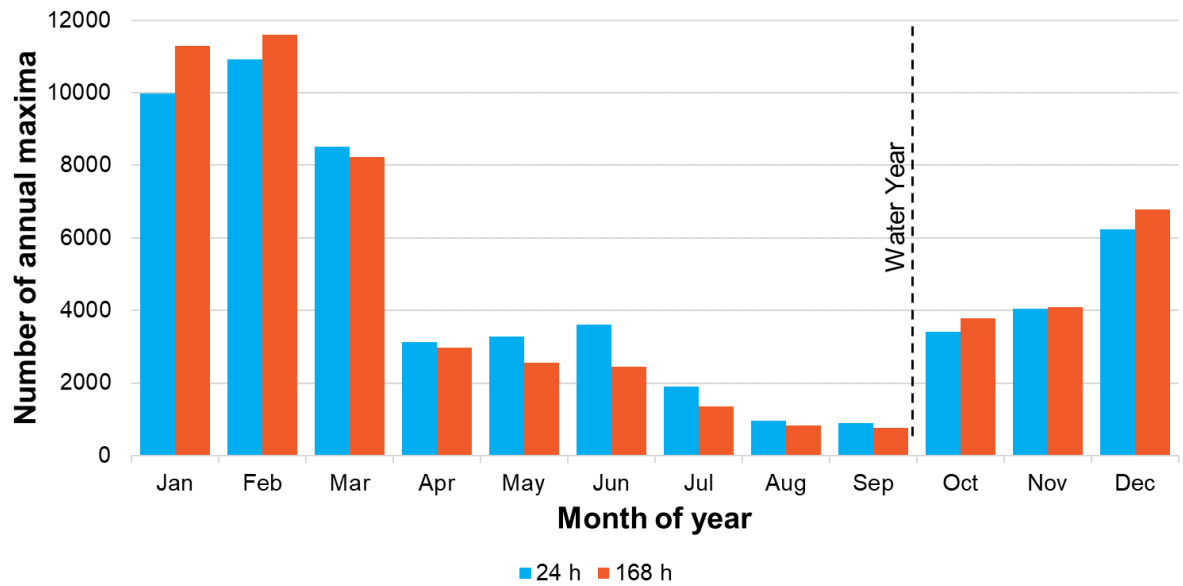


Figure 6-7 Number of valid water year maxima by month of year from sub-daily and daily gauges

6.4 Comparison with data used by BoM 2016

Figure 6-8 compares the spatial coverage of sub-daily rainfall gauges across the study region for the current project against the gauges used by the Bureau (2016) IFD update. There is a substantial increase in both the number of sub-daily rainfall gauges available and the length of record available at many of the sites. The number of sub-daily sites for the current project is 810, compared with 214 sub-daily gauges used by the Bureau (2016) IFD update. In total, there were 4224 annual maxima across the study region used by the Bureau (2016), compared with 14,071 QA'd water year maxima for the 60 minute duration for the current study, an increase of 233%. In summary, the size of the sub-daily rainfall data set was about 3.5 times as large for the current study as was adopted for the Bureau (2016) IFD update.

It was not possible to obtain a definitive list of the daily rainfall gauge sites or years that were used by the Bureau (2016) IFD update in the study region. However, given that daily rainfall data was compiled in 2012 for the IFD update, the number of QA'd 24 hour duration water year maxima at the daily gauge sites used for the current analysis up to and including the 2012 water year was 27,717. The daily gauge data set for the current study therefore contained ~11,000 additional water year maxima, an increase of 40% over the number that would have been available for the Bureau (2016) IFD update.

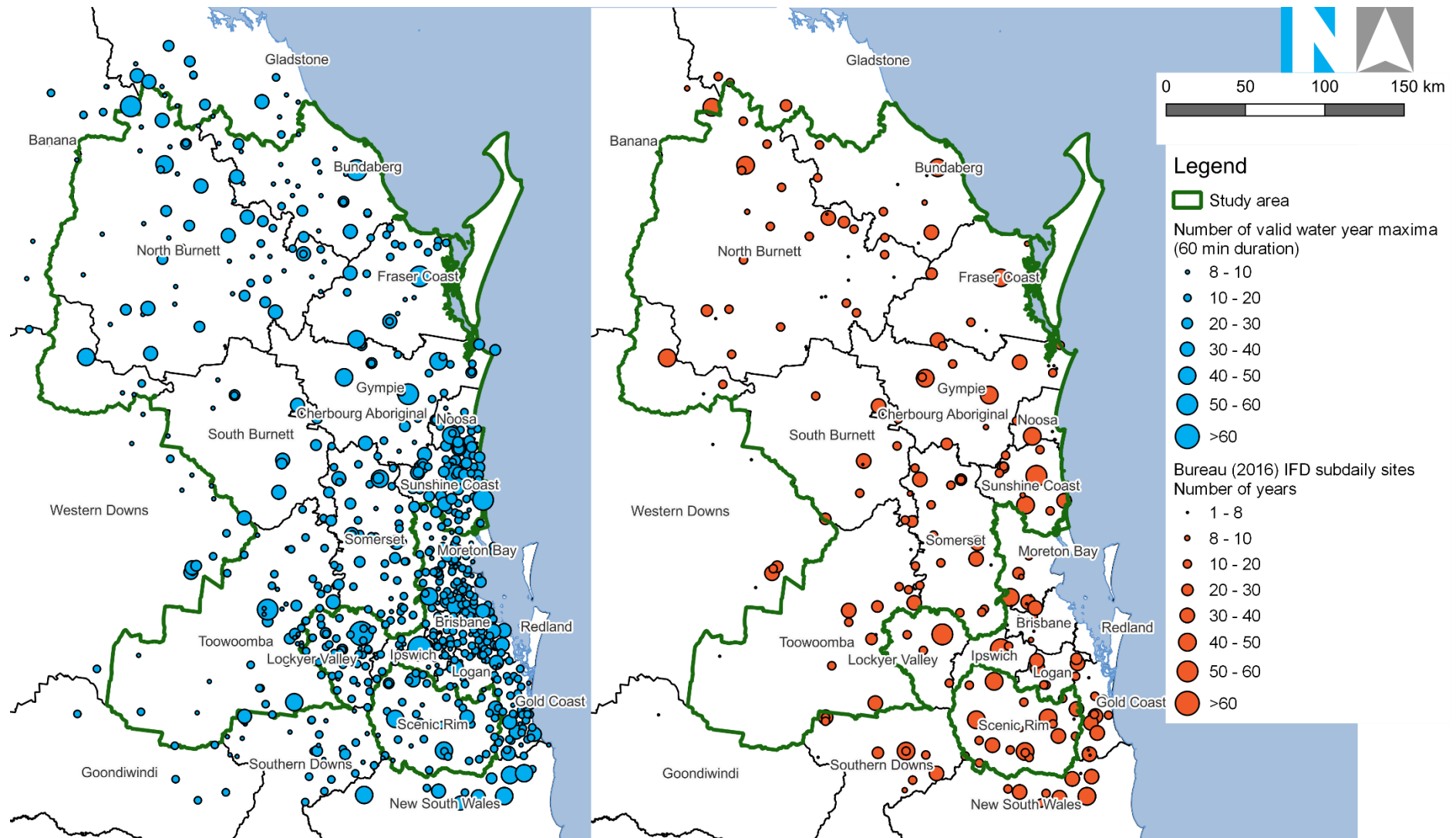


Figure 6-8 Comparison between number of valid water year maxima adopted for the 60 minute duration from sub-daily gauges between the current study (left) and used by the Bureau (2016) IFD analysis (right)

7. Non-stationarity in annual maxima data

Most design flood estimation practice, as currently outlined in ARR2019 (Ball *et al.*, 2019), has assumed that probability distributions of design floods and design rainfalls can be assumed to be stationary over the period of record. However, with climate change, it is now recognised that the flood hazard is changing (Milly *et al.*, 2008).

A recent review of climate change guidance has found that several jurisdictions around the world are already incorporating climate change into their design flood guidance (Wasko and Sharma, 2017; Wasko *et al.*, 2021). For example, Belgium, Denmark, England, New Zealand, Scotland, Sweden, the UK, and Wales are all recommending the use of climate change adjustment factors for IFD rainfall intensities. Shorter duration storms are likely to intensify at a greater rate than longer duration storms (Fowler *et al.*, 2021) and subsequently, some guidance, such as that from New Zealand and the UK, also accounts for storm duration in their climate change adjustment factors (Wasko *et al.*, 2021).

An extensive review of climate science relevant to Australian design flood estimation has been conducted (Wasko *et al.*, 2023b), which informed the Climate Change Considerations chapter of ARR version 4.2 (Wasko *et al.*, 2024). Under version 4.2 of ARR, IFD relationships are now considered as non-stationary. However, due to difficulties in fitting IFDs to non-stationary data, the guidance provided is to make an adjustment for non-stationarity from the baseline period that was used to fit the IFD data. Table 1.6.1 of ARR provides for a 15%/°C change for rainfall burst durations up to and including 60 min, an 8%/°C change for rainfall burst durations of 24 to 168 hours and a gradual transition across the intermediate durations between 1 and 24 hours. The basis for assessing temperature changes in the ARR guidance references the global average air temperature.

As discussed in Section 6, the number of rainfall gauges increases across the period of record, with very few gauges available in at the start of the record (1887) and almost 900 gauges available in the later years of the period of record. The substantial increase in the number of sub-daily gauges across the period from 2005-2015 was notable: from 140 gauges with valid annual maxima to 685. It is reasonable to consider how non-stationarity in processes driving intense rainfall are likely to be detected across the data set and how our understanding of this may be skewed by the substantial changes in the number of gauges reporting valid annual maxima across the overall period of record.

Figure 7-1 shows that global average air temperature has increased since the middle of the 20th century (Intergovernmental Panel on Climate Change, 2021; National Oceanic and Atmospheric Administration, 2023). Global air temperatures are approximately 1.1°C higher than they were prior to worldwide increases in population and industrialisation from around the middle of the 19th century.

Figure 7-1 also shows that the mid-point of the data adopted for the Bureau (2016) IFD update was in the mid-1970's and, on average, global average temperatures had only risen by 0.3°C above pre-industrial by that time. As discussed, in Section 10.3.1, for the current study the L-moments were normalised to be representative of data centred on the year 2010. By this point in time, Figure 7-1 shows that global average temperatures had risen to 0.9°C above pre-industrial. The IFD data for the current study were derived from statistical analysis on data representing 2010 global average temperatures. This period is characterised by global temperatures 0.6°C warmer than the 1961-1990 period that the ARR 2019 IFDs (0.9°C above a 1850-1990 baseline). This difference should be considered when adjusting the IFDs from this study for future climates.

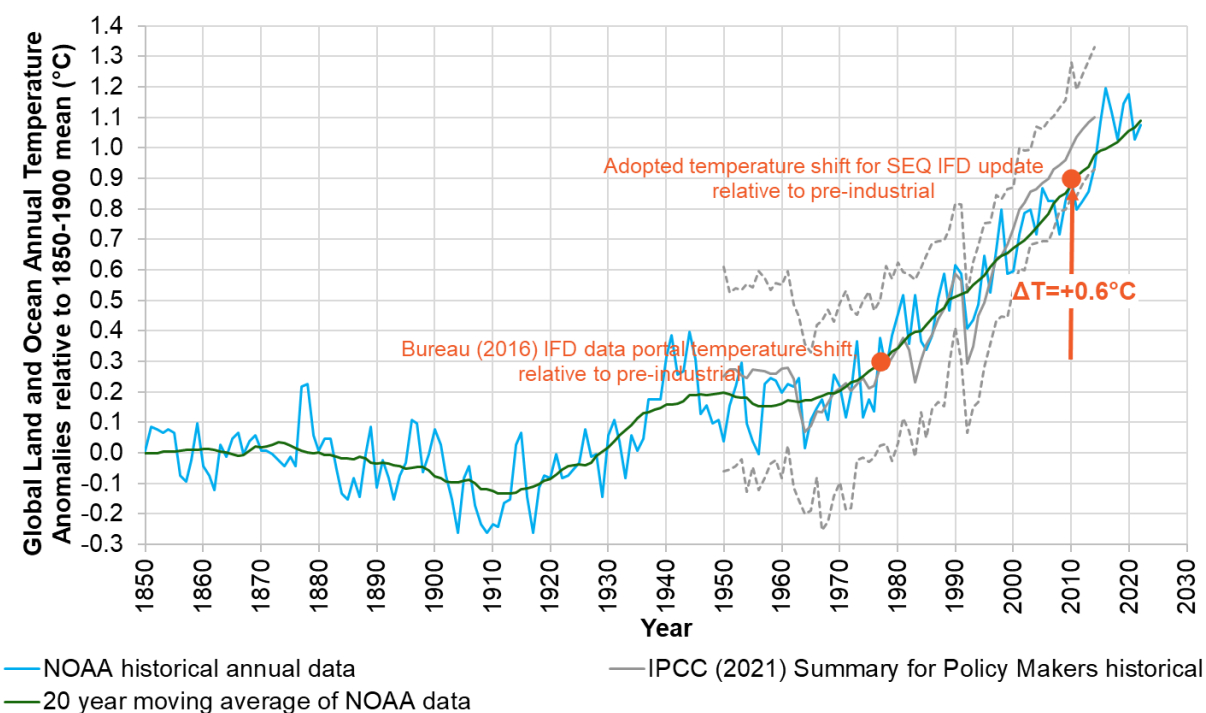


Figure 7-1 Global average air temperature, 1850-2023 and representative temperatures adopted for IFD estimation

8. Estimation of at-site L-moments

L-moments are typically used to summarise the statistical properties of extreme values series. L1 (mean), L-CV (variation), L-Skewness (skewness) and L-Kurtosis for standard durations between 5 minutes and 168 hours were estimated based on the annual maximum rainfall series of the sites using an R-package called `lmom` (Hosking, 2023).

Figure 8-1 shows an example of how different L-moments influence the design rainfalls fitted based on the Generalised Extreme Value (GEV) distribution. L1, also referred to as the index rainfall, is an analogue to the mean of the distribution. Typically, index rainfall is approximately equal to the 50% AEP rainfall. L-CV describes the variability in the data and generally defines the slope of the design rainfall curves. Low L-CV is attributed to less variability between frequent and rare rainfalls compared to high L-CV values. L-Skewness is analogous to the measure of the asymmetry of the distribution and defines the curvature of the design rainfall at the tail end (extreme AEPs).

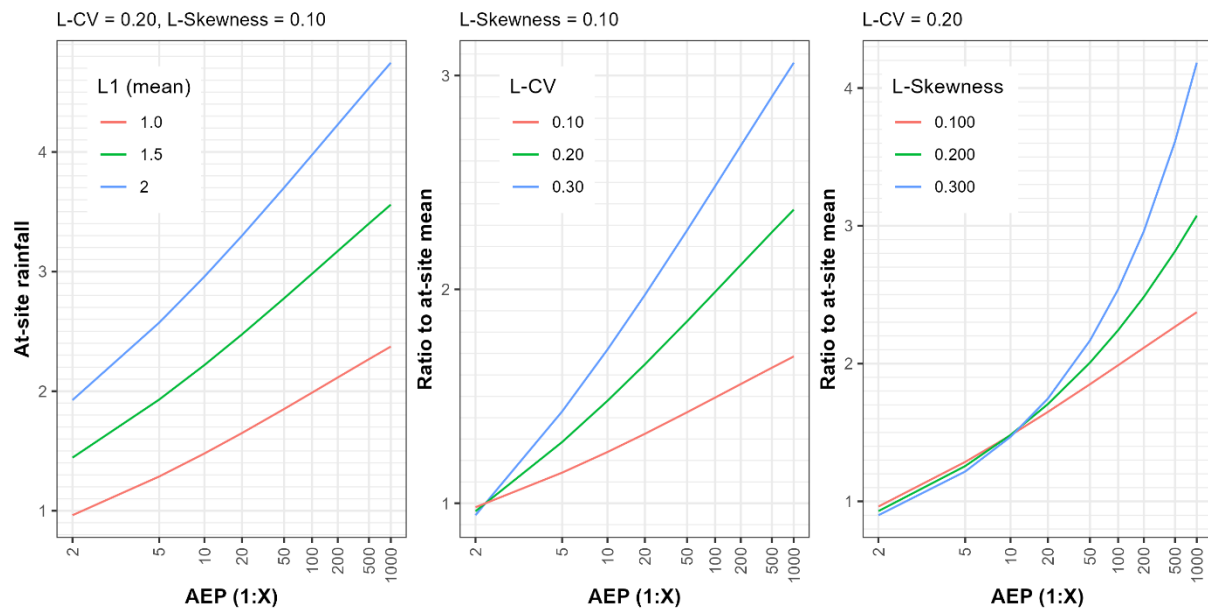


Figure 8-1 The influence of L1 (mean), L-CV and L-Skewness on the design rainfall curves (plotted on a standard normal paper)

While the typical values for L-CV are > 0 and L-Skewness are between -1 and 1, the values estimated for the sites in the study area varied between 0.1 and 0.45 for L-CV and between -0.1 and 0.6 for L-Skewness (only considering sites with record length greater than 30 years).

9. Suitability of GEV Distribution

In order to assess the most appropriate distribution to fit the design rainfalls for the study area, a range of distributions were tested based on the at-site L-Skewness and L-Kurtosis ratios as outlined in Hosking and Wallis (1997).

Five distributions – Generalised Extreme Value (GEV), Generalised Logistic, Log Normal, Pearson Type 3 and Generalised Pareto distributions were fitted to the annual maximum rainfall series for all the sites as shown in Figure 9-1 (an example illustration based on daily sites).

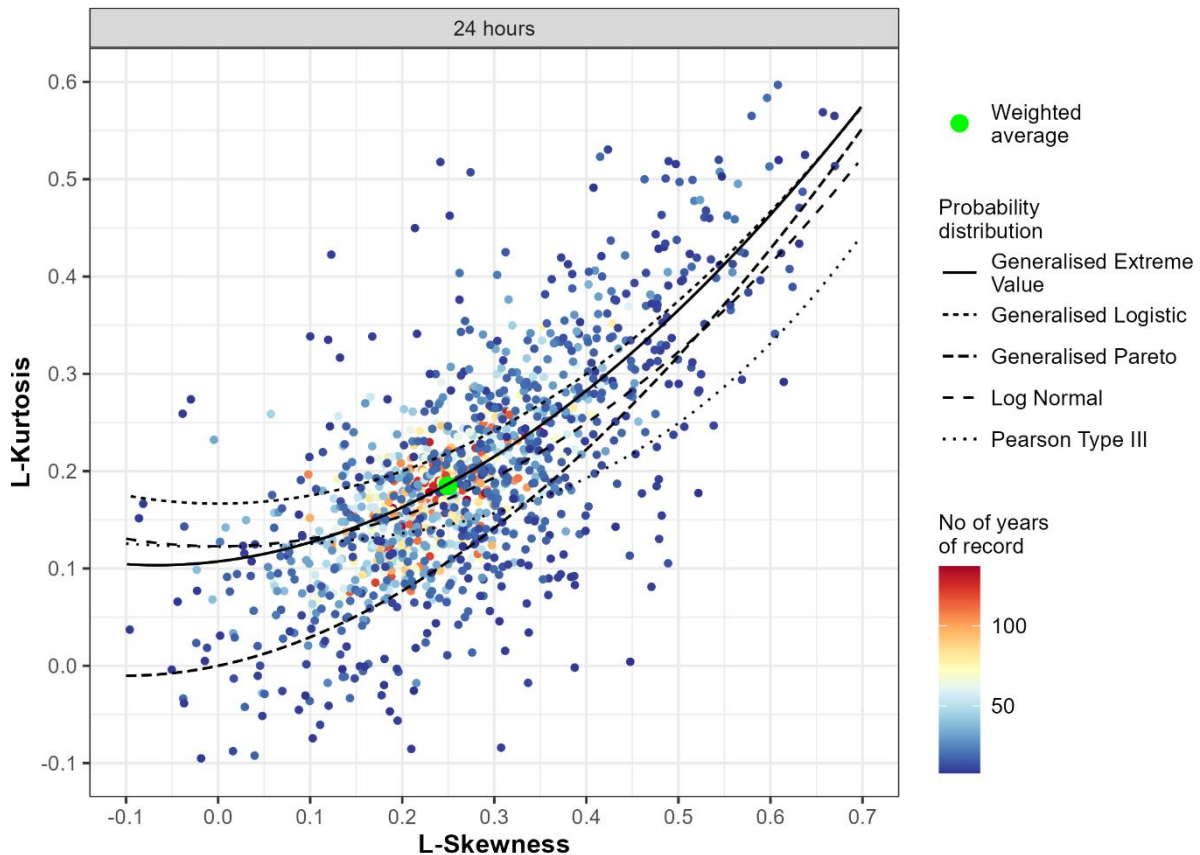


Figure 9-1 L-moment ratio diagram for daily gauges. The at-site L-moment ratios are colour-ramped based on their record lengths. The weighted average L-moment ratio is shown in fluorescent green. The theoretical ratios of the probability distributions are shown in different line types.

Accordingly, the Generalised Extreme Value (GEV) distribution produced the best fit considering the weighted average ratios, which is consistent with the distribution adopted in the ARR (2016) and LIMB (2021) studies. The fit was better for sites with longer record lengths compared to sites with shorter record lengths. The same process was followed for all standard durations separately as shown in Figure 9-2. It was noted that the L-moment ratios for shorter durations (< 3 hours) were slightly above the GEV line. All other durations showed a good fit to the GEV distribution.

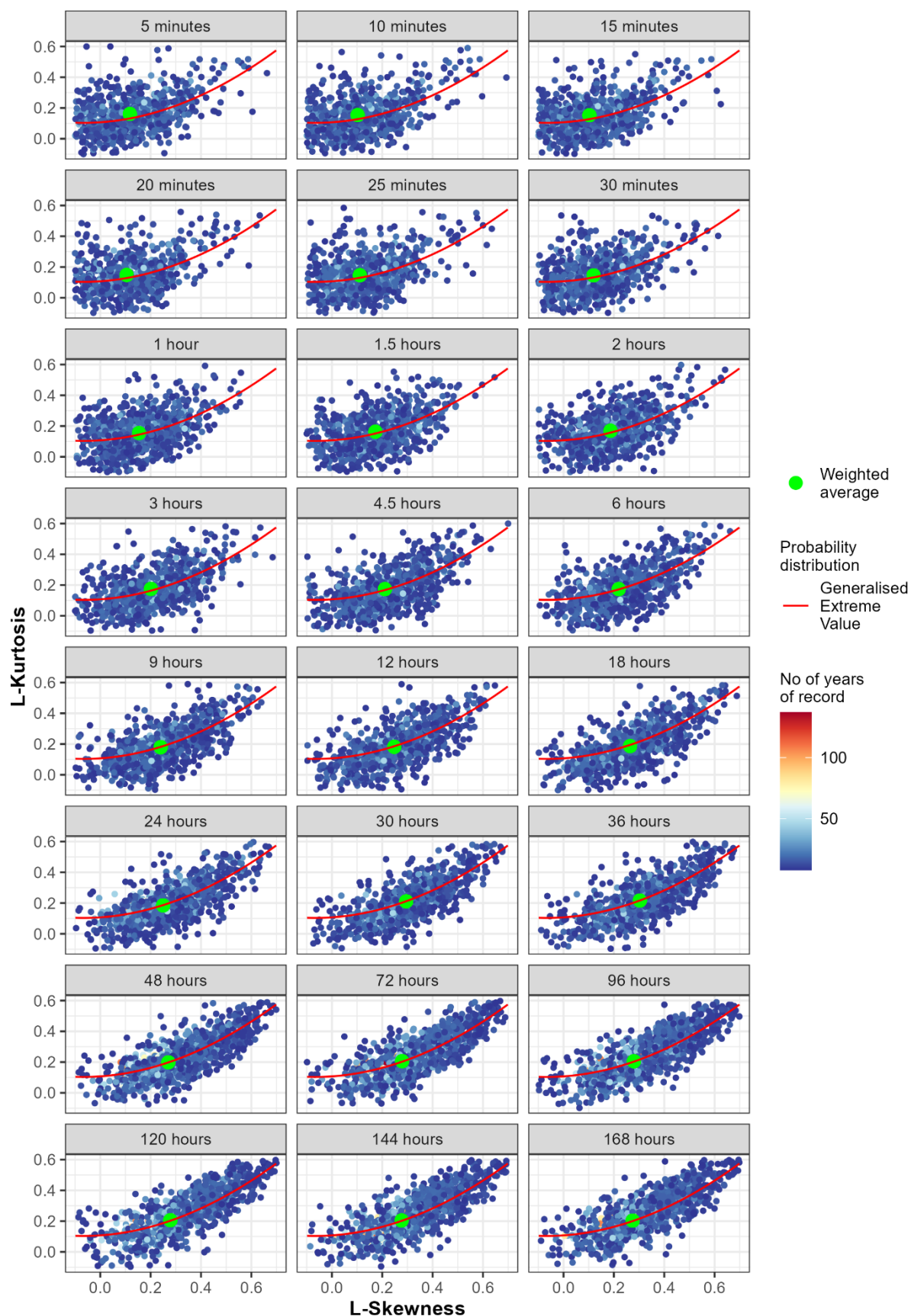


Figure 9-2 L-moment ratio diagram. The at-site L-moment ratios are colour-ramped based on their record lengths and the weighted average L-moment ratio is shown in fluorescent green.

10. Regionalisation of L-moments

The IFD distribution at a given location needs to be inferred from rainfall gauge data. However, rainfall gauge records at any one site are too short and have too few water year maxima to provide accurate estimates on their own of the true IFD values, particularly for rarer AEPs. Information content from many rainfall gauges across the study area is “regionalised” or “pooled” to produce more accurate estimates of true IFD values that change smoothly and in accordance with recognised hydrometeorological drivers. Since IFD distributions can be characterised by their L-moments, regionalisation of IFD is achieved by regionalising the L-moments from many gauges to produce regionalised L-moments, and therefore regionalised IFD estimates, at each location or grid cell. Regionalisation approaches aim to pool data across sites in order to provide more robust estimates of L-moments, recognising that there is considerable uncertainty associated with estimating L-moments for a gauge with a short period of record. The uncertainty associated with estimates of L-moments increases in higher statistical orders (i.e. increasing uncertainty when moving to L1, L-CV and L-skewness), which was reflected in the degree of regionalisation adopted for each L-moment.

Selection of an appropriate regionalisation approach required decisions to be made about how many water years of data (and hence how many gauges are averaged) to produce a robust estimate of the L-CV and L-skewness for a grid cell, what covariate(s) are useful for spatially interpolating L1 and how adjustments should be made (if any) for influences of climate change that have already occurred in the underlying rainfall gauge data. Various options were tested for how many water years or gauges to pool to construct L-moments, influence of different covariates on L-moments (such as mean annual rainfall, elevation, slope and standard deviation of elevation) and whether climate influences in the historical data should be corrected for, or excluded, before arriving at the adopted approach. The BoM (2016) IFD analyses came to different decisions about these matters because it was an Australia-wide study with much lower densities of subdaily gauges across most of the country, the rainfall data ended in 2012 and there was lower consensus evidence in the literature at that time of how climate shifts had affected IFD estimates from data collected prior to 2012. Further discussion of differences in approaches between the current study, BoM (2016) and LIMB is provided in Section 13.

Table 10-1 summaries the adopted regionalisation approaches used. Regionalisation of L1 (Section 10.3) was based on spatial interpolation using kriging with mean annual rainfall as a covariate. Prior to kriging values of L1 for all durations were factored such that they all represent the same climate period (notionally 2010) using a scaling approach (Wasko *et al.*, 2023a). Regionalisation of L-CV and L-skewness (Section 10.4) was based on a hybrid approach that used:

- a single fixed value for the whole study area for short durations (≤ 2 hours)
- a region of influence (ROI) approach where L-CV and L-skewness were estimated the using the record length weighted average of the nearest 500 station years of maxima for long durations (≥ 48 hours) and
- interpolation approach implemented in between the 2- and 48-hour durations.

Initial analyses of rainfall statistics of the sub-hourly durations across the study region appeared to support L-skewness values of less than 0.17, which would produce a positive shape parameter for resulting the GEV distributions. A positive GEV shape parameter leads to a GEV quantile function that has a finite upper bound, which can lead to issues in extrapolating IFD curves for extreme rainfall beyond 1 in 2,000 AEP out to the PMP. To overcome this, a minimum threshold of 0.17 was set for L-skewness, which ensured that the fitted GEV distribution's shape parameter was negative and hence

the GEV quantile function had an infinite upper bound. The threshold generally was applied to durations of 1 hour and shorter. In conjunction with this, the L-CV values for durations where L-skewness was at the threshold of 0.17 were set to the value of the shortest duration with L-skewness above 0.17. As a result, the growth curves (ratio of design intensity to L1) were the same at almost all grid cells across the study area for durations of 1 hour and shorter. The IFD estimates for sub-hourly durations therefore only vary across the study region due to spatial variations in L1. The adopted approach produced conservative IFD estimates for sub-hourly durations, which would be equal to or greater than the IFD estimates that would have been produced had thresholding of L-skewness not been adopted.

Table 10-1 Methods used to regionalise mean (L1), L-CV and L-Skewness

L - moments	Approach
Mean (L1)	- Adjustment of L1 values for all durations to reflect 2010 global temperatures. - Spatial interpolation of 2010 adjusted L1 using kriging, with mean annual rainfall used as the covariate.
L-CV	- For durations of ≤ 2 hours fixed values of L-CV and L-skewness were adopted for the entire study region, which vary only with rainfall burst duration. - L-skewness was constrained to a minimum value of 0.17 and L-CV for all shorter durations was adopted from the L-CV values for the duration where the regional L-skewness was first capped at 0.17
L-skewness	- For durations ≥ 48 hours a Region of Influence (ROI) approach was adopted where L-CV and L-skewness were estimated using the record length weighted average of the nearest 500 station years of maxima. - For durations between 2 – 48 hours an interpolation approach was used.

Further research is recommended into IFD estimates for durations shorter than 1 hour and whether a positive GEV shape parameter can be supported. Rainfall gauges and the systems used to digitise and record the data from those gauges may cause anomalies in the annual maxima extracted for sub-hourly durations and particularly in higher-intensity rainfall events. More extensive QA of sub-hourly rainfall maxima would be required to identify event maxima data that is sufficiently reliable for analysis of the L-moments and GEV distributions at these short durations.

10.1 Characteristics of sub-daily and daily gauge data

Table 10-2 summaries the availability of daily and sub-daily gauge data in the study region. The table shows the availability of sub-daily data as a function of different record length thresholds. For each threshold the number of gauges, total number of station years and midpoint year of all the gauges is reported. The midpoint year was calculated as the average of the midpoint year for all gauges (e.g. a gauge with data from 2000-2022 will have a midpoint of 2011). The number of gauges varies between the 5 and 10 minute durations and other sub-daily durations as sub-daily data from Seqwater was supplied at a 15 minute timestep.

Table 10-2: Availability of sub-daily and daily data as a function of gauge record length

	≥ 8 years	≥ 18 years	≥ 20 years	≥ 30 years
Sub-daily (5 & 10 minutes)	691 stations 12,177 years 2012 midpoint	278 stations 7,458 years 2006 midpoint	157 stations 5,030 years 2002 midpoint	80 stations 3088 years 1997 midpoint
Sub-daily (15 minutes to 18 hours, 30 and 36 hours)	810 stations 14,554 years 2011 midpoint	378 stations 9,453 years 2007 midpoint	174 stations 5,645 years 2000 midpoint	96 stations 3,674 years 1995 midpoint
Daily				555 stations 38,389 years 1967 midpoint
Combined daily & sub-daily for long duration (≥ X for sub-daily and ≥30 years for daily)	1365 stations 57,030 years 1992 midpoint	950 stations 52,058 years 1981 midpoint	786 stations 49,003 years 1975 midpoint	685 stations 46,502 years 1970 midpoint

A lower threshold of inclusion for sub-daily data of 8 years was used for L1, compared to 18 years for L-CV and L-skewness due to the additional data required to robustly estimate the higher order L-moment ratios. 18 years was selected as the preferred threshold of inclusion for L-CV and L-skewness to balance preferencing gauges with long record lengths which provide better estimates L-CV and L-skewness while ensuring adequate inclusion of available sub-daily data. Around 200 additional gauges (representing nearly 4,000 station years) are retained compared to using 20 years as the threshold.

Investigation of the regional averaged behaviour in the L-moments of the daily and sub-daily datasets found noticeable differences, with regional average values of L1, L-CV and L-skewness for daily durations calculated using sub-daily data found to be higher than those calculated using daily data. Figure 10-1 demonstrates this difference for L1 on both an arithmetic (left) and logarithmic (right), Figure 10-2 demonstrates this difference for L-CV (left) and L-skewness (right).

Potential reasons for these differences include:

- Intensification of rainfall extremes due to climate change.
- Sampling variability. The most recent 20-year period, over which the majority of the sub-daily data gauge has been collected, has experienced several strong La Niña events which have results in heavy rainfall and flooding in south east Queensland, which could contribute to the greater observed L-moment ratios in the sub-daily data. An investigation where daily gauge L-moments were recalculated using only maxima data from after 2000 found that study wide average L-CV rose approximately 0.025 and L-skewness rose 0.05 when the more recent maxima was used.
- Sub-daily gauges are distributed in different areas to the daily gauges, particularly the ALERT network often placed in wet, flood prone areas. Sub-daily gauges are typically in areas with higher mean annual rainfall and closer to the coast than daily gauges, which as shown in Appendix C means they may display larger L-CV and L-skewness values than the daily gauges (but not for short durations). The mean of mean annual rainfalls was 1030 mm for sub-daily gauges compared to 920 mm for daily gauges. The mean of distance to coast was 60 km for sub-daily gauges compared to 80 km for daily gauges.
- The influence of restricted-to-unrestricted conversion factor could also play some role in the difference between daily and sub-daily averages. However, the impact of this is thought to be insignificant because the difference between the daily and sub-daily L-moment ratios is more or

less constant for 24 to 168 hours. Noting that the adopted restricted-to-unrestricted conversion factor for 96-168 hours in this study was very close to 1, it would be expected to see the difference decrease for increasing duration if this conversion was a contributing factor to the difference in L-CV and L-skewness.

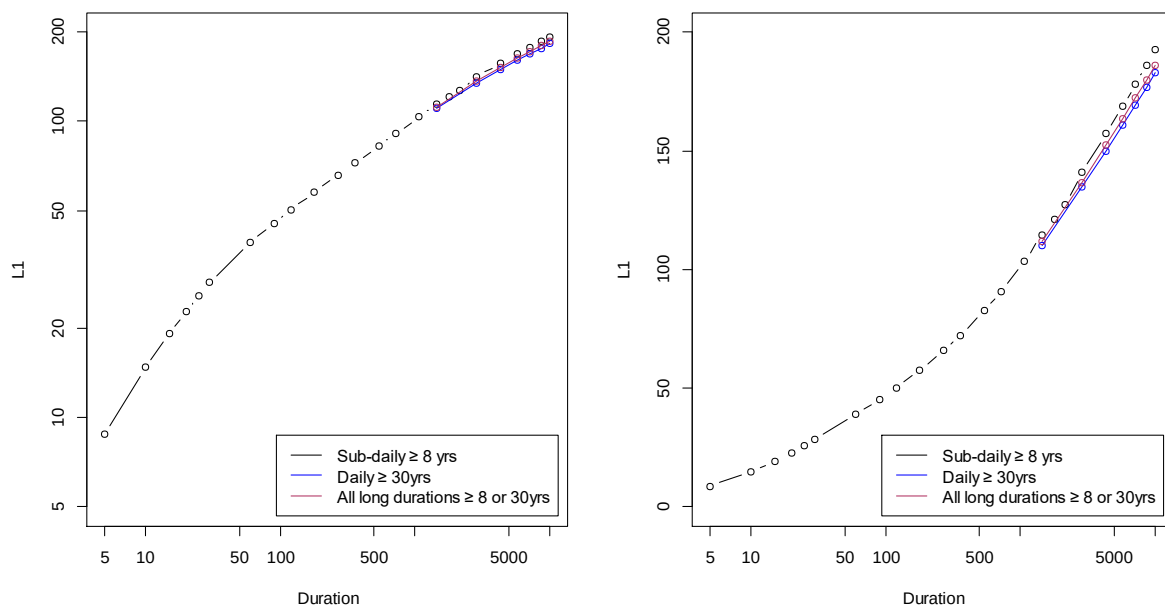


Figure 10-1 Record length weighted L1 as a function of duration, considering daily gauges only, sub-daily gauges only and all gauges combined. Both a logarithmic (left) and arithmetic axis (right) are shown.

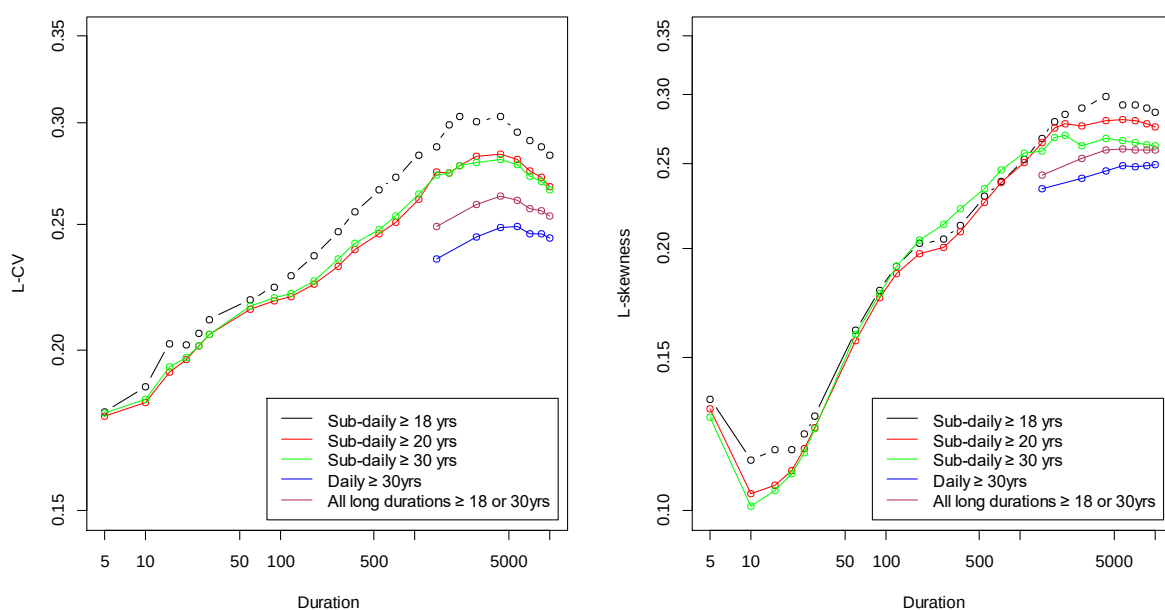


Figure 10-2 Record length weighted L-CV (left) and L-skewness (right) as a function of duration, considering daily gauges only, sub-daily gauges only and all gauges combined.

10.2 Covariates

Spatial variations in IFD characteristics and L-moments may be correlated with hydrometeorological or physical drivers. If relationships can be identified between the L-moments and one or more co-variates, then these could be used to constrain the spatial interpolation and pooling of the L-moments. If no statistically reliable relationships between a particular L-moment and covariate can be identified, then pooling and spatial interpolation would default back to physical horizontal distance as the best measure of spatial variation in L-moments, i.e. the closest gauges by distance to a particular location provide the most appropriate measure of estimating the L-moments.

For this study, the following covariates were considered:

1. Elevation,
2. Standard deviation of elevation (SDE),
3. Distance to coast, and
4. Mean annual rainfall

Elevation data was sourced from the Bureau of Meteorology (BoM), Queensland Water Management Information (QWMIP), Environmental Information Explorer (BoM) and SRTM Digital Elevation Maps (DEM). The standard deviation of elevations was derived from SRTM data. Distance to the coast was estimated based on the straight-line distance between each site and the nearest point on the coastline. Mean annual rainfall totals were provided by BoM (in gridded formatted) for the period between 1991 and 2020.

Figure 10-3 shows the relationship between 24-hour duration L-moments and the covariates (refer to **Error! Reference source not found.** for all other durations). L1 had a better correlation with the potential covariates compared to the higher-order L-moments (L-CV and L-Skewness). Also, there was a higher correlation between longer duration L-moments compared to the shorter durations. In general, mean annual rainfall has shown a higher correlation with the L-moments (especially L1, index rainfall) compared to the other variables.

It was noted that elevation has been used as the covariate in spatial interpolation of index rainfall in ARR (2016) and LIMB (2021) IFD updates. However, this study found that the elevation and standard deviation of elevation seem less correlated to the L-moments for the current study area. This is primarily due to the wetter coast (mostly low elevations) and wetter mountain ranges (mostly very high elevations) compared to the dryer inland (moderate elevations). For example, both the Sunshine Coast (~ 10 m AHD) and The Great Dividing Range (~ 1000 m AHD) have higher L1 while other areas like Toowoomba (~ 600 m AHD) have lower L1. This has resulted in poor correlation between L1 and elevation for this study area. The LIMB study possibly found a stronger relationship between standard deviation of elevation and L-moments as the LIMB study area was limited to the coastal side of the Great Dividing Range, which avoided the confounding influence of the moderate elevation areas to the west of the ranges, which are further from the coast and generally have less intense rainfall bursts.

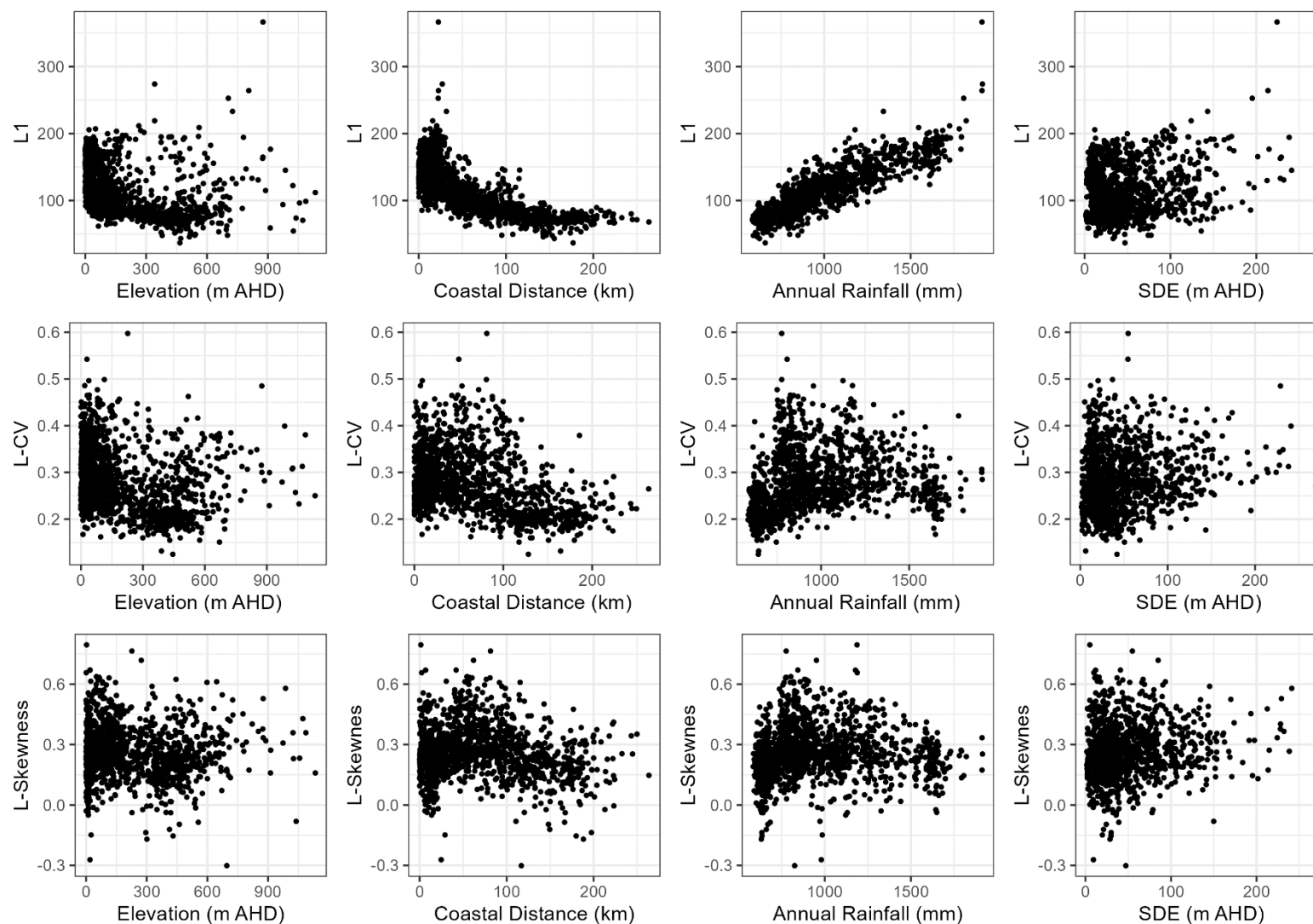


Figure 10-3 Correlation between L-moments and covariates (for 24-hour duration)

10.3 L1 (Index Rainfall)

10.3.1 Adjustment to 2010 global mean temperature

The difference in representative periods between the sub-daily (centred on 2011) and the daily (centred on 1967) gauges represents a potential challenge when wanting to adjust rainfall frequency curves up to a common climate baseline year, as quantile estimates of daily and sub-daily durations will be representative of different periods. To account for this, L1 estimates for each gauge were adjusted to represent the same temperature (notionally 2010) using a scaling approach (Wasko *et al.*, 2023a). This involves the following process:

- Raw L1 ($L1_{AM}$) estimated from observed AM for sub-daily sites with at least 8 years of data and daily sites with at least 30 years of data.
- L1 adjusted to 2010 using the following equation:

$$L1_{2010} = L1_{AM}(1 + \alpha)^{\Delta T}$$

where α is the rate of change of extreme rainfall with respect to temperature rise, values of $\alpha = 8$ to $15\%/^{\circ}\text{C}$ are employed for different durations as outlined in Wasko *et al.* (2023a), $\Delta T = T_{2010} - T_{AM,mid}$ is the difference in global average temperature between 2010 and the midpoint year of the gauge of interest, such that a unique ΔT was used for each gauge. NOAA historic annual global temperature data (NOAA National Centers for Environmental Information, 2024) is used with a 20-year moving window average applied to smooth out inter-annual variation in the global temperature.

- Adjusted L1 was then used for kriging (see Section 5.3.2).

Due to the linear nature of L-moments, multiplying raw L1 estimated from annual maxima by a scaling factor has the same effect as multiplying the resultant raw GEV location and scale parameters by that scaling factor, which in turn is equivalent to multiplying quantiles estimated from the raw GEV distribution by that scaling factor. Therefore, adjusting L1 values to a single climate is analogous to adjusting the final quantiles produced from regionalisation. However, scaling L1 is conceptually cleaner, as it allows the whole study area to be adjusted to represent a single representative climate prior to regionalisation and spatial interpolation. Note that the scaling approach recommended in ARR Climate Change Considerations (Wasko *et al.*, 2023a) does not impact L-CV or L-skewness.

The process of scaling L1 to reflect 2010 is shown in Figure 10-4. A closer match was observed than the equivalent Figure 10-1. The sub-daily data still shows slightly higher L1 on average, but this could be due to either sampling variability or because the sub-daily gauges are biased to represent wetter areas compared to the daily gauges.

The 2016 IFD grids produced by the Bureau of Meteorology are fitted to rainfall data centred on 1961-1990. The 2010 global mean temperature IFD grids in this study represent is approximately 0.6°C warmer than this period. Summarised in Table 10-3 this difference was calculated by comparing NOAA historic annual global temperature data (NOAA National Centers for Environmental Information, 2024) for the two periods. Given a 20-year moving average was used to adjust L1, the same 20-year average (2000-2019) was used to represent 2010 global temperature.

Table 10-3: Comparative representative global temperate between this study and the BoM IFD (2016) study

Global Land and Ocean Annual Temperature Anomalies relative to 1850-1900 mean (°C)	
HARC 2024 (2000-2019)	0.9
BoM IFD 2016 (1961-1990)	0.3
Difference	$\Delta T = 0.6$

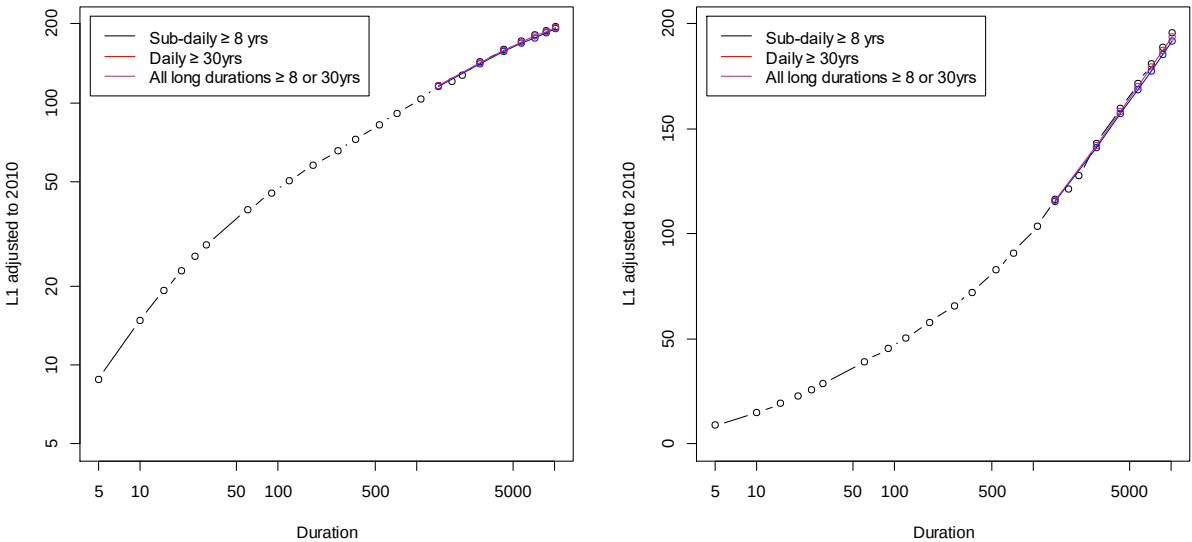


Figure 10-4 Record length weighted L1 adjusted to 2010 global temperature as a function of duration, considering daily gauges only, sub-daily gauges only and all gauges combined. Both a logarithmic axis (left) and arithmetic (right) are shown.

10.3.2 Kriging

L1 which had been adjusted to represent 2010 global mean temperature was then spatially interpolated using kriging. Kriging was used to derive grids from known point data by fitting a statistical relationship between the physical distance and other covariates. In this study, Index Rainfalls were kriged using mean annual rainfall as a covariate using an R package called ‘gstat’ (Gräler *et al.*, 2016). A spherical model was adopted for the variogram.. The range (minimum distance at which gauges are not considered to spatially autocorrelated) was found to decrease with increasing duration. Mean annual rainfall was selected as the covariate as it provided the highest Coefficient of Determination (R^2) for all durations considered compared to other covariates.

The results of the kriging process (for some selected durations) are presented in Figure 10-5. Figure 10-6 provides a comparison between the at-site L1 and the spatially interpolated (kriged) L1. Results of L1 grids and the at-site comparison for all durations are presented in Appendix B. The results show that the kriged L1 values (using mean annual rainfall as a covariate) were reasonably close to the at-site L1 values, producing R^2 between 0.55 (for the 5-minute duration) and 0.89 (for the 168-hour duration). R^2 were greater than 0.8 for durations greater than 1 hour and approximately 0.9 for durations greater than a day. The gradual reduction in R^2 between at-site and kriged L1 values with

decreasing duration is an artefact of the use of mean annual rainfall as a covariate in kriging, with mean annual rainfall better explaining the variation in longer duration rainfalls than shorter ones (see Appendix A). In the absence of a better covariate for short duration rainfalls, mean annual rainfall was considered appropriate for all durations to in order to maintain consistency between durations and avoid cross overs in final frequency curves.

Although the gridded L1 used mean annual rainfall as the covariate, the variations in L1 due to elevation differences were also appreciated in this process. The elevated areas such as The Great Diving Range, mountain ranges of Lamington National Park in the southern state border and elevated areas in the hinterland areas of Brisbane and the Gold and Sunshine coasts had greater L1. However, these relationships between L1 and elevation were not consistent across the study area in a way that would make elevation a useful covariate for kriging.

10.3.3 Smoothing

It is intuitive that values of L1 should increase with increasing duration (as L1 is the mean of annual maxima). The kriged L1 values of all the grid cells were checked for any potential inconsistencies across durations. Immediately after kriging, around 57% of grid cells were not monotonically increasing with increasing duration, the vast majority of these occurring around 24-hours due to the transition from sub-daily to daily datasets. A LOESS local regression smoothing function based on $\log_{10}(L1) \propto \log_{10}(\text{Duration})$ was therefore applied to all grid cells, with a modest span parameter of $\alpha = 0.3$ (which dictates the proportion of data used in the local regression). This left 6 grid cells that were not monotonically increasing. For these 6 grid cells, an additional smoothing with $\alpha = 0.5$ was applied to ensure they were strictly increasing. An example of the impact of smoothing of L1 is shown in Figure 10-7, highlighting the discontinuity between L1 derived from daily gauges and sub-daily gauges. Note that, this Figure shows an example where L1 estimates derived from sub daily gauges are less than those derived from daily gauges, however as discussed in Section 10.1, for most of the study area it was found that L1 estimates from sub-daily gauges were greater than daily gauges.

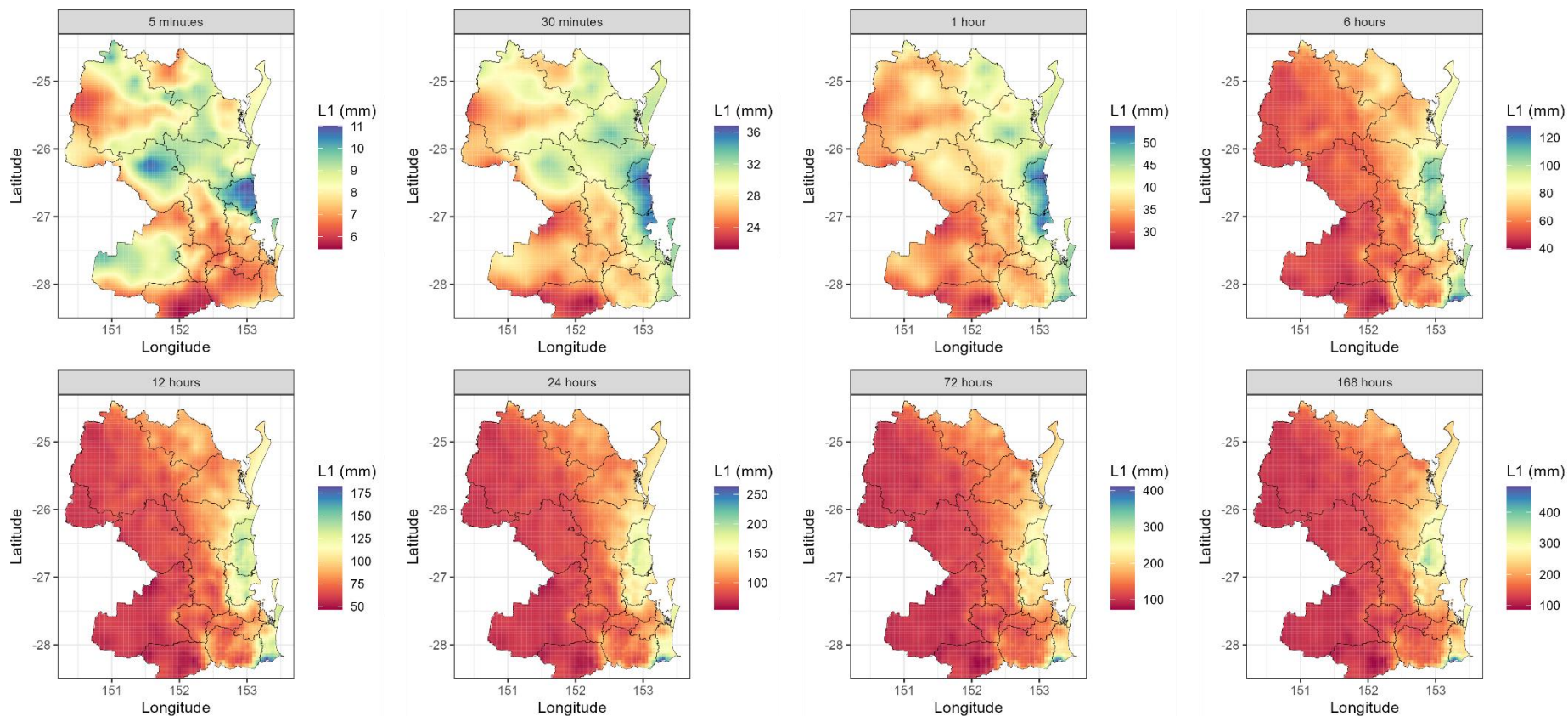


Figure 10-5 Gridded L1 (Index Rainfall) for selected durations

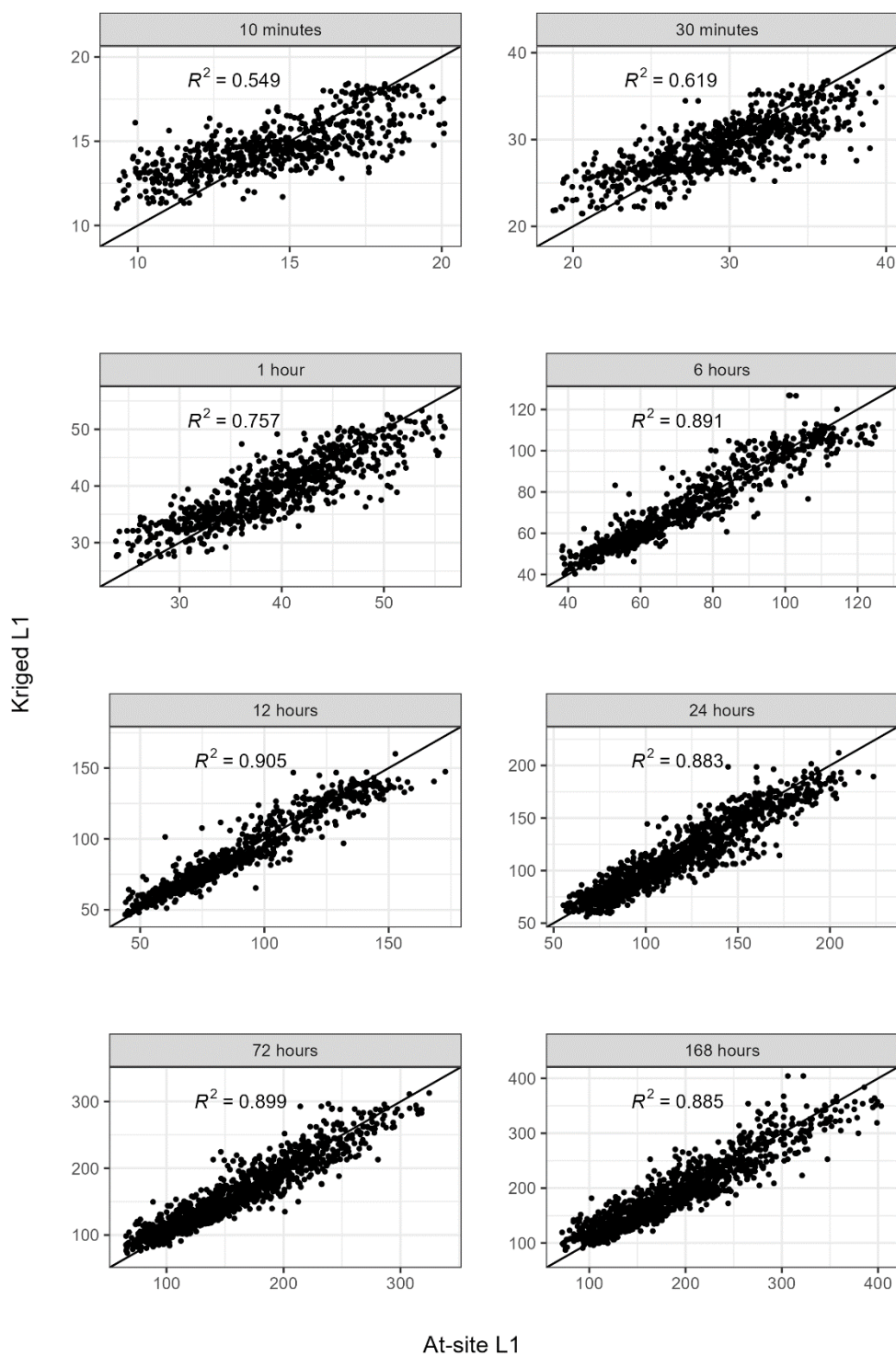


Figure 10-6 Comparison of at-site and kriged L1 (Index Rainfall).

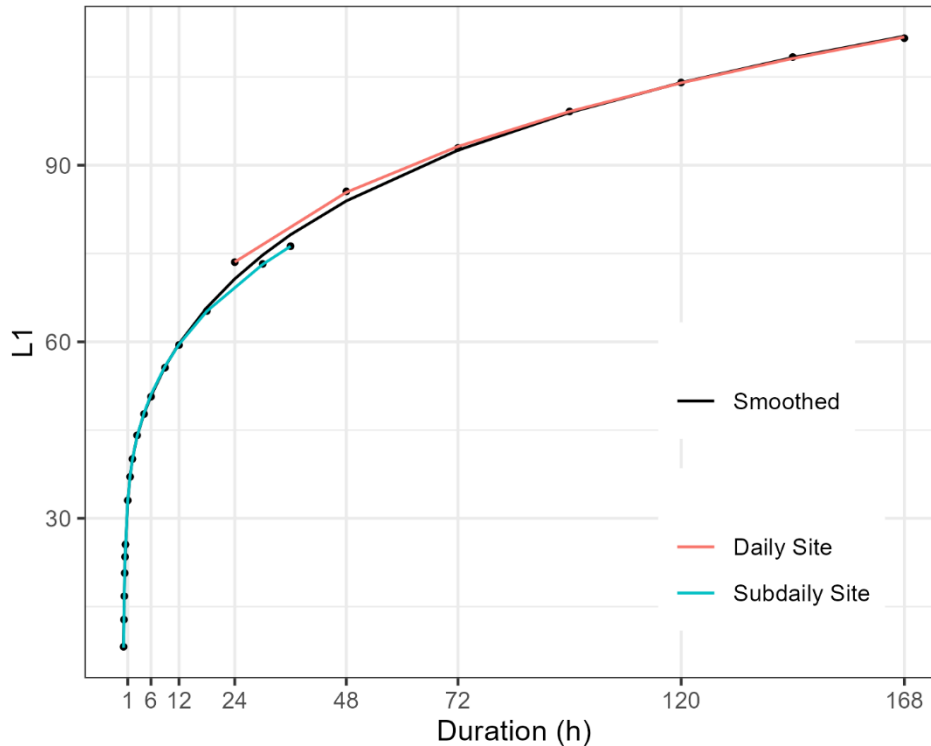


Figure 10-7 Example smoothing of L1

10.4 L-CV and L-skewness

Unlike L1 where there is clear guidance on how to adjust values to account for different representative temperatures, there is currently no clear guidance in the literature on adjustments to L-CV and L-skewness. As explained in Section 5.1, differences in values of L-CV and L-skewness between the daily and sub-daily gauges shown in Figure 10-2 could be due to climate change, sampling variability or gauge placement. As a result, a hybrid approach is applied to regionalise L-CV and L-skewness with no adjustments made to account for non-stationarity due to climate change. This hybrid approach involves:

- For durations of ≤ 2 hours, fixed values of L-CV and L-skewness were adopted for the entire study region, which vary only with rainfall burst duration. This is based on finding no clear evidence that L-CV and L-skewness at these durations vary systematically across the study area.
- For durations of ≥ 48 hours and greater clear evidence was found that L-CV and L-skewness vary systematically throughout the study area. Therefore, a Region of Influence (ROI) approach was utilised where L-CV and L-skewness were estimated from the record length weighted average of the nearest 500 station years of maxima.
- For durations between 2 and 48 hours an interpolation approach was used to transition from the short-duration regional averages to the long duration ROI values.

10.4.1 Justification of hybrid approach

Figures 10-8 to 10-11 show four-panel plots which plot either L-CV or L-skewness against the following attributes of the gauge: distance to coast, mean annual rainfall, elevation and latitude. Plots for both 2-hour and 48-hour durations are shown for each L-moment ratio. Appendix C provides the plots for all durations. The panels show all sub-daily sites with over 18 years of data. Each plot also includes a horizontal line for the record-length-weighted regional average off all gauges (black), a local regression fit to the data (blue) and the record length weighted average of six bins (selected to have approximately the same number of gauges in each bin) (red). Observations from these plots for all durations noted that:

- For longer durations there is evidence of relationships between L-CV and L-skewness between different attributes, particularly distance to coast and mean annual rainfall
- For short durations around 2 hours and less, these relationships are not clear, with the local regression line and the binned averages generally sitting close to the regional average.

Based on these observations it was considered justifiable to use a single regional average for L-CV and L-skewness for durations of 2 hours and less. While for longer durations it is necessary to adopt local estimates of L-CV and L-skewness using the region of influence approach to capture the variation in these L-moment ratios throughout the study area.

Due to the extra data available at daily sites, ROI L-moment ratios were estimated for durations of ≥ 48 hours only, 24-hour ROI estimates were excluded because they consistently behaved differently to longer duration L-moment ratios.

An interpolation approach was then employed to estimate values between the 2-hour regional average and 48-hour ROI estimate for a particular site.

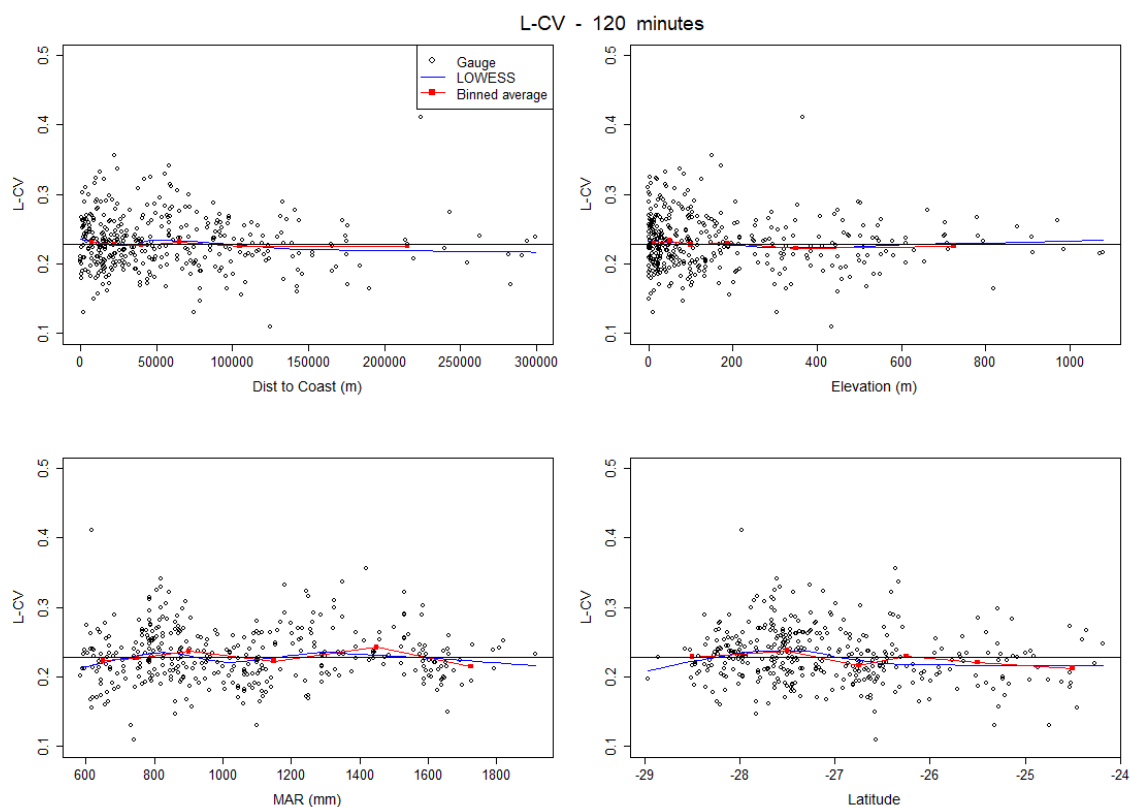


Figure 10-8: 2-hour (120 minute) L-CV versus physical gauge attributes

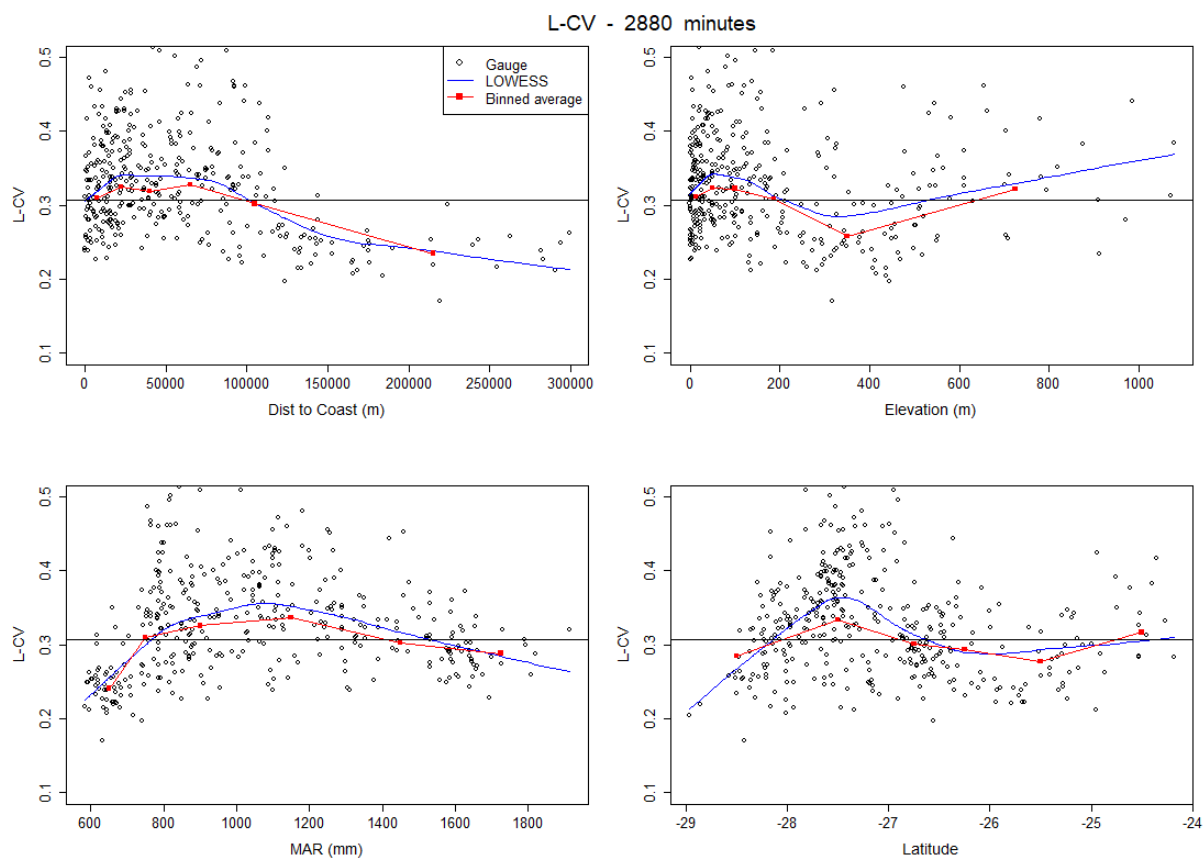


Figure 10-9: 48-hour (2880 minute) L-CV versus physical gauge attributes

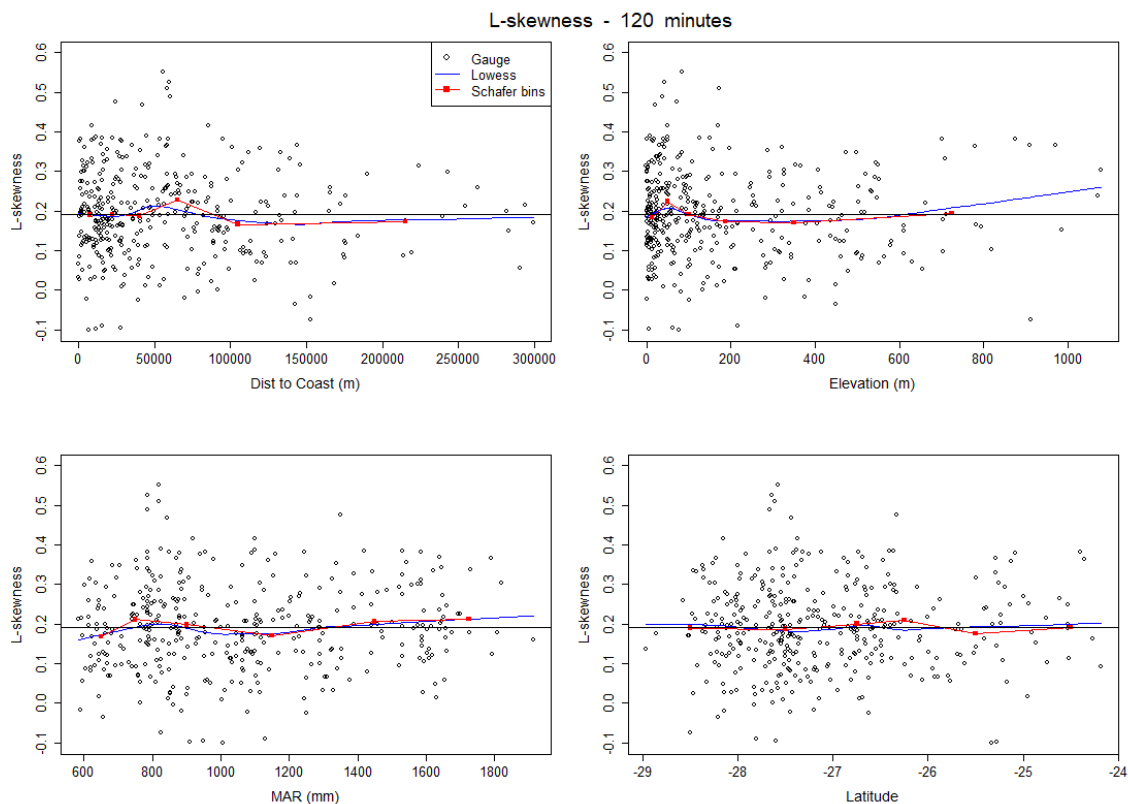


Figure 10-10: 2-hour (120 minute) L-skewness versus physical gauge attributes

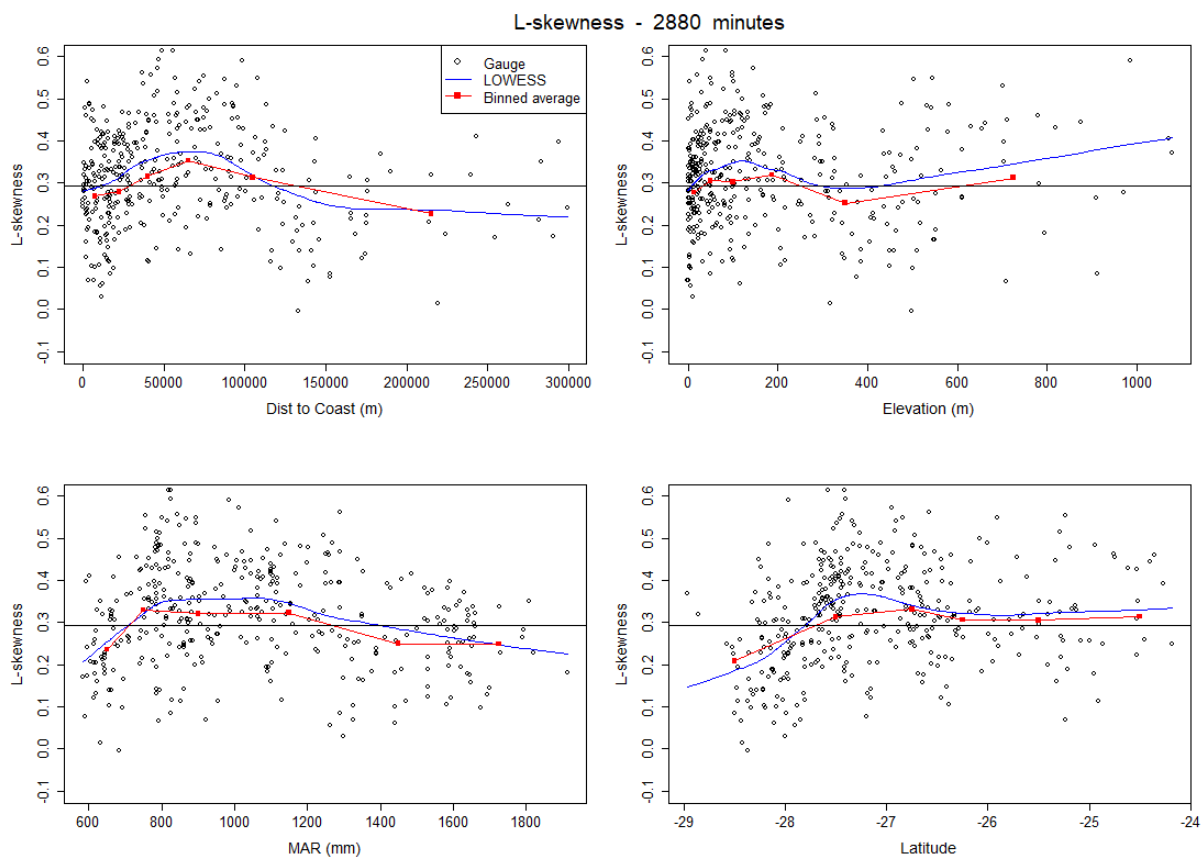


Figure 10-11: 48-hour (2880 minute) L-skewness versus physical gauge attributes

10.4.2 Regionalisation approach

10.4.2.1 Regional average – durations ≤ 2 hours

The record length weighted regional average of L-CV and L-skewness were estimated using all available sub-daily gauges with ≥ 18 station years. This considers 378 gauges (278 for 5- and 10-minute durations)

10.4.2.2 Region of influence – durations ≥ 48 hours

For durations ≥ 48 -hours a Region of Influence (ROI) approach was utilised where L-CV and L-skewness were estimated from the record length weighted average of the nearest 500 station years of maxima. Physical distance was used to select sites to be included in the ROI, investigation of non-Euclidean distances based on distance and elevation was found to add little additional value (see Appendix D).

The choice of 500 station years represented a trade-off between including additional station years to give more robust estimates of L-CV and L-skewness and reducing the pooling distance to ensure local variation is well represented. Initial sensitivity testing on the number of years to be included in pooling found that 500 years led to a good balance between maintaining local variation whilst also leading to smooth grids of L-CV and L-skewness. Additionally, due to the smoothing procedures applied to L-CV and L-skewness to avoid crossing of final quantile curves, it is not thought adopting a longer ROI (i.e. 1,000 or 2,000 station years) would materially change results.

Initial attempts were made to include the 24-hour ROI L-moments (as opposed to interpolating) but these were found to behave quite differently to the L-moment ratios for 48-hour and above. This caused issues in producing physically consistent quantile curves, which did not cross over for increasing durations at a given AEP. Previous studies in tropical Australia have found that behaviour of 24-hour L-moment ratios from daily rainfall gauges do not align with longer daily durations (HARC, 2019), potentially due to paucity of storm mechanisms that last for 24 hours or due to the influence of the restricted to unrestricted conversion on 24-hour totals. Similar to here, these studies have also elected to derive 24-hour L-moment ratios from longer durations ratios, in this case through interpolation.

10.4.2.3 Interpolation – durations 3-36 hours

To guide the smoothing function fitted between L-CV, L-skewness and duration estimates of L-moment ratios between 3 and 36 hours were needed. These estimates were produced through linear interpolation between the L-moment ratio and the $\log_{10}$ transform of duration (in hours):

$$T_{est,X} = T_{reg,2h} + \frac{\log_{10}(X) - \log_{10}(2 \times 60)}{\log_{10}(48 \times 60) - \log_{10}(2 \times 60)} (T_{ROI,48h} - T_{reg,2h})$$

where for duration X (minutes), $T_{est,X}$ is the interpolated L-moment ratio, $T_{ROI,48h}$ is the at-site region of influence estimate and $T_{reg,2h}$ is the record length weighted regional average for 2 hours. An example of this interpolation is shown for a single grid cell in Figure 10-12.

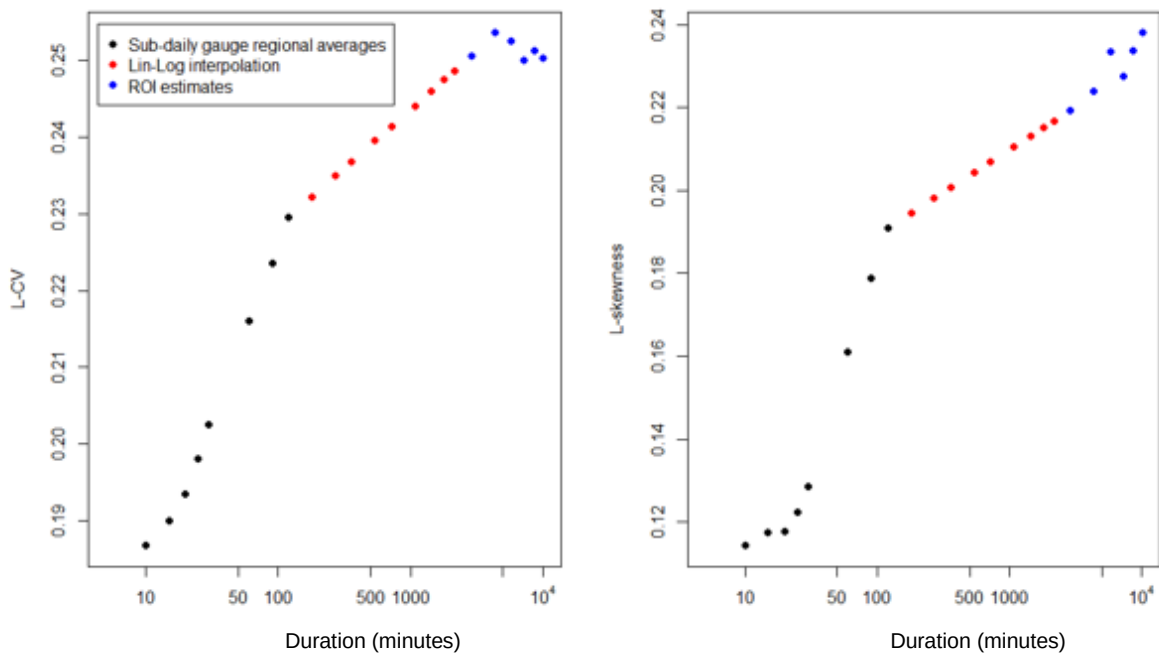


Figure 10-12: Example of interpolation procedure for single grid cell (centred on 24.4624° S, 153.3125° E).

In addition to log-linear interpolation, an approach where the regional average L-moment curve (black curve in Figure 10-2) was linearly factored up or down to match the 48-hour at site L-moment ratio from the ROI approach. However, due to the fact this curve is not continuously increasing between 3-36 hours (specifically it dips at 24 hours), this approach was found to lead to overlap in final quantile curves. The difference in adopted L-moments is at most 5% between these two methods. This difference is captured in Figure 10-13.

At a considerable number of locations in the study area L-moment ratios for the 2-hour sub-daily regional average were higher than the ROI 48-hour estimate. This was found at 43% of sites for L-CV and 10% of sites for L-skewness. In these instances, the lower bound of interpolation was moved from 2 hours down until the longest duration, Y such that $T_{ROI,48h} - T_{reg,Y} > 0.01$.

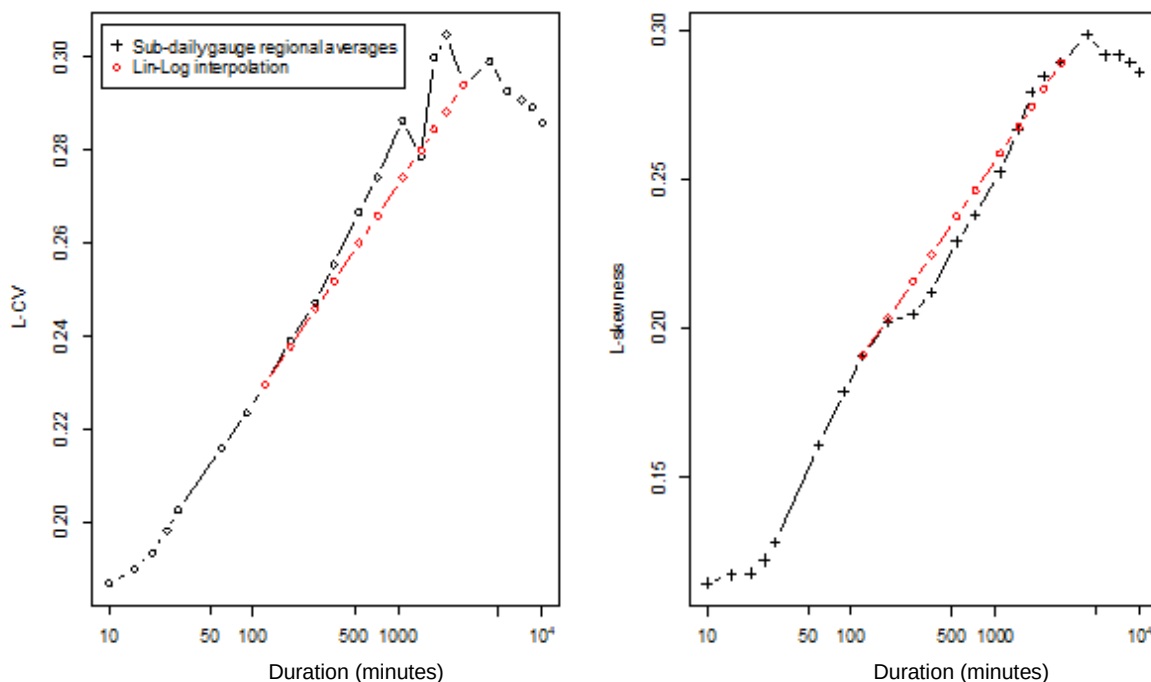


Figure 10-13: Comparison of linear-log interpolation approach to use of the sub-daily regional growth curve for interpolating L-moment ratios between 2 and 48 hours.

10.4.2.4 Smoothing

Regional average L-moments pooled across the region (e.g. Figure 10-2) show increasing trends of L-CV and L-skewness with increasing duration. Smoothing approaches were therefore adopted to preserve this increasing trend where appropriate.

5-minute L-moments were removed from the smoothing owing to the regional average departing from otherwise monotonically increasing with increasing duration. This was thought to be a result of issues associated with recording very intense short duration rainfalls and accurately estimating the 5-minute duration burst totals from the recorded data. As a result the 10-minute estimates of L-CV and L-skewness were adopted for the 5-minute duration.

For L-CV, regionalised values were multiplied by L1 obtained from kriging to obtain regional estimates of L2 (which like L1 should intuitively increase with increasing duration). In cases where L2 was not found to increase monotonically with duration (0.24% of grid cells) a LOWESS local regression

smoothing function based on $\log_{10}(L - CV) \propto \log_{10}(\text{Duration})$ with $\alpha = 0.5$ was applied, this removed all cases of cross overs.

For L-skewness, non-monotonically increasing behaviour with duration was found for the vast majority of grid cells (93%). This was primarily due to there is often a slight decrease in L-skewness for longer durations particularly when moving to 168-hour rainfalls. Peak L-skewness was typically observed around 48-96 hours. This may be because it is difficult to observe long multiday storms in practice. To avoid cross-overs, for 48 hours and above, L-skewness values which were less than the previous duration were set to the L-skewness value of previous duration (i.e. durations longer than the maximum L-skewness value were set to the maximum value), this removed cross overs for all grid cells.

An alternative to this approach for L-skewness would be to apply parametric smoothing functions that are strictly monotonically increasing, or have a fixed upper bound. However, this requires the pragmatic decision that the slight dip in L-skewness for long durations is an artefact due to the difficulty of observing long duration storms. Ultimately, it was not thought that adopting of one smoothing approach over the other would materially affect final quantile results.

Figure 10-14 shows an example of smoothing applied to L-CV and L-skewness for a single site. These plots show a LOWESS smoothing in $\log_{10}(L\text{moment ratio}) \propto \log_{10}(\text{Duration})$ space. Smoothed values of L1, L-CV and L-skewness were then used to estimate GEV parameters which are in turn used to estimate rainfall frequency curves. Regionalised and smoothed L-CV and L-skewness of some selected duration is shown in Figure 10-15 and Figure 10-16 (see Appendix E for gridded L-CV and L-skewness of all durations). Figure 10-17 and Figure 10-18 provides a comparison between the at-site and regionalised values of L-CV and L-skewness respectively. Only durations for 48 hours and longer are shown, because these are the durations for which Region of Influences values were adopted. From these plots a large reduction in the variance of L-CV and L-skewness due to pooling is evident compared to at-site values. This reduction is intuitive and reflects the intent of the ROI regionalisation approach, which by using additional station years to estimate L-CV and L-skewness reduces the impact of sampling variability at individual sites leading to a tighter range of estimates of L-CV and L-skewness.

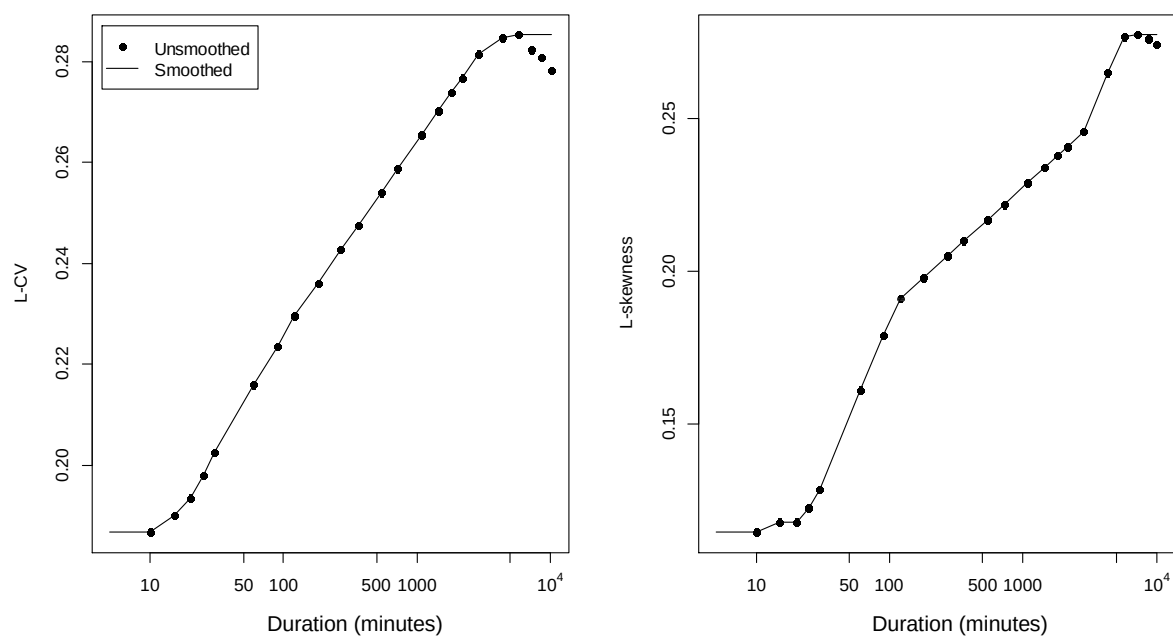


Figure 10-14: Example of smoothing of L-CV and L-skewness

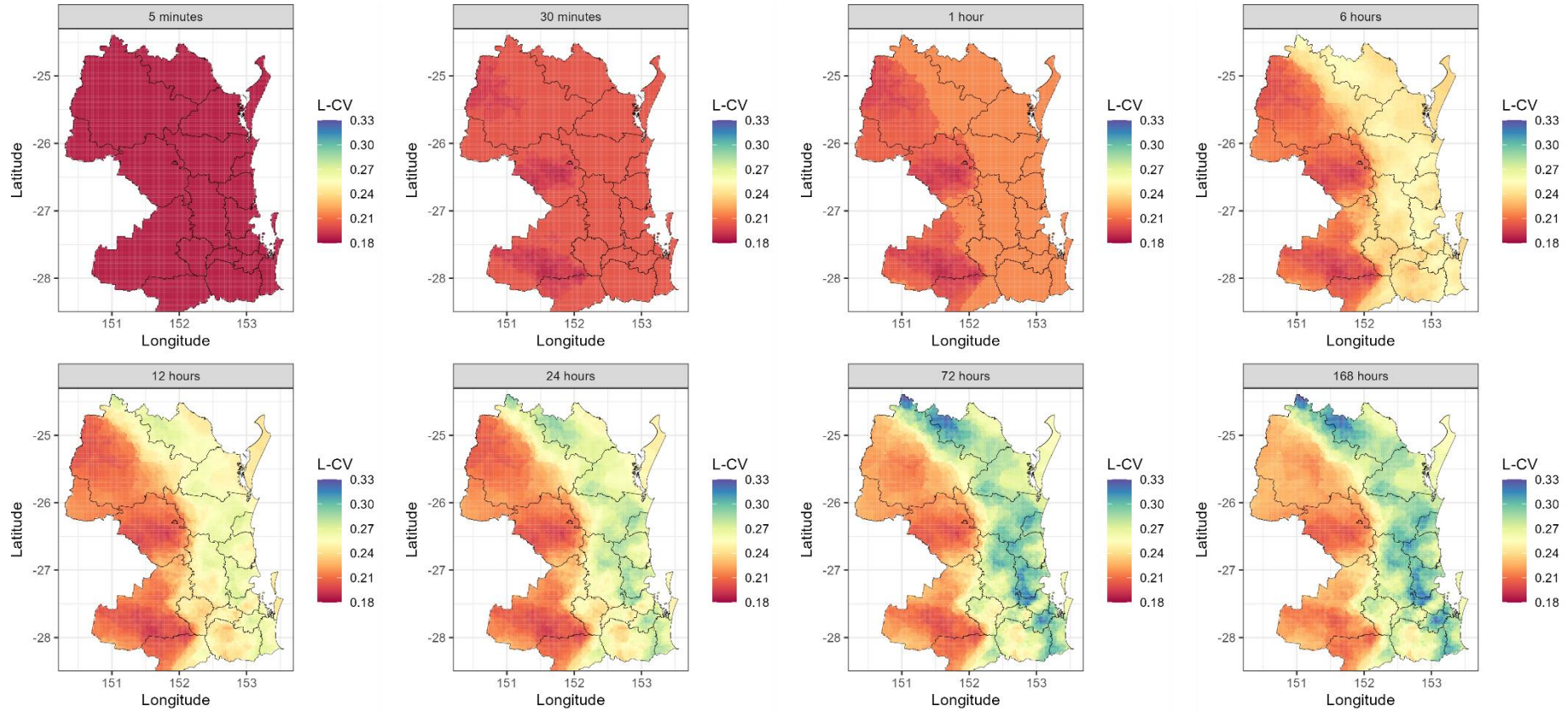


Figure 10-15 Gridded L-CV for selected durations

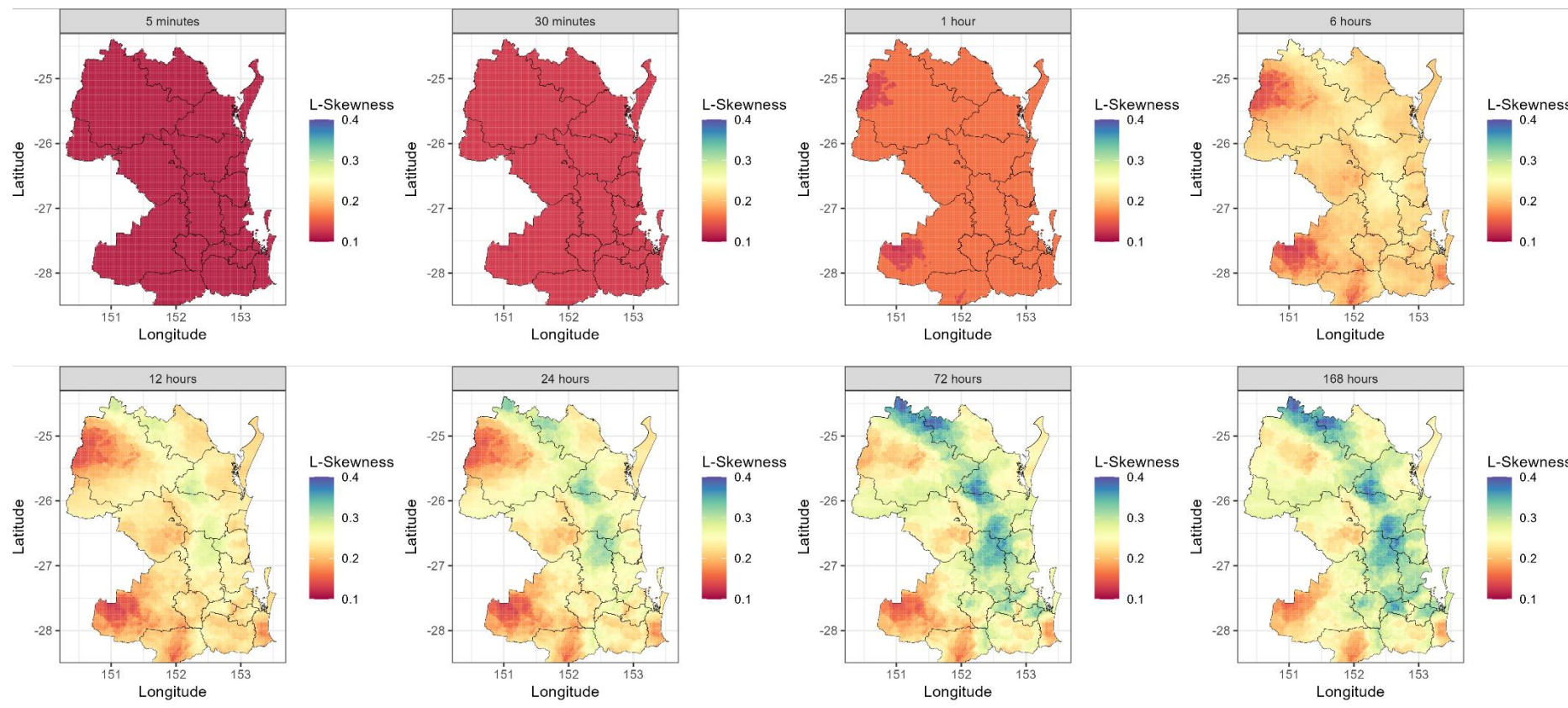


Figure 10-16 Gridded L-skewness for selected durations

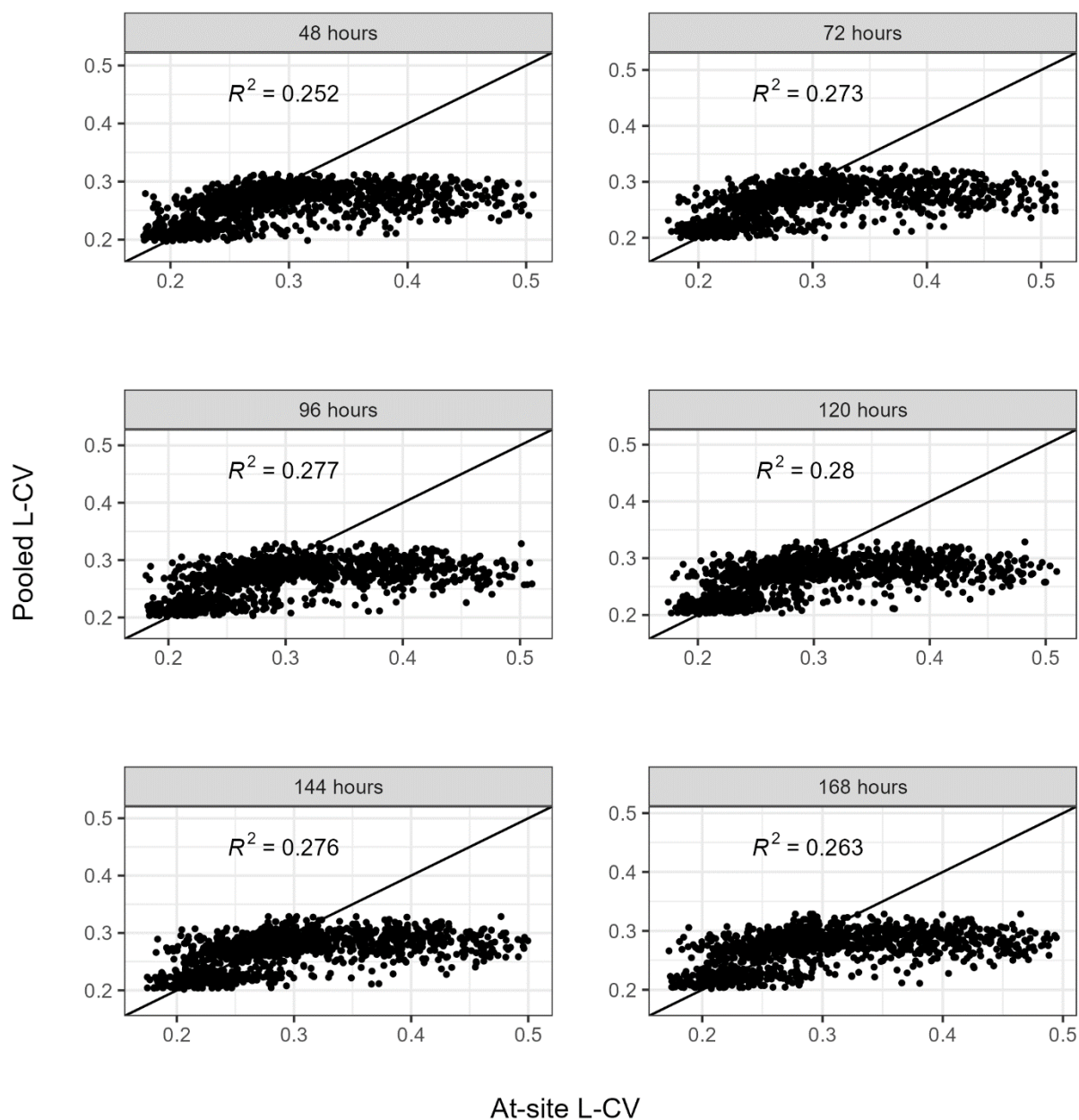


Figure 10-17 Comparison of at-site and pooled L-CV

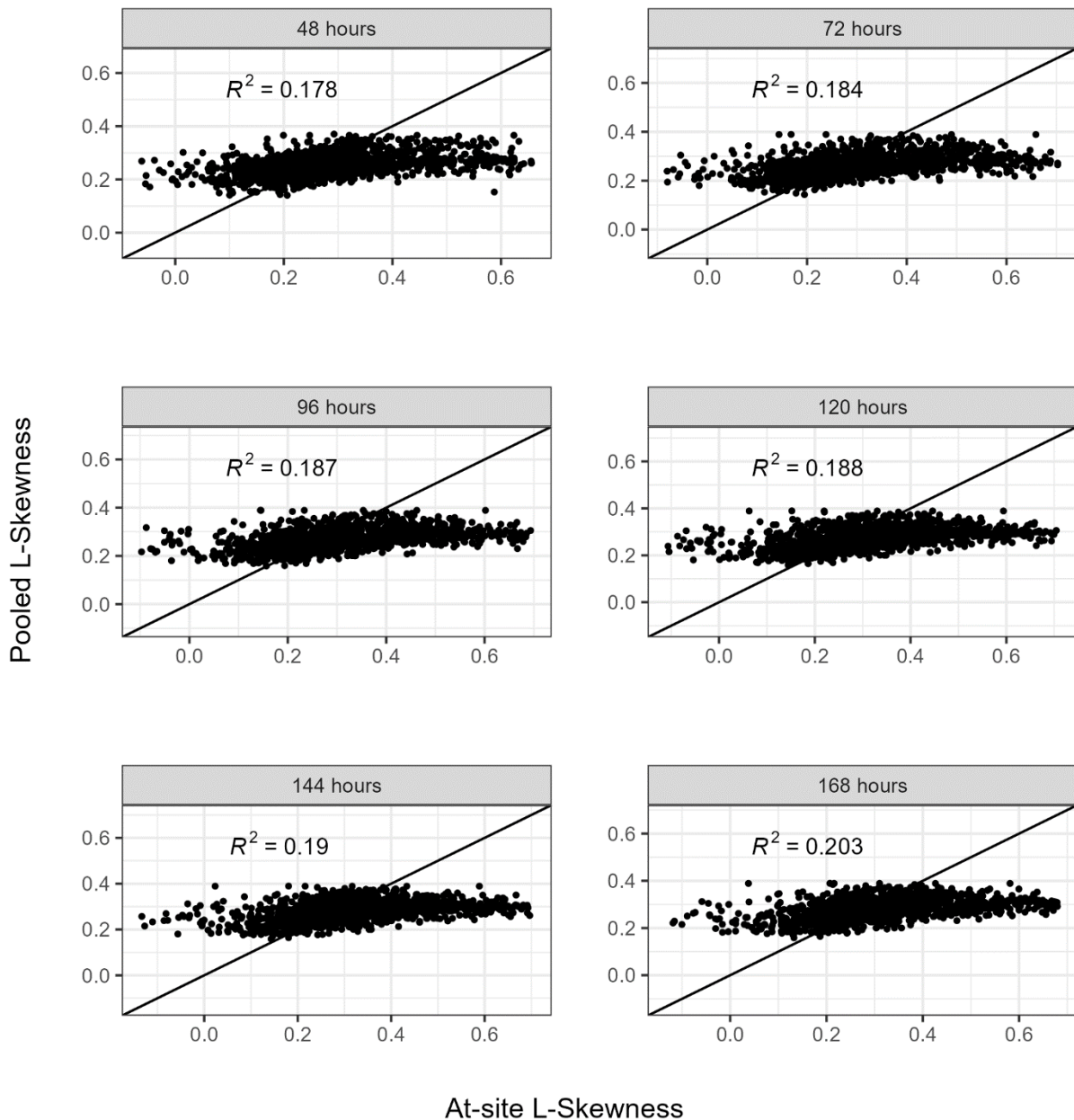


Figure 10-18 Comparison of at-site and pooled L-skewness

10.5 Growth factors for large to extreme rainfall events and extrapolation to GSDM point PMP estimates

There was discussion at the second project workshop on the shape of the IFD curves, particularly for rare and very rare rainfall events, between 1 in 50 and 1 in 2,000 AEP and for shorter durations, less than about 6 hours. On first examination of curves at individual sites, which were plotted on a Gumbel transformed frequency versus log-depth scale, it appeared as though some of the shorter duration growth curves may have had slopes that were too shallow, with a curvature that would result in a maximum depth being reached before the AEP of the PMP. If this were the case, it could cause difficulty for practical application of the gridded IFD data.

Alternatively, it is possible that the fitted IFD curves at some grid cells could be too steep, which could also cause issues with interpolation between the 1 in 2,000 AEP design rainfall depth and the PMP depth. Book 8 of Australian Rainfall and Runoff (Nathan and Weinmann, 2019) provides a procedure for interpolating between the credible limit of extrapolation, or the 1 in 2,000 AEP design rainfall depth and Probable Maximum Precipitation (PMP) depths. The recommended interpolation process fits a quadratic in log-AEP versus log-depth transformed space, with a smooth transition in slope between the 1 in 1,000 and 1 in 2,000 AEP design rainfall estimates and the PMP, at the nominated AEP of the PMP.

10.5.1 Comparison with short duration growth factors

Book 8 of Australian Rainfall and Runoff (Nathan and Weinmann, 2019) recommends that for rainfall burst durations shorter than 6 hours inclusive, design rainfall estimates should be computed using the growth factors from Jordan et al. (2005). The Jordan et al. (2005) growth factors were calculated by combining the records from 10 sub-daily rainfall gauges with long records around Australia, after normalising the burst depths by the 2% AEP rainfall depth at each gauge and then fitting GEV distributions for durations between 0.5 and 12 hours. The Jordan et al. (2005) growth factors provide a useful benchmark on the shape of the design rainfall frequency curves that are fitted for the study area.

Table 10-4 lists the regional average L-moments and GEV parameters for burst durations between 0.25 and 6 hours. These parameters were calculated by pooling data from 378 sub-daily rainfall sites, with each site having at least 18 years of valid water year maxima. For durations up to and including 1 hour, the GEV shape parameter (k) is positive, so the distribution will have a positive upper limit (at an extremely rare AEP) and the shape of the distribution is concave downward on a Gumbel-frequency versus linear-depth plot. Durations of 1.5 hours and longer have a GEV shape parameter that is negative, so these have no upper bound and a concave upward shape on a Gumbel-plot.

Table 10-4 Regional average L-moments and GEV parameters for durations between 0.25 and 6 hours

Duration (h)	L-CV	L-skewness	GEV scale parameter (α)	GEV shape parameter (k)
0.25*	0.198	0.117	0.307	0.085
0.5*	0.208	0.136	0.314	0.053
1*	0.218	0.158	0.320	0.018
Adopted for all durations 1 h and shorter after thresholding*	0.223	0.170	0.322	0
1.5	0.225	0.173	0.323	-0.004
2	0.230	0.184	0.325	-0.021
3	0.238	0.199	0.329	-0.044
4.5	0.247	0.211	0.336	-0.063
6	0.255	0.218	0.342	-0.075

* L-moments and GEV parameters for durations shorter than 1 hour from regional average. As discussed in section 8, thresholding was applied to sub-hourly L-moments and GEV parameters

The regional average GEV parameters from Table 10-4 were used to calculate growth curves of design rainfall depth, for each duration, compared with the 2% AEP design rainfall depth. These are equivalent in form to the growth curves from (Jordan *et al.*, 2005), with the growth curves starting at a value of 1 for the 2% AEP.

Figure 10-19 shows that there is consistency between the growth curves for the SEQ region and the equivalent curves from Jordan *et al.* (2005). The growth curve for the 1 hour duration for the SEQ region differs by just over 2% from the 1 hour duration curve and the all duration average curve provided in Table 2 of Jordan *et al.* (2005). Both the SEQ regional analysis and Jordan *et al.* (2005) found that the growth curves spread out with duration, with shorter durations having flatter growth curves and longer durations having steeper growth curves. Slightly greater spread was identified in growth curves for the current study in the SEQ region than was identified by Jordan *et al.* (2005). Even given this, the growth factors for the SEQ region varied, across combinations of AEP and duration, between 3% lower and 12% greater than the growth factors at the same duration from Jordan *et al.* (2005). In other words, if an alternative approach were to be contemplated whereby the 2% AEP design rainfall depths were adopted from the SEQ regional distribution and design depths for 1% to 1 in 2,000 AEP for durations less than 6 hours were to be calculated from the Jordan *et al.* (2005) growth curves the design rainfall depths would change by no more than 12%. The consistency between the two approaches is pleasing, if somewhat surprising, given the differences in the period and spatial coverage of the sub-daily rainfall data sets for the two studies.

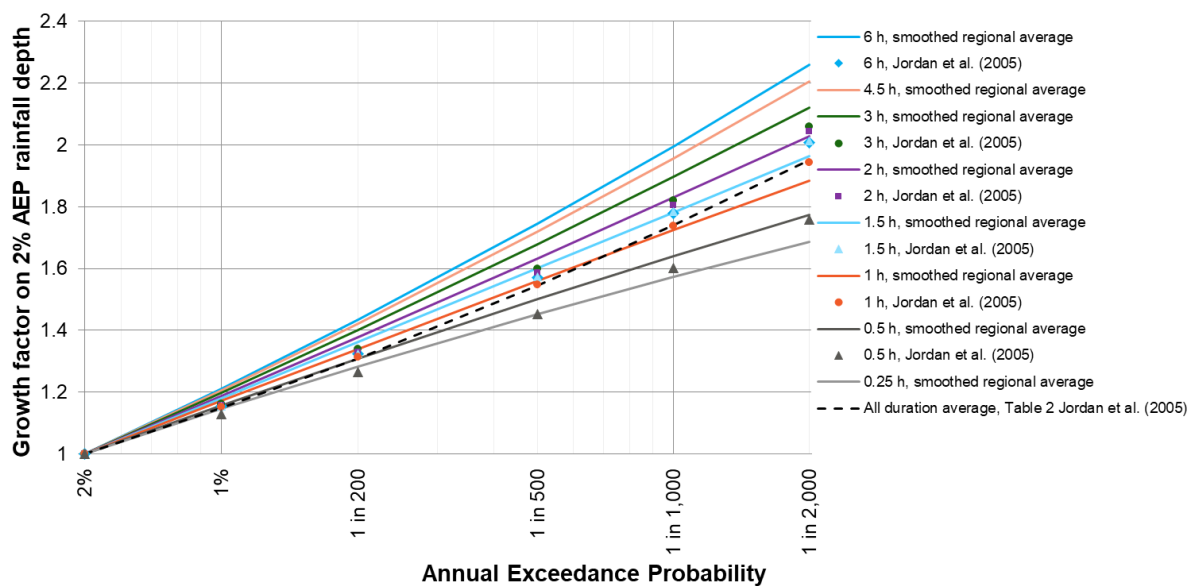


Figure 10-19 Comparison of growth factors on 2% AEP design rainfall depths, for durations between 0.25 and 6 hours, between HARC (2024) regional average values for SEQ study area and Jordan *et al.* (2005)

10.5.2 Interpolation to the PMP depth

PMP depths are normally calculated for catchment areas, rather than point estimates. Generalised Short Duration Method (GSDM) PMP estimates are provided at the point scale, which are used for estimating PMP depths on very small catchments, less than 1 km² in area and for durations up to and including 6 hours.

Point PMP depths were calculated, for durations between 0.25 and 6 hours, by applying the GSDM for every grid cell in the SEQ study region. The point PMP depth was defined by the product of the Moisture Adjustment Factor and the standard point value for either “rough” and “smooth” terrain, as defined in the GSDM Guidebook (Bureau of Meteorology, 2003). Elevation adjustment was not applicable, as there were no locations in the SEQ study region where the elevation exceeded 1,500 m AHD. The 1-second (~30 m) Shuttle Radar Terrain Mission (SRTM) Digital Elevation Model (DEM) data was used to identify areas of “rough” and “smooth” terrain, as defined in the GSDM Guidebook:

- Rough terrain is defined as regions where elevation changes of at least 50 m in 400 m “are common”, or areas that are within 20 km of regions where elevation changes of at least 50 m in 400 m “are common”.
- Terrain analysis was undertaken on each 30 m grid cell of the SRTM DEM to calculate the maximum elevation change within a 400 m diameter of the centre grid cell.
- Contiguous areas were identified where this maximum elevation change exceeded 50 m in 400 m. Very small contiguous areas, less than 10 km², were removed from the data set. This was a somewhat arbitrary decision but the remaining larger areas were areas where elevation changes of 50 m or more in 400 m were common and that were spatially consistent with the hillier and mountain range areas of the SEQ region, as shown in the DEM.
- A 20 km buffer was then expanded in every direction around the remaining contiguous areas to define the extent of “rough terrain”.

Growth factors from the 2% AEP to the point PMP depth were calculated, for every grid cell in the SEQ region and for every duration between 0.25 and 6 hours. The 2% AEP design rainfall depths were those calculated from the SEQ region gridded design rainfall depths. The AEP of the PMP was assigned to 1 in 10,000,000, as per Laurenson and Kuczera (1999). For each duration, grid cells were identified where the ratio of PMP to 2% AEP design rainfall were at their maximum and minimum values. These are the grid cells where there is the greatest possibility that a practitioner could have difficulty in producing a relatively smooth interpolation between the SEQ region design rainfall depths (from this study) and GSDM PMP estimates.

Figure 10-20 shows an example for the 2 hour GSDM point PMP depths across the study area. Point PMP depths for 2 hours range between about 700 and 800 mm in rough terrain and between 560 and 650 mm in smooth terrain. Therefore, the areas with the largest PMP depth to 2% AEP design rainfall ratio are toward the western edge of the rough terrain areas, near Cracow, Dalby and Allora. The areas with the lowest PMP depth to 2% AEP design rainfall are on North Stradbroke Island. For the 2 hour duration, it was therefore prudent to check the implications for extrapolation of the growth factors to the PMP depth for grid cells near the maximum of the study area range (i.e. near Cracow, Quinalow and Allora) and for grid cells near the minimum of the study area range (i.e. on Bribie and North Stradbroke islands).

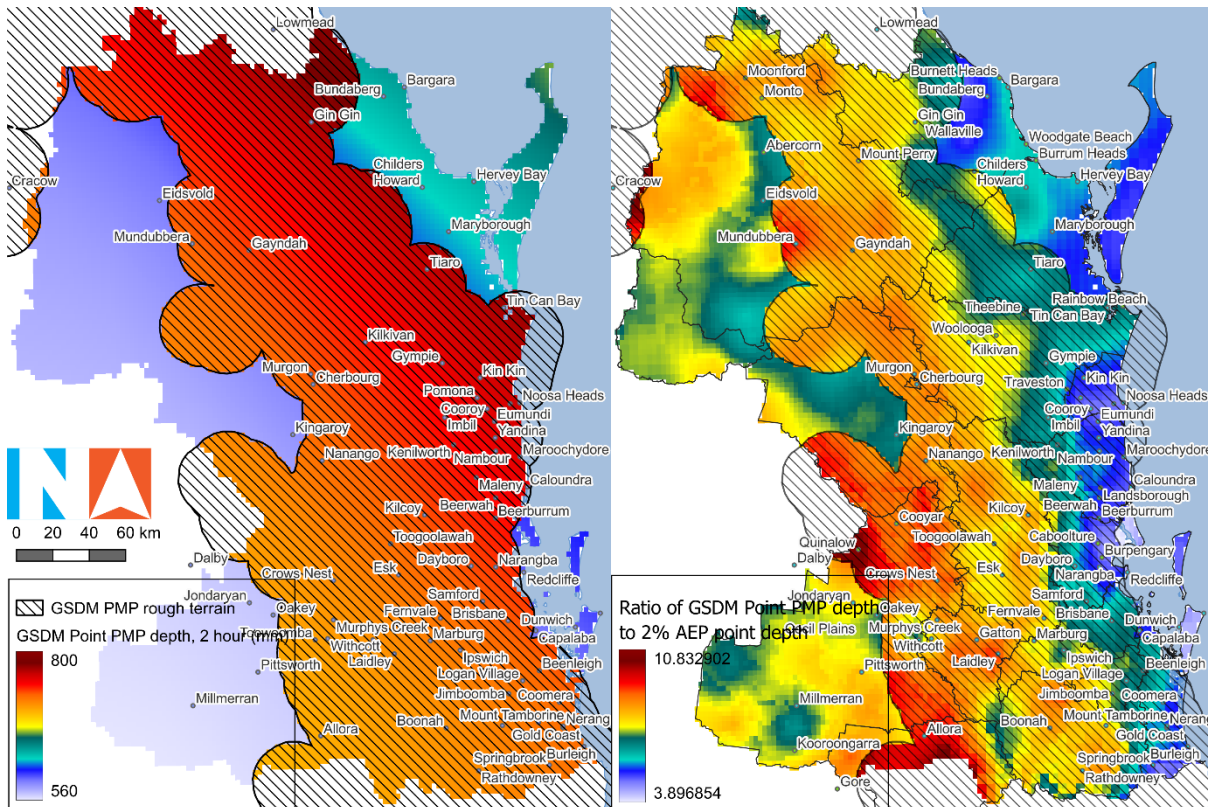


Figure 10-20 GSDM Point PMP depths (left) and ratio of GSDM PMP depth to 2% AEP design rainfall depth (right), for 2 hour burst duration at 0.025° grid resolution across the study area

Figure 10-21 shows the interpolation of design rainfall estimates at the grid cell where the PMP depths are greatest compared to the 2% AEP design rainfall estimates. At this grid cell, the slope of the design rainfall frequency curves for the study area (solid lines) are similar enough to the required slope from the 1 in 2,000 AEP to the PMP to produce a smooth design rainfall curve (top panel of Figure 10-21) and an unremarkable change in slope (bottom panel of Figure 10-21).

Figure 10-22 shows the opposite situation, for the grid cell where the PMP depths are smallest compared to the 2% AEP design rainfall estimates. The grid cell where this occurs is on North Stradbroke Island, within the GSDM “smooth” PMP zone and where design rainfall estimates (particularly L1) are enhanced by proximity to the coast and higher rainfall areas of the Gold Coast and hinterland. For this grid cell, the slope between the 1 in 1,000 and 1 in 2,000 AEP design rainfall estimates is more than twice the slope between the 1 in 2,000 AEP and the AEP of the PMP (after transforming to a log-AEP versus log-depth scale). The standard log-AEP versus log-depth interpolation procedure in Book 8 of Australian Rainfall and Runoff (Nathan and Weinmann, 2019) produces a non-sensical design rainfall maximum at an AEP that is more common than the AEP of the PMP for durations between 3 and 6 hours. This is an infrequent occurrence across the study area: it generally only occurs at a few grid cells on the offshore islands. Similar problems have been noted by Hill et al. (2000) for 13 small catchments in South Australia. Book 8 of Australian Rainfall and Runoff (Nathan and Weinmann, 2019) recommends that, in this situation, interpolation should be undertaken in the log-normal domain to avoid non-sensical results. The lower panel of Figure 10-22 shows that interpolation in log-Normal probability space would address interpolation to the GSDM point PMP depths at all durations, except for 6 hours. Interpolation in Gumbel versus linear space would address the interpolation to GSDM point PMP depths for all durations, including 6 hours.

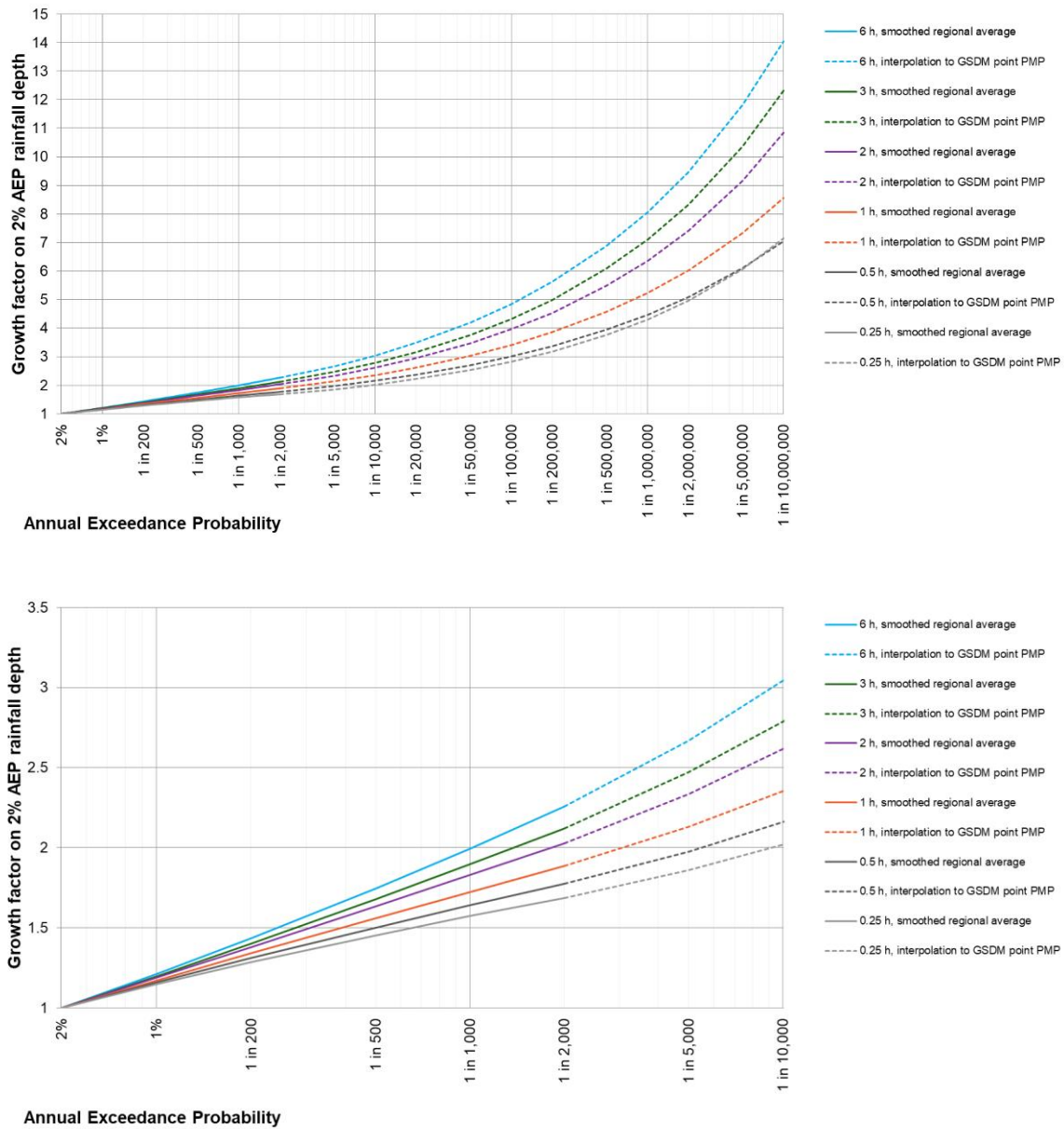


Figure 10-21 Interpolation between 1 in 2,000 AEP design rainfall estimates for the SEQ region and PMP depths at the grid cell in the region with the largest PMP to 2% design AEP ratio, for durations between 0.25 and 6 hours. The top panel shows the whole frequency curve from the 2% AEP to the PMP, whilst the bottom panel focusses on the transition zone around the 1 in 2,000 to the 1 in 10,000 AEP design rainfall depths. Both panels are shown on Gumbel-frequency versus linear depth scale.

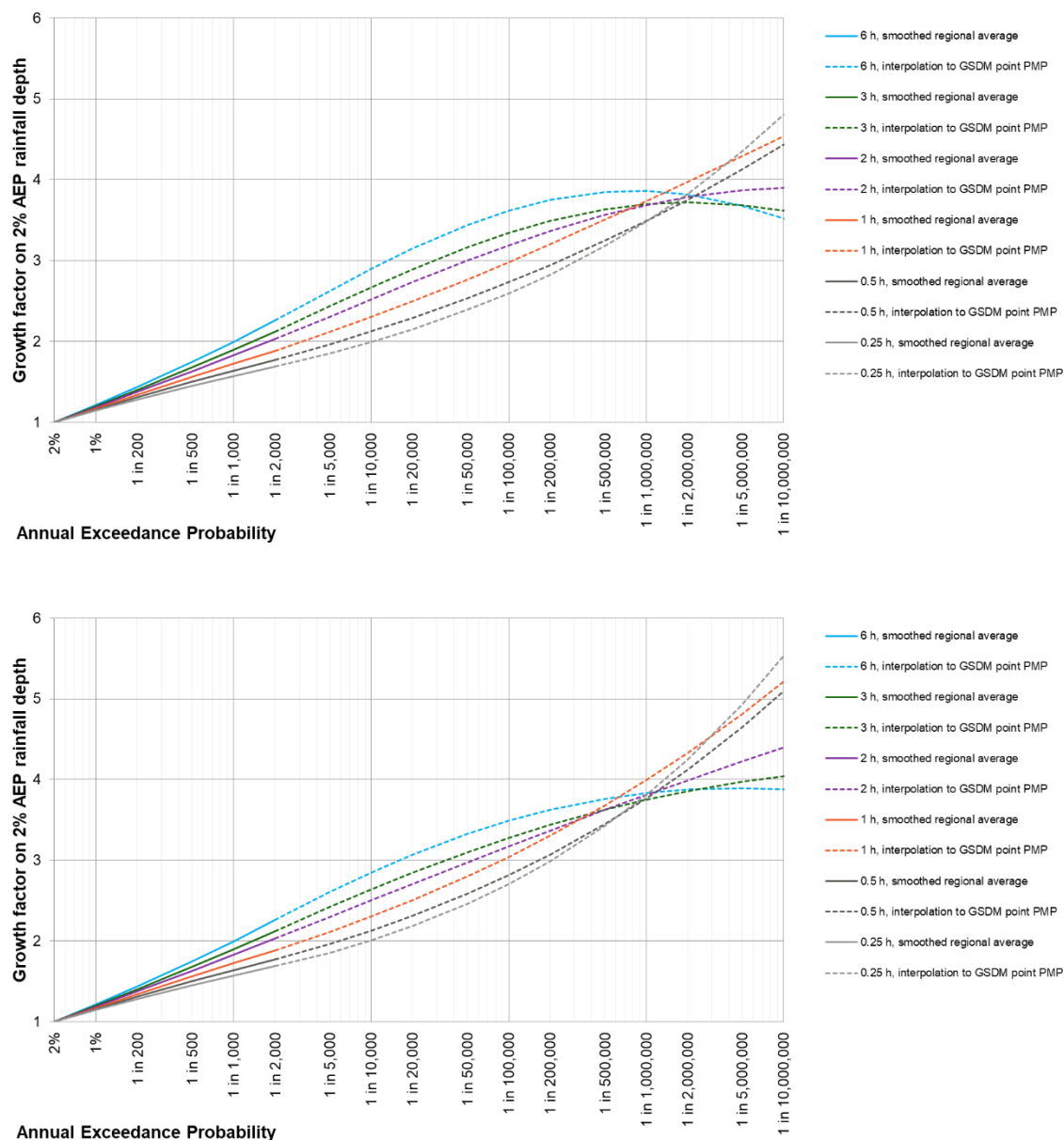


Figure 10-22 Interpolation between 1 in 2,000 AEP design rainfall estimates for the SEQ region and PMP depths at the grid cell in the region with the smallest PMP to 2% design AEP ratio, for durations between 0.25 and 6 hours. The top panel shows attempted interpolation in log-log domain, which produces non-sensical results for the 3 and 6 hour durations. The bottom panel shows interpolation in the log-normal domain, with PMP estimates updated to reflect 1°C increase in global air and sea temperature since the BoM (2016) baseline period (approx. 1970 to 2024).

11. IFD estimates

IFD estimates were produced for every grid cell across the study area, using two different approaches:

1. Applying regionalised L-moments to calculate GEV distributions at each 0.025° grid cell in the study area, calculating design depths for standard durations and AEP combinations at each grid cell and checking for and removing any minor remaining inconsistencies. These IFD data grids are considered the best-estimates based upon the data, for climate centred around 2010, or 0.6°C above the BoM (2016) IFD baseline for global mean temperature change.
2. At each grid cell, for each combination of standard duration and AEP, taking the maximum of:
 - Design rainfall depth from approach 1 (derived from this study) and
 - BoM (2016) IFD estimate that has been adjusted forward to the same 2010 global mean temperature, by allowing for 0.6°C increase in global mean temperature and applying the factors for sensitivity in IFD estimates with duration from Tables 1.6.1 and 1.6.5 of ARR version 4.2 (Ball *et al.*, 2019; Wasko *et al.*, 2024).

These two IFD data sets, which are both aligned to 2010 global mean temperature, serve different purposes:

- The first approach (HARC, 2024) provides the closest fit to the rainfall data that was available across the SEQ region, using the adopted methods for regionalisation. The first approach is more scientifically robust and preferable for design of critical infrastructure, such as large dams, and flood studies for rivers and creeks in SEQ.
- The second approach recognises that the BoM (2016) IFD data sets often produced higher design rainfall intensities for shorter duration and less rare (higher ARI or lower AEP) combinations. In situations where it is desirable to retain consistency for design of lower-risk infrastructure on smaller catchments, such as stormwater drainage assets, the grids from the second approach provide a conservative envelope of the IFD derived from this study and BoM (2016) adjusted to 2010 global mean temperature.

11.1 IFD estimates from adopted approach

The parameters of the GEV distributions were calculated based on the regionalised L-moments for each grid in the study area. The grid resolution was set to 0.025° x 0.025°, which was consistent with the current BoM IFD grids. The inconsistencies (crossovers) across the IFDs of different durations were checked for every cell in the study area. These inconsistencies were nearly all removed by smoothing of L-moments as explained in Sections 10.3 and 10.4.

A final check after L-moment smoothing found that for four grid cells (0.1% of the study area), the 1 in 2 AEP 96- and 120-hour duration curves crossed over. A manual smoothing of the GEV location parameter was undertaken for these four grid cells setting the 120-hour location parameter to be the average of the 96- and 144-hour location parameters. This removed all cross overs.

The gridded IFDs of 10%, 1% and 1 in 1,000 AEPs for selected durations (5 minutes and 30 minutes, 1, 6, 12, 24, 72, and 168 hours) is presented in Figure 11-1 to Figure 11-3. IFDs for all AEPs and durations are presented in Appendix F.

11.2 Maximum of adopted approach and BoM (2016) adjusted for climate shift

Design rainfall estimates were adjusted to a common baseline year of around 2010, for which the global average temperature was 0.6°C above the baseline temperature adopted for the BoM (2016) IFD data set. Design IFD estimates at every grid cell across the study area, for each duration and AEP combination, were adjusted using the factors provided in Table 11-1.

After adjustment to a common baseline year, the IFD estimate at every grid cell, for every combination of duration and AEP, was calculated as the maximum of the HARC (2024) value (see Section 11.1) and the BoM (2016) IFD estimate shifted to 2010.

Table 11-1 Rates of change in IFD with global temperature change (see Tables 1.61 and 1.6.5 of ARR version 4.2) and increases applied to BoM (2016) IFD estimates to bring them to a common baseline year with the IFD derived in this study.

Rainfall durations	Rate of change (%/°C) Central estimate from ARR (Wasko et al., 2023)	Global average temperature change from BoM (2016) to HARC (2024) mid-point (°C)	Increase applied to BoM (2016) IFD to shift to HARC (2024) mid- point (%)
5 min to 1 h	15	0.6	8.7
1.5h	13.7	0.6	8.0
2 h	12.8	0.6	7.5
3 h	11.8	0.6	6.9
4.5 h	10.8	0.6	6.3
6 h	10.2	0.6	6.0
9 h	9.5	0.6	5.6
12 h	9.0	0.6	5.3
18 h	8.4	0.6	5.0
24 h to 168 h	8	0.6	4.7

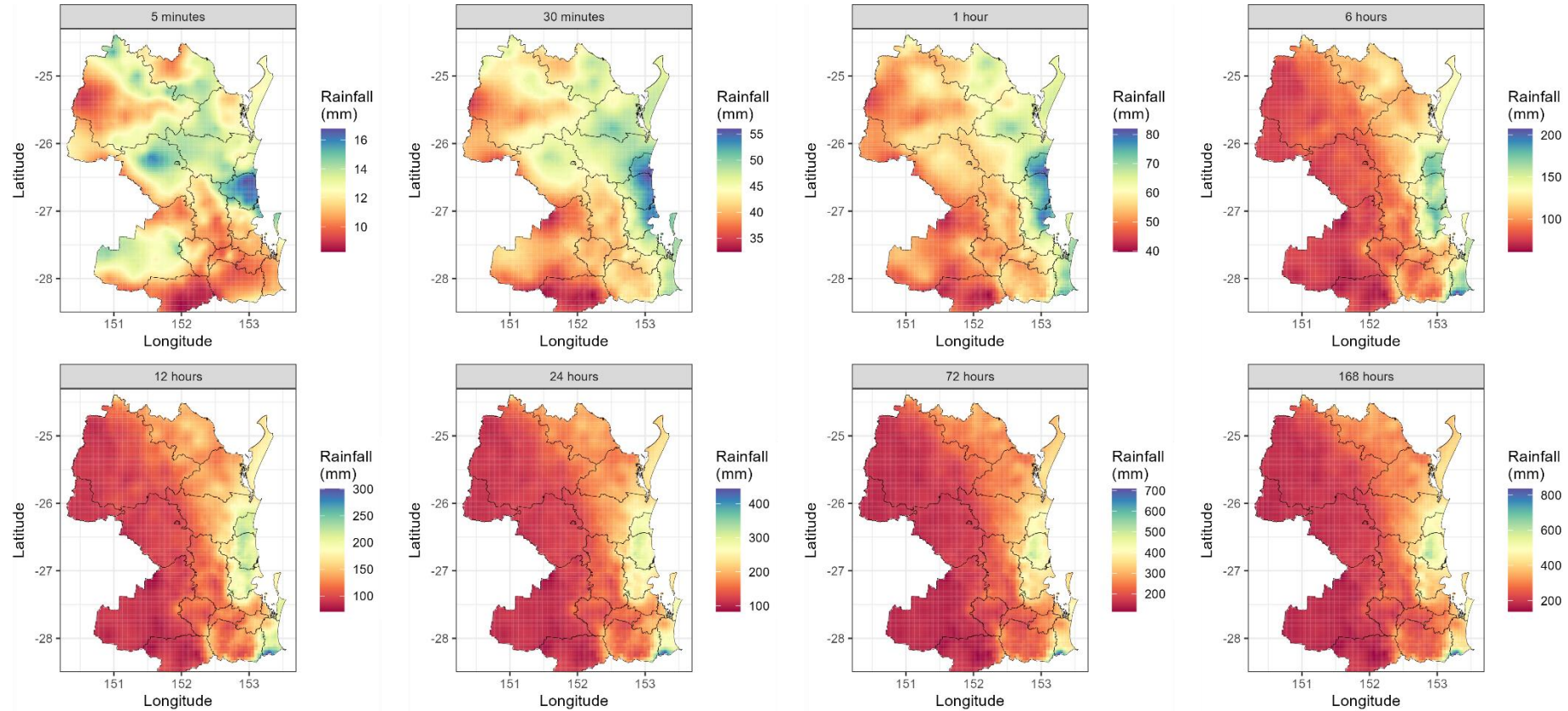


Figure 11-1 10% AEP IFDs

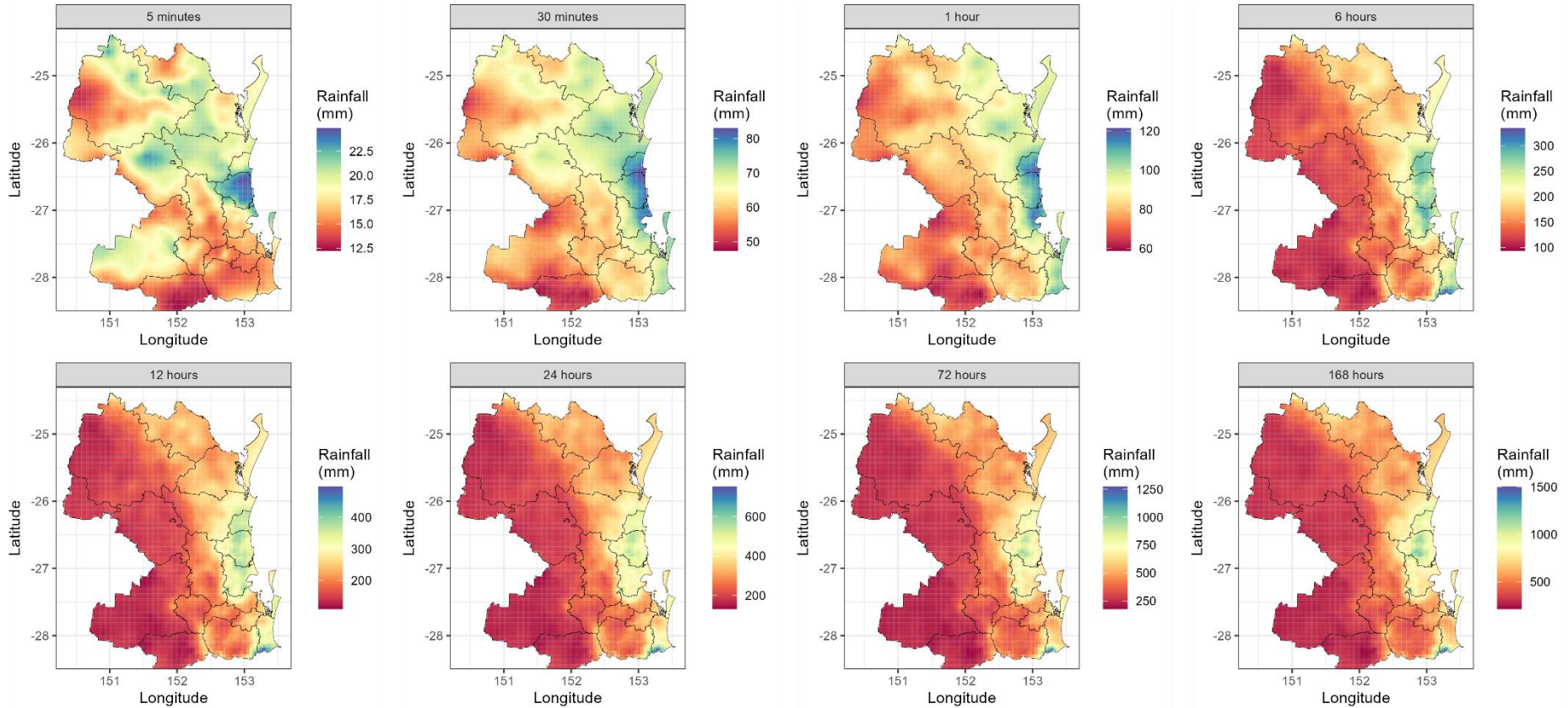


Figure 11-2 1% AEP IFDs

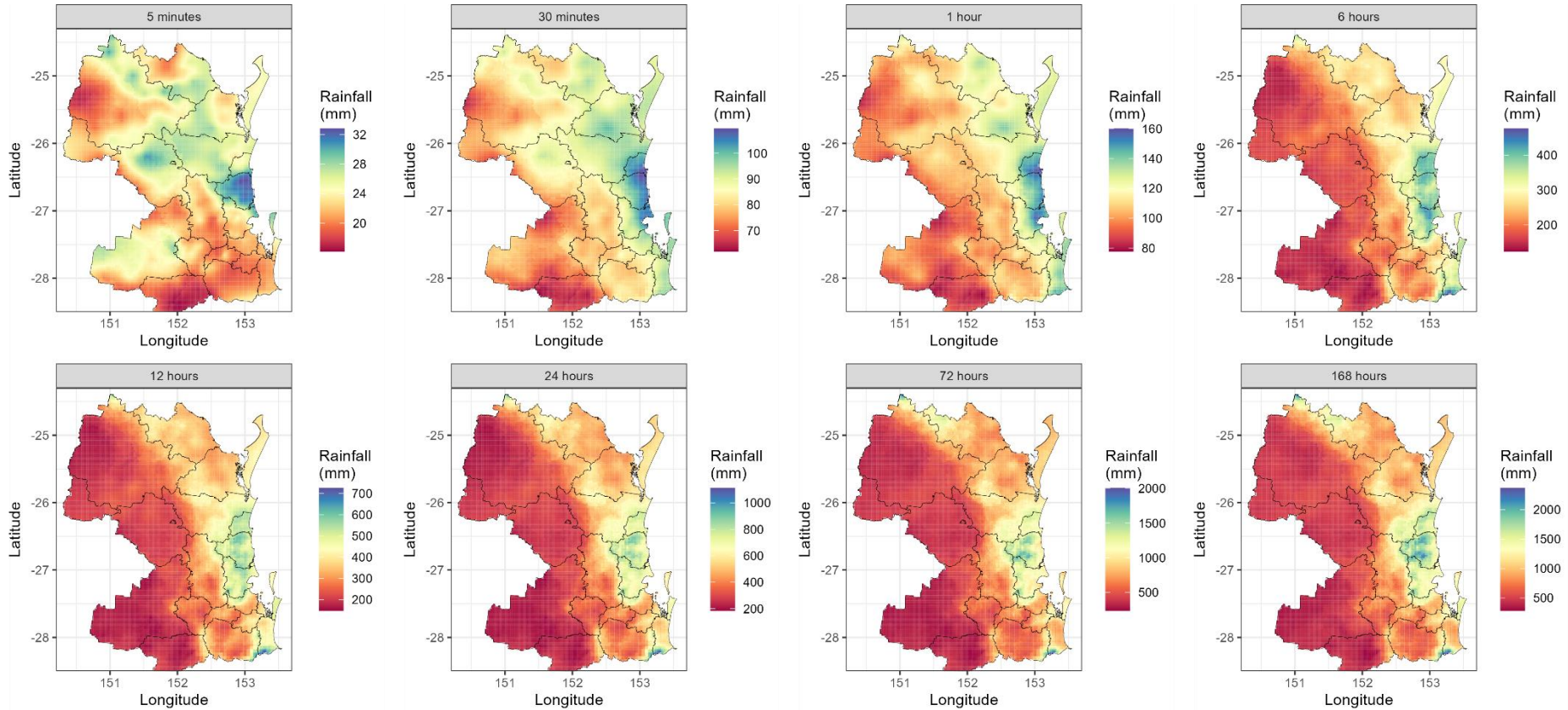


Figure 11-3 1 in 1,000 AEP IFDs

12. Comparison of at-site and regionalised IFDs

Twenty sub-daily stations (spread across the study area) with longer record periods and from different topography were selected to compare the at-site IFDs (estimates based on the at-site L-moments) with the gridded IFDs of the respective locations. Figure 12-1 presents an example of an at-site and gridded IFDs (from both ARR (2016) and this study) for Oakey Aerodrome Station (Site CO41359, Longitude = 151.741, Latitude = 27.403, Elevation = 405.7 m AHD). The comparisons of all other sites are presented in Appendix F. It can be seen from the figure and Appendix F that the inconsistencies (crossovers) in the IFD curves of different durations were removed in the gridded IFDs. This was primarily achieved by regionalisation and smoothing the L-moments.

In order to verify that the regionalisation and smoothing techniques adopted in this study has not introduced systematic bias in the estimation of IFDs across different AEPs, durations or different part of the study area, the percentage differences between the at-site and the gridded IFDs were estimated as shown in Figure 12-2.

These figures show that there is no considerable bias introduced across any particular durations or AEPs when compared against the at-site values. However, the frequent AEPs showed a smaller percentage difference compared to the rarer AEPs.

Figure 12-3 shows an example illustration of the spatial variation of the percentage differences between the at-site and gridded IFDs (also see Appendix H for results of all AEPs). The percentage changes were scattered across the study area. There were many areas where one site had an increase in the gridded IFDs and the closest next site had a decrease compared to the respective at-site values. There were no obvious areas identified with increased or decreased gridded IFDs compared to at-site values across the study area.

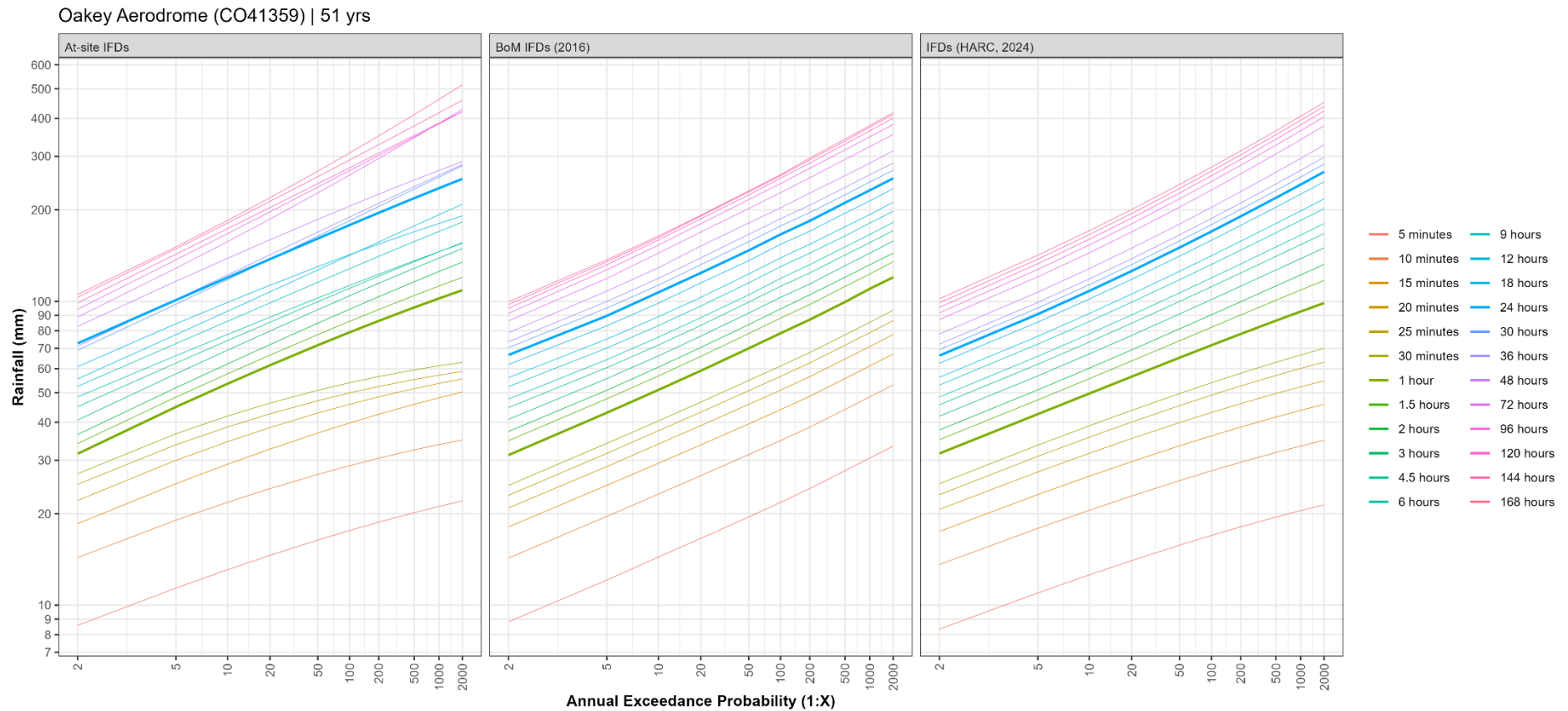


Figure 12-1 At-site and Gridded IFDs at CO41359 (Elevation = 405.7 m AHD, Record length = 51 years)

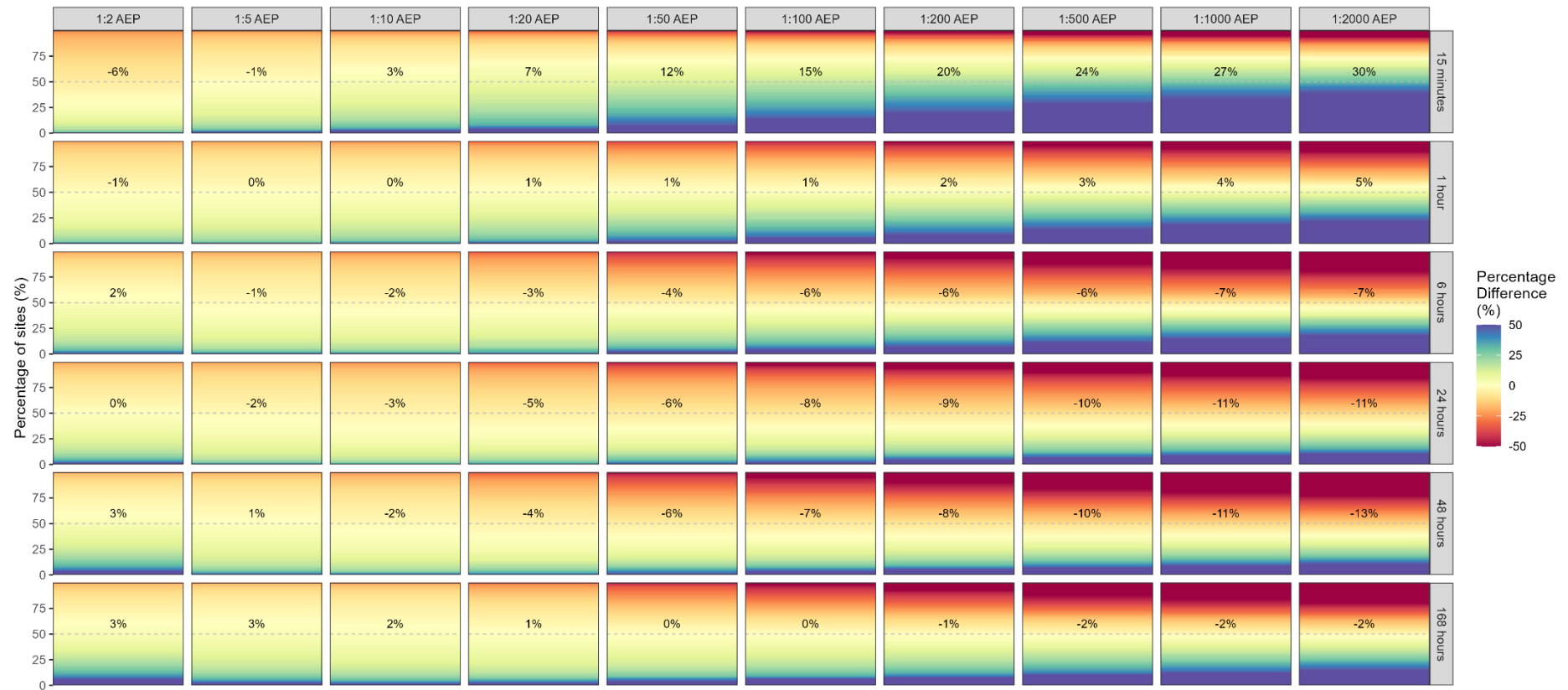


Figure 12-2 Percentage difference in the at-site and gridded IFDs for different AEPs and durations

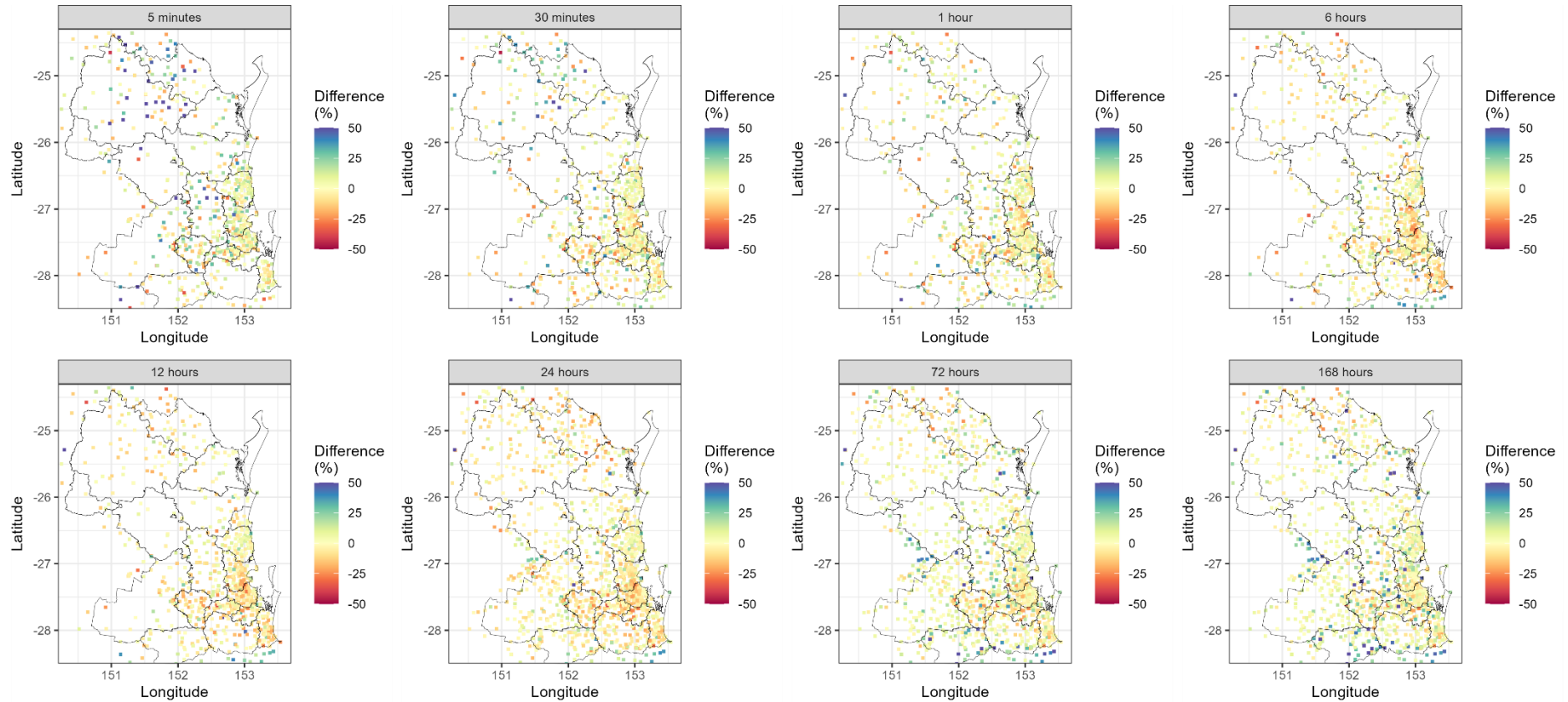


Figure 12-3 Percentage changes in at-site and gridded IFDs for 10% AEP

13. Comparison to Bureau (2016) and LIMB IFD

13.1 Differences in the methods

The difference in the IFDs of ARR (2016), LIMB (2021) and this study were due to the methods adopted in regionalising L-moments, methods used for the temporal interpolations (or regression) of L moments and IFDs, and the use of different pool of sites with different record periods for the analysis. A comparison of different steps and methods used across these studies are presented in Table 13-1.

Table 13-1 Comparison of methods

Steps/ methods	ARR (2016)	LIMB (2021)	HARC (2024)
Study area	Australia	Ipswich, Brisbane, Lockyer Valley and Moreton Bay LGAs	Southeast Queensland
Extraction of annual maximum rainfalls	Used data collected up to 2012 by BoM	Used data collected up to 2019 by BoM and councils	Used data collected up to 2022 by BoM and councils
Fitting at-site L-moments	Standard LH0 fit of L-moments	Standard LH0 and L-moments	Standard L-moments
Interpolation/regression of L-moments	BGLSR is used to get sub-daily L-moment estimates at daily stations	No regression	No regression
Distribution selected for fitting design rainfalls	GEV	GEV	GEV
Regionalisation of L1	Spline surface fitting technique (ANUSPLIN). Elevation was used as the covariate based on 24-hour duration data. A polynomial regression was used to estimate the L1 for other duration	Kriging using elevation and standard deviation of elevation as covariates	Adjustment of L1 to 2010 global average temperature Kriging using mean annual rainfalls as the covariate
Regionalisation of L-CV	Pooling of 500 years of data of neighbouring sites inside a circular homogeneous ROI, based on 24-hour duration data Neighbouring sites were defined by distance in latitude, longitude and elevation.	Pooling of 100 years of data of neighbouring sites for all durations, separately. Neighbouring sites were defined by distance in latitude, longitude, elevation and standard deviation of elevation	Hybrid approach that varies with duration: For durations ≤ 2 hours use of regional average For durations ≥ 48 hours pooling of 500 years of data of neighbouring sites, where neighbouring sites were defined by distance (latitude and longitude) For durations 3-36 hours, an interpolation approach was applied
Regionalisation of L-Skew	Same as above	Same as above	Same as above

Steps/ methods	ARR (2016)	LIMB (2021)	HARC (2024)
Interpolations/ smoothing of IFDs	Polynomials fitting across durations to remove inconsistencies in IFDs	Polynomials fitting across durations to remove inconsistencies in IFDs. 48-hour duration IFDs considered the point of truth and L moments were interpolated across 6–48-hour durations to achieve consistencies across all IFDs. 2-3 hr duration IFDs were then revised by applying weighted average L-CV and L-Skew. IDFs for < 1hr were estimated based on a polynomial regression	L-moment smoothing, based on the philosophy that L1, L-CV and L-skewness should increase with increasing duration was used to reduce inconsistencies in the IFD grids After L-moment smoothing four grid cells (0.1%) required minor manual adjustments to avoid cross over after L-moment smoothing.

13.2 Differences in gridded IFD estimates

The percentage difference between the BoM/ARR (2016) and HARC (2024) studies was estimated across the study area. Figure 13-2, Figure 13-3 and Figure 13-4 show the spatial variation of the percentage differences for 10%, 1% and 1 in 1,000 AEP rainfalls, respectively, for selected durations (see Appendix I for all AEPs and durations). Figure 13-5 shows a summary of the percentage difference for different durations and AEPs (also see Appendix J). The following general observations are noted:

- HARC (2024) estimates tend to be lower than ARR (2016) for shorter durations (< 3 hours). The cause for these lower values for short duration IFDs is thought to be due to the different methods adopted:
 - BoM (2016) applied simple scaling to smooth the IFD estimates across durations between 1 minute and 6 hour durations (Xuereb and Green, 2012). Applying simple scaling in this manner tends more often to over-estimate design IFDs for durations shorter than about 2 hours. HARC (2024) did not adopt this scaling approach and instead fitted distributions to the annual maxima from all durations down to 5 minutes (see top panel of Figure 13-1).
 - BoM (2016) L-moments for short durations were estimated from daily data using Bayesian Generalised Least Squares Regression, whereas a regionalisation approach based on sub-daily data was adopted here. These differences are greater for rare/extreme AEPs compared to frequent AEPs.
- HARC (2024) estimates tend to be greater for longer durations (>6 hours) compared to that of ARR (2016). Again, these differences are greater for rare/extreme AEPs compared to frequent AEPs. The increases are most pronounced in elevated areas along the Great Dividing Range and ranges closer to the coast. It is thought these increases are driven by the fact L1 was adjusted to represent 2010 and the tendency for more recent gauge data used in this study to display higher values of L-CV and L-skewness (see Section 10.1).

- BoM (2016) calculated growth factors in IFD estimates between the 1% and 1 in 2,000 AEP at 24 hour duration, which were then applied to all shorter durations. The BoM (2016) therefore ignored the sub-daily data, which in general would suggest that the skew reduces with duration and causes the regionalised IFD curves to “fan out” with increasing AEP (see bottom panel of Figure 13-1).

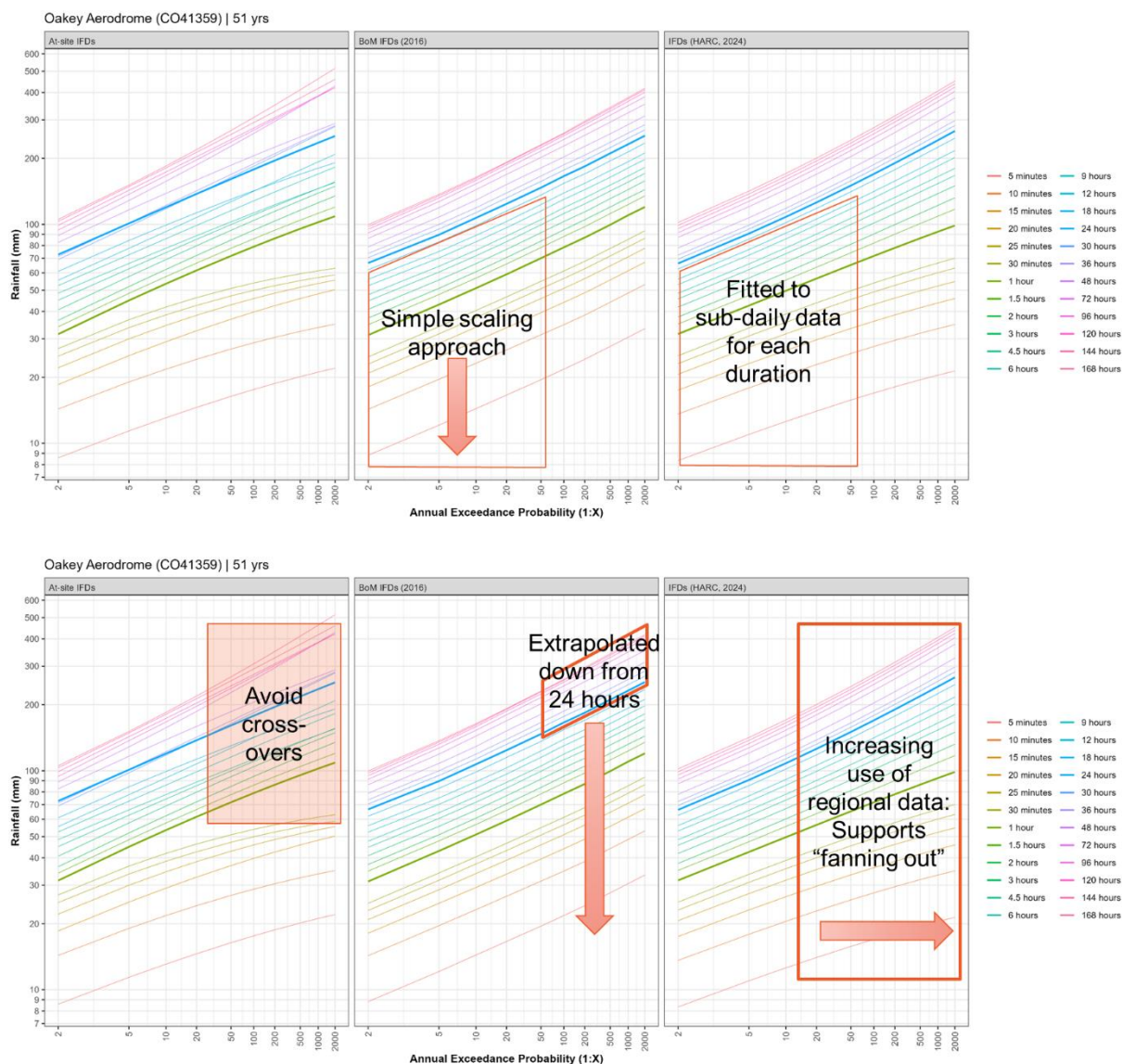


Figure 13-1 At-site and Gridded IFDs at Oakey Aerodrome, site CO41359, annotated with different approaches taken by BoM (2016) and the current study

There were several differences in analysis method between the LIMB (WMAwater, 2021) and HARC (2024) studies. The scope of the current project was to provide IFD estimates for the study region, which excluded LIMB. The LIMB LGAs, along with Logan, Redlands and Gold Coast, were in the “buffer” zone where the current study had rainfall data although the search for rainfall data in the current study was not as exhaustive in this area as it was in the focus area for the study.

Because there were several differences in method and data between the LIMB and HARC studies, it is almost impossible to unscramble the influences of each of these on the IFD grids that were produced. However, the main differences between the studies were:

- Differences in the restricted to unrestricted duration factors adopted, for converting annual maxima at daily gauges to equivalent annual maxima on an unrestricted period (see Section 5.6).
- LIMB used Elevation and Standard Deviation of Elevation as the covariates for spatial interpolation of the L1 values, whereas HARC found a higher correlation with Mean Annual Rainfall and used this for regionalisation of L1.
- LIMB made no adjustments for non-stationarity due to climate change across the data period. HARC made explicit adjustments to correct all the data to a consistent baseline date (~2010 or +0.6°C above ARR 2016 IFD data baseline). This would be most influential for durations 24 hours and longer, since most of the sub-daily sites used by both studies would have had relatively short records. However, there were a few sub-daily rainfall sites with long records and there was some smoothing across durations so IFDs for all durations could be somewhat affected by this.
- HARC used sub-daily ALERT / Environmon data from several councils that were not used in LIMB and vice-versa. The effects of this are probably most pronounced in and near the borders of Toowoomba and Sunshine Coast regional councils, as those councils provided large quantities of sub-daily data for the current project and in and near the borders of Lockyer, Ipswich, Brisbane and Moreton Bay councils, which supplied data to the LIMB study.
- LIMB adopted the growth factors from BoM (2016) for extrapolation of IFDs from 1 in 100 AEP to 1 in 2,000 AEP. BoM (2016) adopted the 24 hour growth factors for 1 in 100 to 1 in 2,000 AEP for all shorter durations. HARC used regionalised parameters of the GEV distributions for shorter durations for all AEPs (out to 1 in 2,000 AEP) (see bottom panel of Figure 13-1), as this was well supported by the sub-daily data in the region.
- There were differences in QA approach and the data used to cross-check annual maxima data between the LIMB and HARC studies.
- HARC included all rainfall data collected up to about October 2023, whereas LIMB finished with data to late-2020. The HARC data set includes the significant rainfall event in 2022, which is not in the LIMB data set.

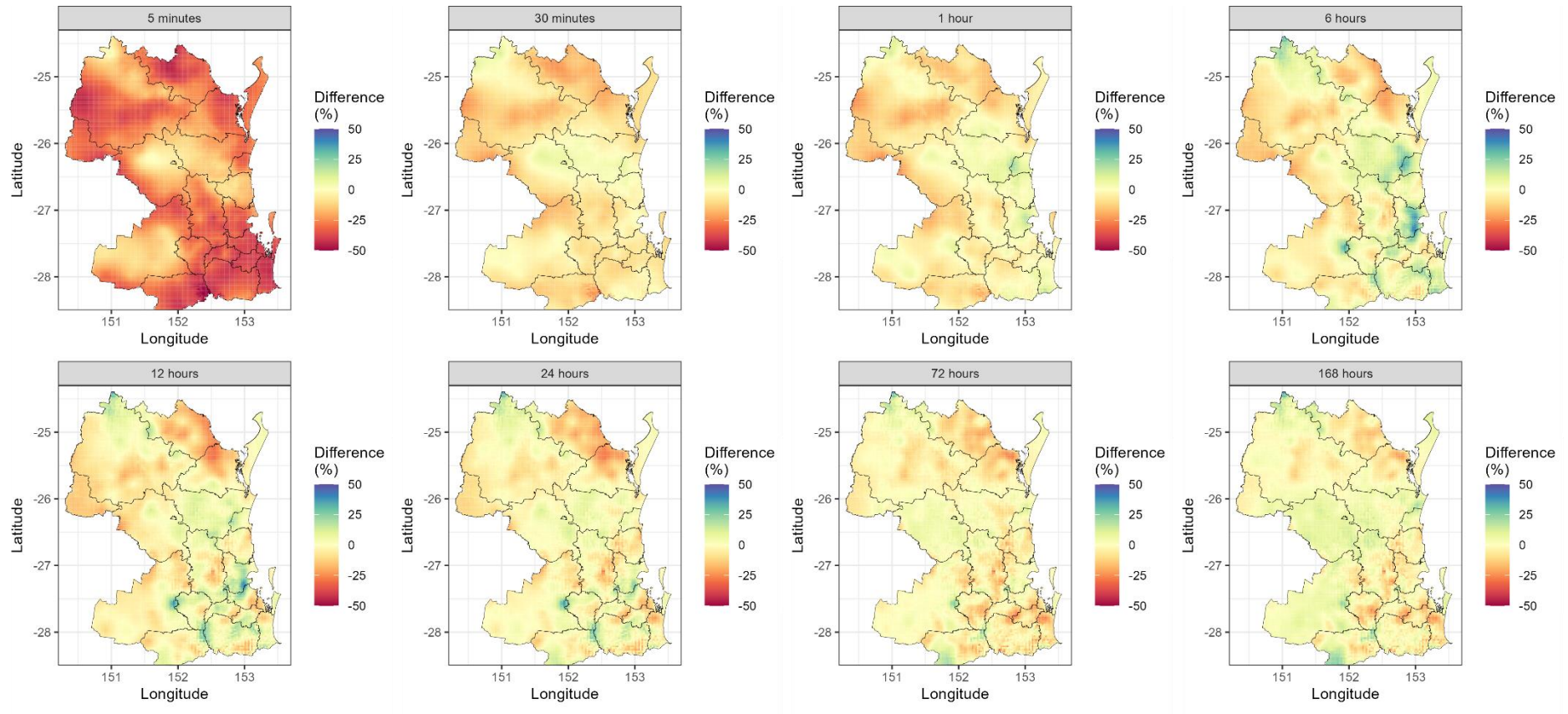


Figure 13-2 Percentage difference between 10% AEP BoM IFDs (ARR, 2016) and IFDs from this study (HARC, 2024)

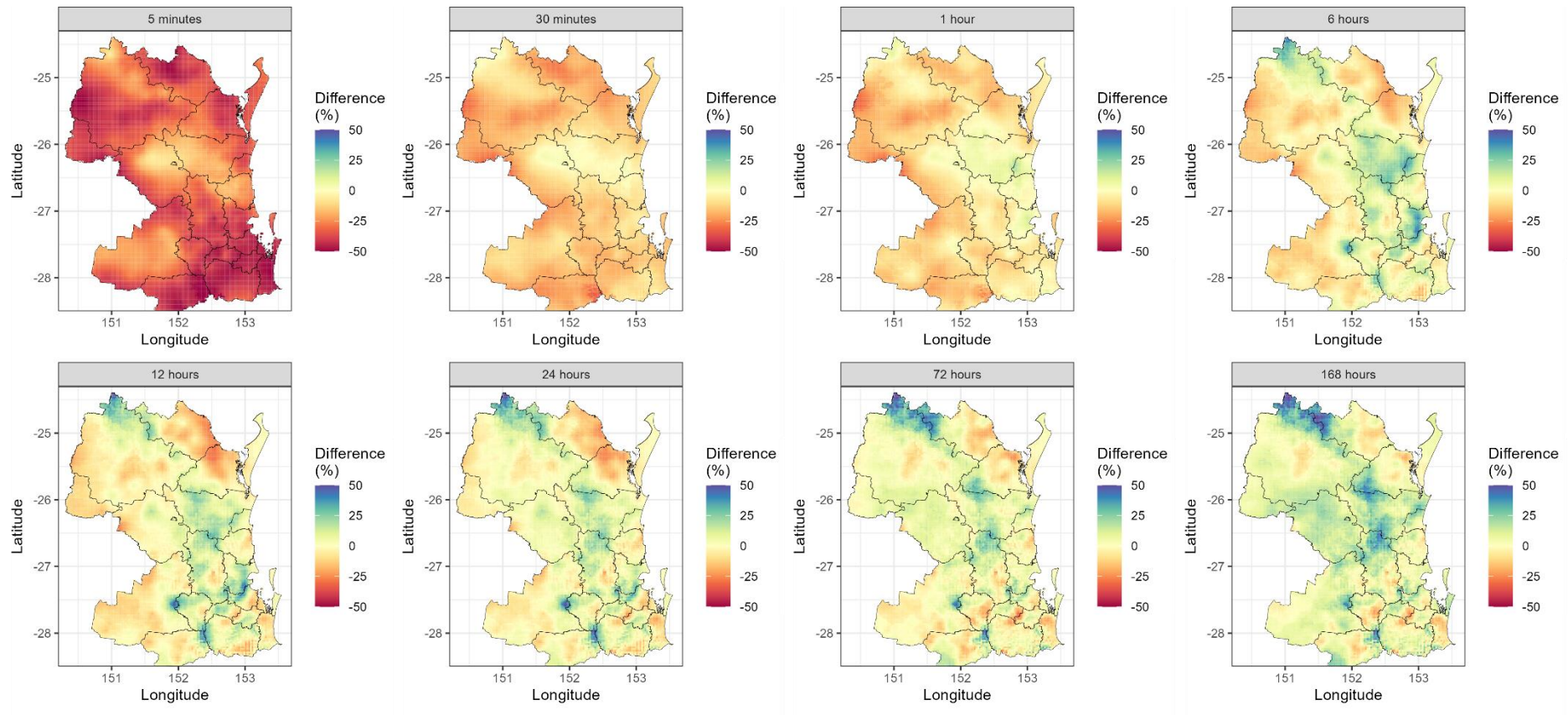


Figure 13-3 Percentage difference between 1% AEP BoM IFDs (ARR, 2016) and IFDs from this study (HARC, 2024)

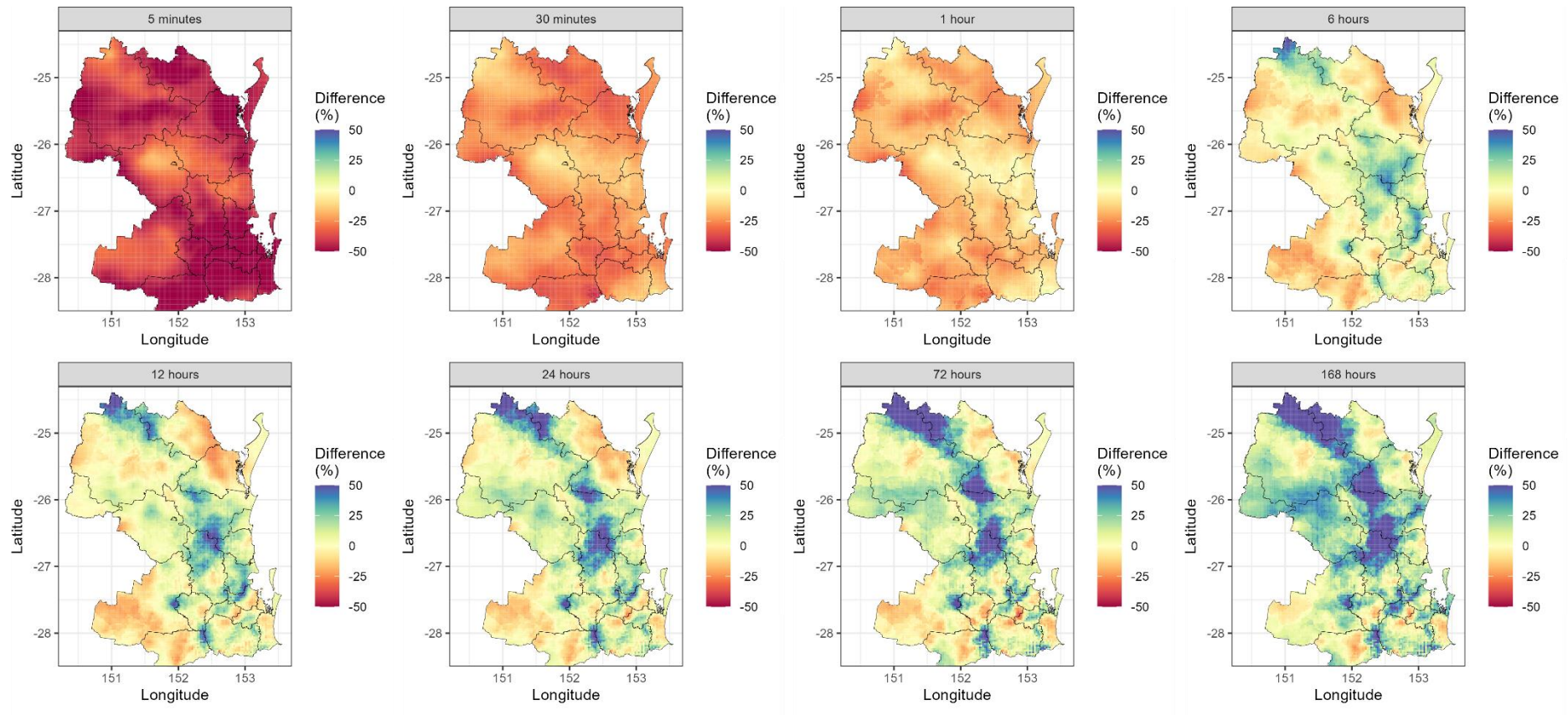


Figure 13-4 Percentage difference between 1 in 1,000 AEP BoM IFDs (ARR, 2016) and IFDs from this study (HARC, 2024)



Figure 13-5 Summary of percentage changes across different AEPs and durations. The median change for the given durations and AEPs is displayed in the respective tiles.

14. Conclusions and recommendations

Updated design Intensity Frequency Duration (IFD) depths were produced for all combinations of 24 durations from 5 minutes to 168 hours for 13 annual exceedance probabilities from 63% to 0.05% (1 in 2,000 AEP) for an area covering 11 local government areas in south-eastern Queensland and the surrounding region. This update represents a significant increase in available rainfall data, for the number of rainfall gauges applied to the analysis and with an additional 11 years (2013-2023) of gauge records available, compared the BoM 2016 IFDs.

The methodology for producing the IFD curves using regionalisation of L-moments has also been tailored to suit the high density of rainfall gauges in south-eastern Queensland. In particular, the method makes use of a hybrid approach for the regionalisation of L-CV and L-skewness, which uses regional wide averages for short durations (≤ 2 hours) and a region of influence approach for long durations (≥ 48 hours) to account for systematic difference in daily and sub-daily gauge data. Estimates of L1 are regionalised using kriging with mean annual rainfall as a covariate. The methodology also makes use of an L-moment smoothing approach, based on the observation that regional averages of L-moments typically increase monotonically with increase duration. This smoothing approach largely avoids issues associated with IFD curves crossing in physically inconsistent ways. Differences in methodology between the BoM 2016 IFDs can explain many of the differences, particularly the tendency for short duration (≤ 3 hours) design rainfalls to be higher in BoM 2016 IFD's than in this study.

IFD estimates were produced for every grid cell across the study area, using two different approaches:

1. Applying regionalised L-moments to calculate GEV distributions at each 0.025° grid cell in the study area, calculating design depths for standard durations and AEP combinations at each grid cell and checking for and removing any minor remaining inconsistencies. These IFD data grids are considered the best-estimates based upon the data, for climate centred around 2010, or 0.6°C above the BoM (2016) IFD baseline for global mean temperature change.
2. At each grid cell, for each combination of standard duration and AEP, taking the maximum of:
 - Design rainfall depth from approach 1 (derived from this study) and
 - BoM (2016) IFD estimate that has been adjusted forward to the same 2010 global mean temperature, by allowing for 0.6°C increase in global mean temperature and applying the factors for sensitivity in IFD estimates with duration from ARR version 4.2.

These two IFD data sets, which are both aligned to 2010 global mean temperature, serve different purposes:

- The first set is based on all available QA'd data to 2023 using latest statistical techniques including advanced smoothing algorithms as per this report to derive a set of IFD tables that are minimally biased. This set is referred to as the HARC (2024) data set.
- The second set is based on an envelope approach that adopts, for all durations, the maximum of either the HARC (2024) data set and the uplifted BoM (2016) IFD data set. This set is referred to as the eHUB (2024) data set. This set is included as it was noted that predominantly for the shorter durations (<3 hours) the uplifted BoM (2016) data set was generally higher than the HARC (2024) data set. While this introduces bias relative to the HARC (2024) data set, it allows LGA's to retain the same level of flooding/drainage infrastructure serviceability into the future.

These IFD data sets will be made available on the ARR data hub.



The IFD data sets presented here represent 2010 global average temperatures (defined by the 20-year average). This period is characterised by global temperatures 0.6°C warmer than the 1961-1990 period that the BoM 2016 IFDs (0.9°C above a 1850-1900 baseline referenced by IPCC data). This difference should be considered when adjusting the IFDs from this study for future climates. Table 1.6.2 of the updated climate change considerations chapter of ARR (version 4.2) provides global mean surface temperature projections relative to the BoM (2016) IFD estimates. However, when using the either of the two IFD data sets provided with this study, this table should be replaced by Table 14-1.

Table 14-1 IPCC Sixth Assessment Report global mean surface temperature projections for four socio-economic pathways relative to the baseline temperature for the updated IFD estimates for the SEQ region (HARC, 2024). The 90% uncertainty interval is provided in parenthesis*

Projection scenario	SSP1-2.6	SSP2-4.5	SSP3-7.0	SSP5-8.5
Current and near-term (2021-2040)	0.6 (0.3-0.9)	0.6 (0.3-0.9)	0.6 (0.3-0.9)	0.7 (0.4-1.0)
Medium term (2041-2060)	0.8 (0.4-1.3)	1.1 (0.7-1.6)	1.2 (0.8-1.7)	1.5 (1.0-2.1)
Long-term (2081-2100)	0.9 (0.4-1.5)	1.8 (1.2-2.6)	2.7 (1.9-3.7)	3.5 (2.4-4.8)

* Projections obtained from the Summary for Policymakers of the Working Group I Contribution to the IPCC Sixth Assessment Report (AR6)

The IFD data and this report have undergone independent peer review. The peer reviewer’s statement is included in Appendix M.

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Appendix A Covariates

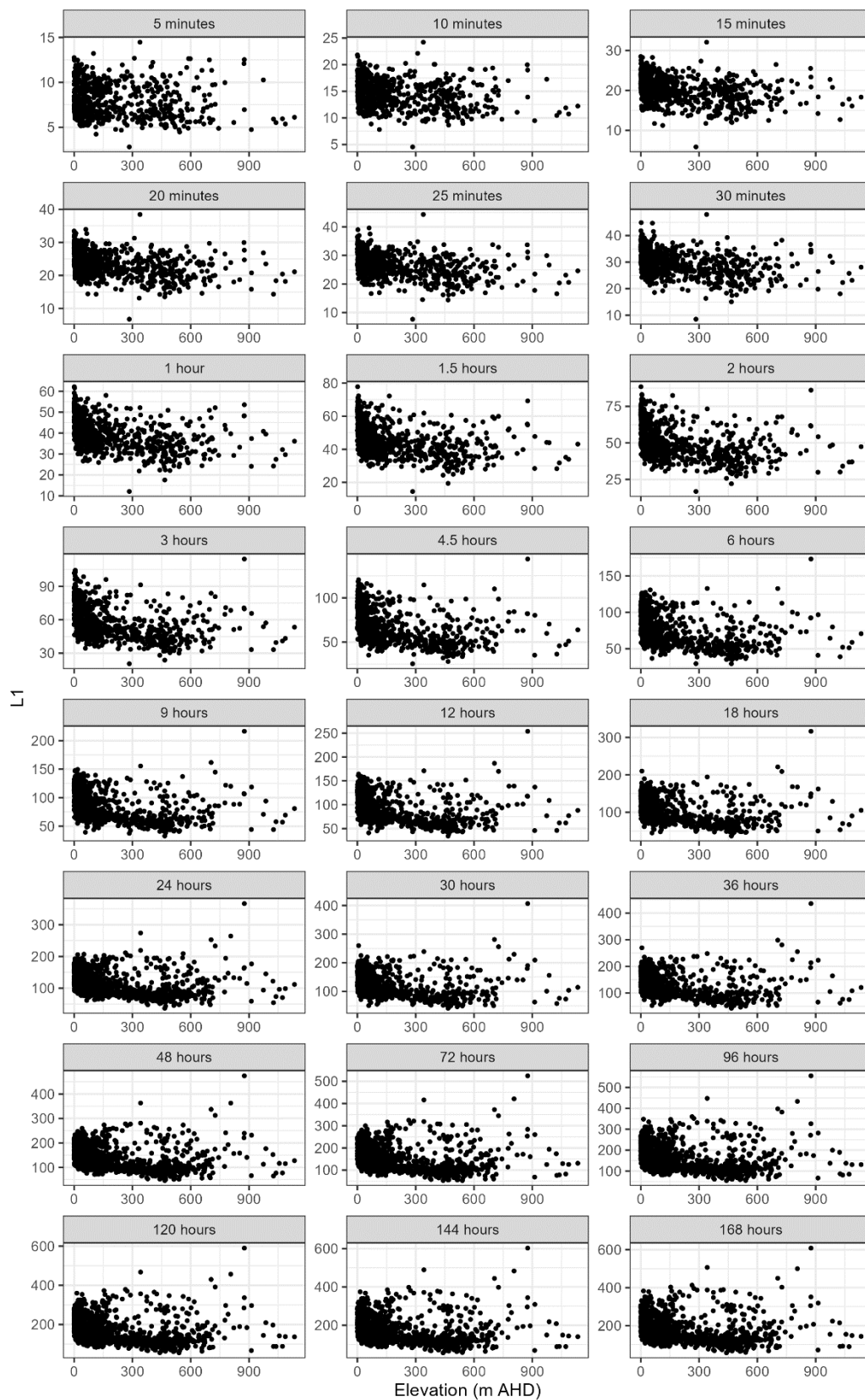


Figure A 1 Variation of L1 with elevation

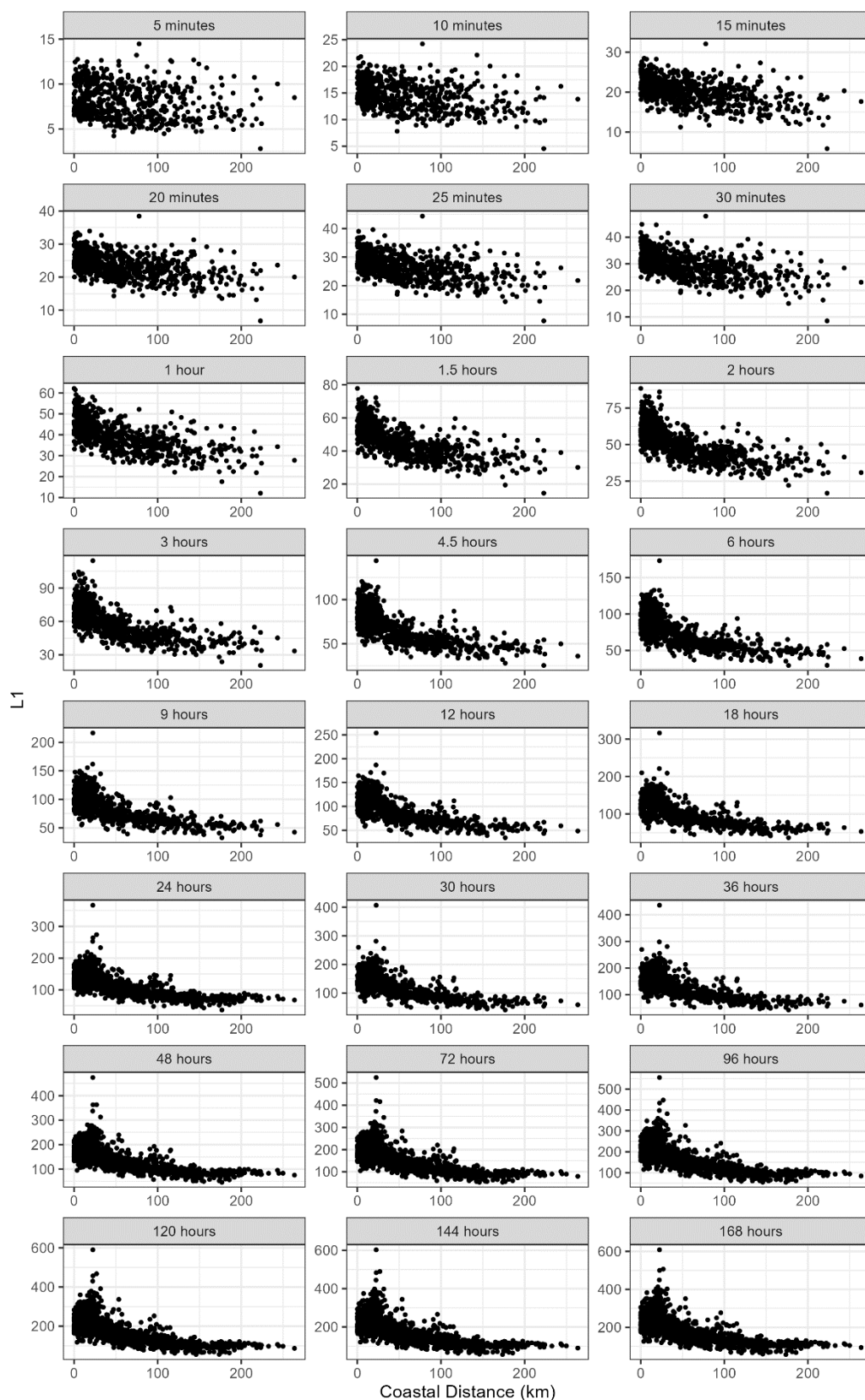


Figure A 2 Variation of L1 with coastal distance

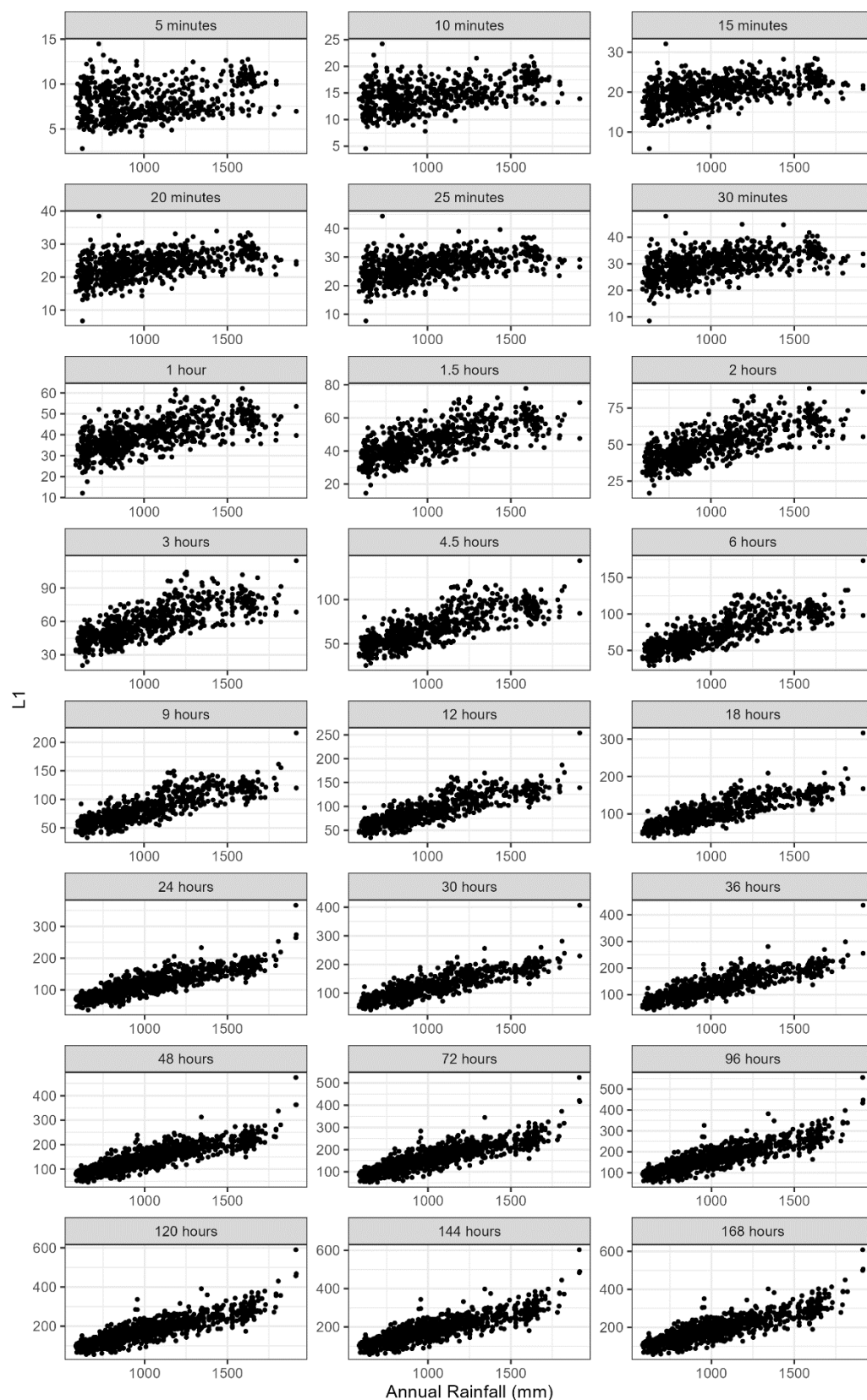


Figure A 3 Variation of L1 with mean annual rainfalls

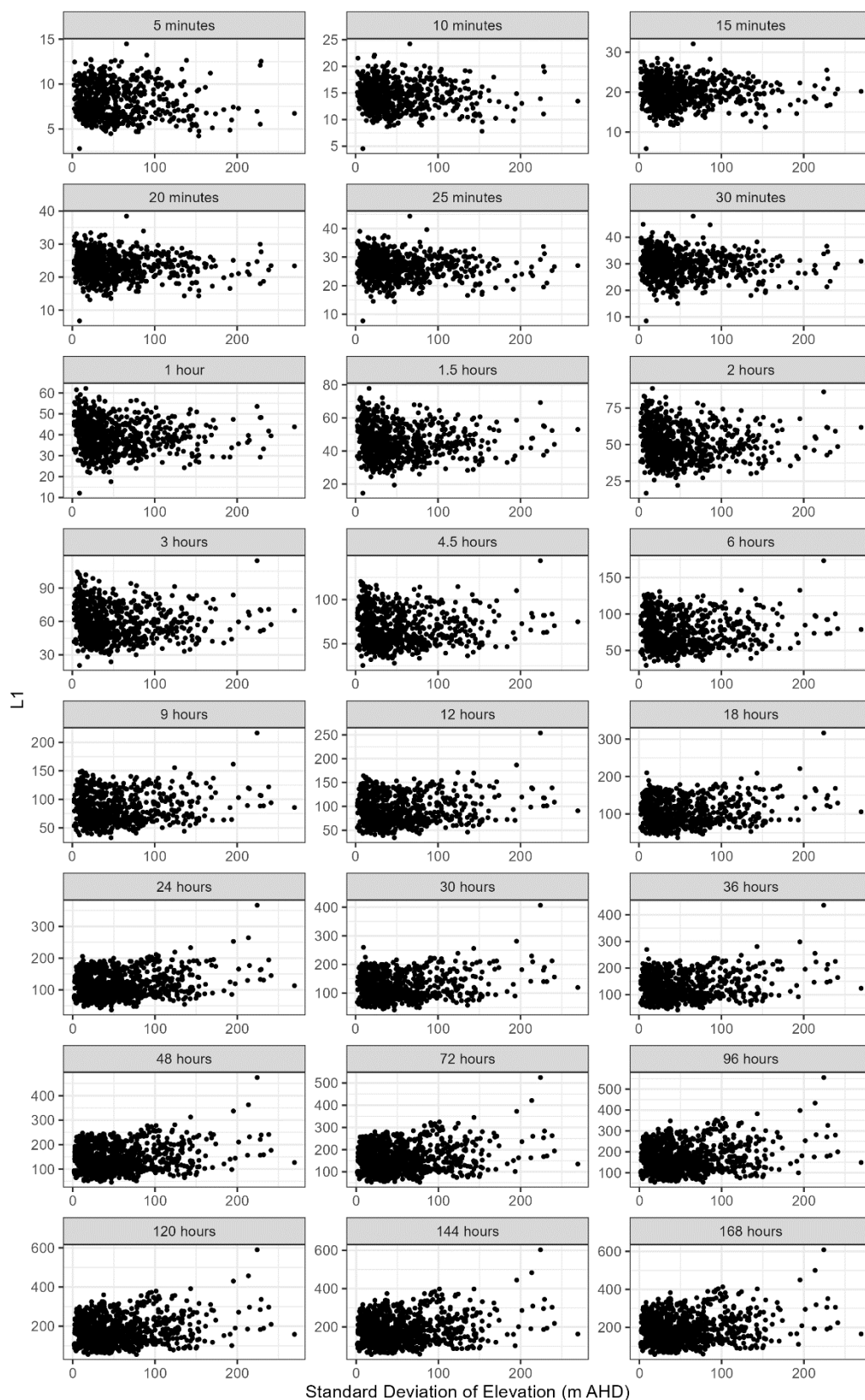


Figure A 4 Variation of L1 with standard deviation of elevation

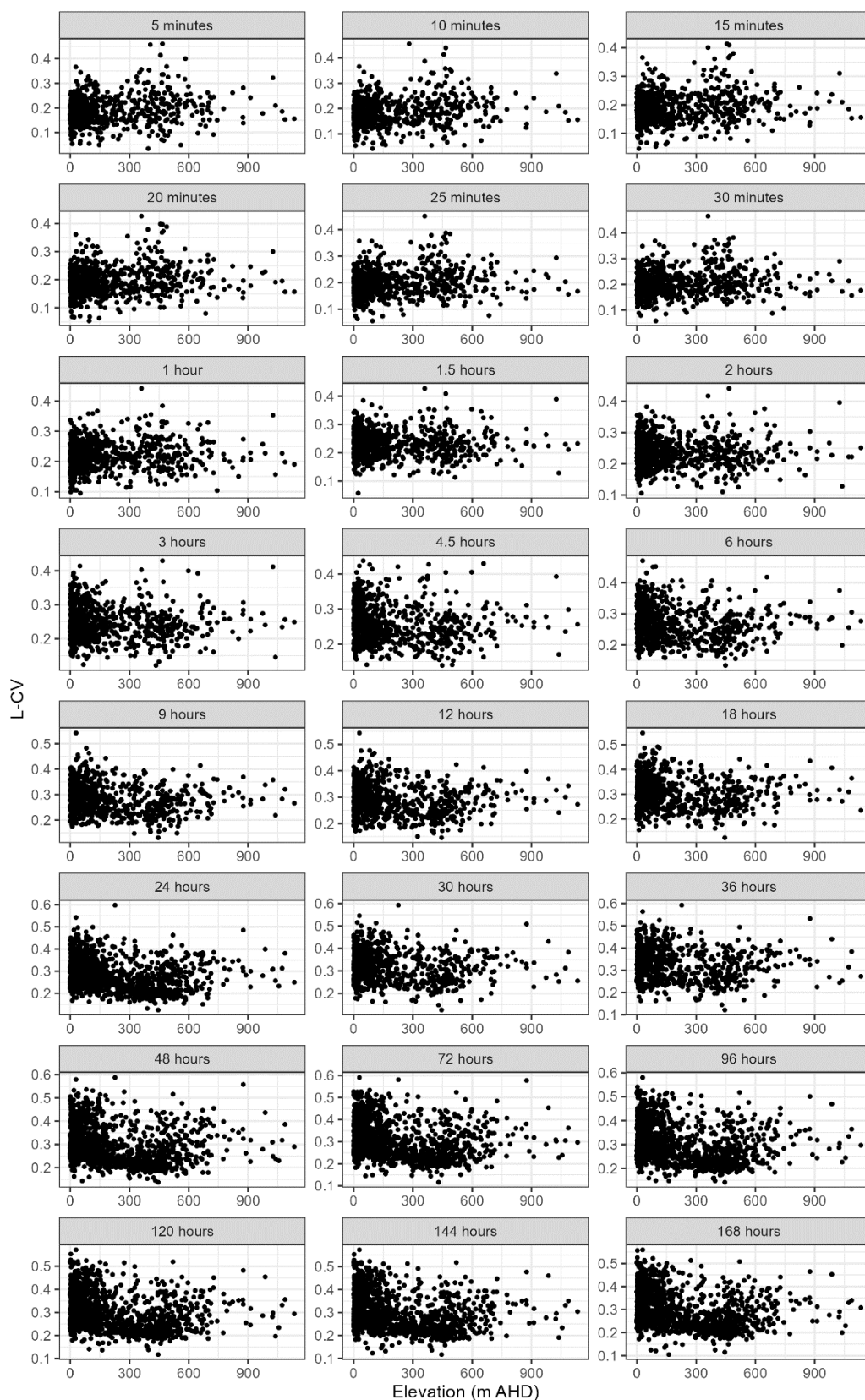


Figure A 5 Variation of L-CV with elevation

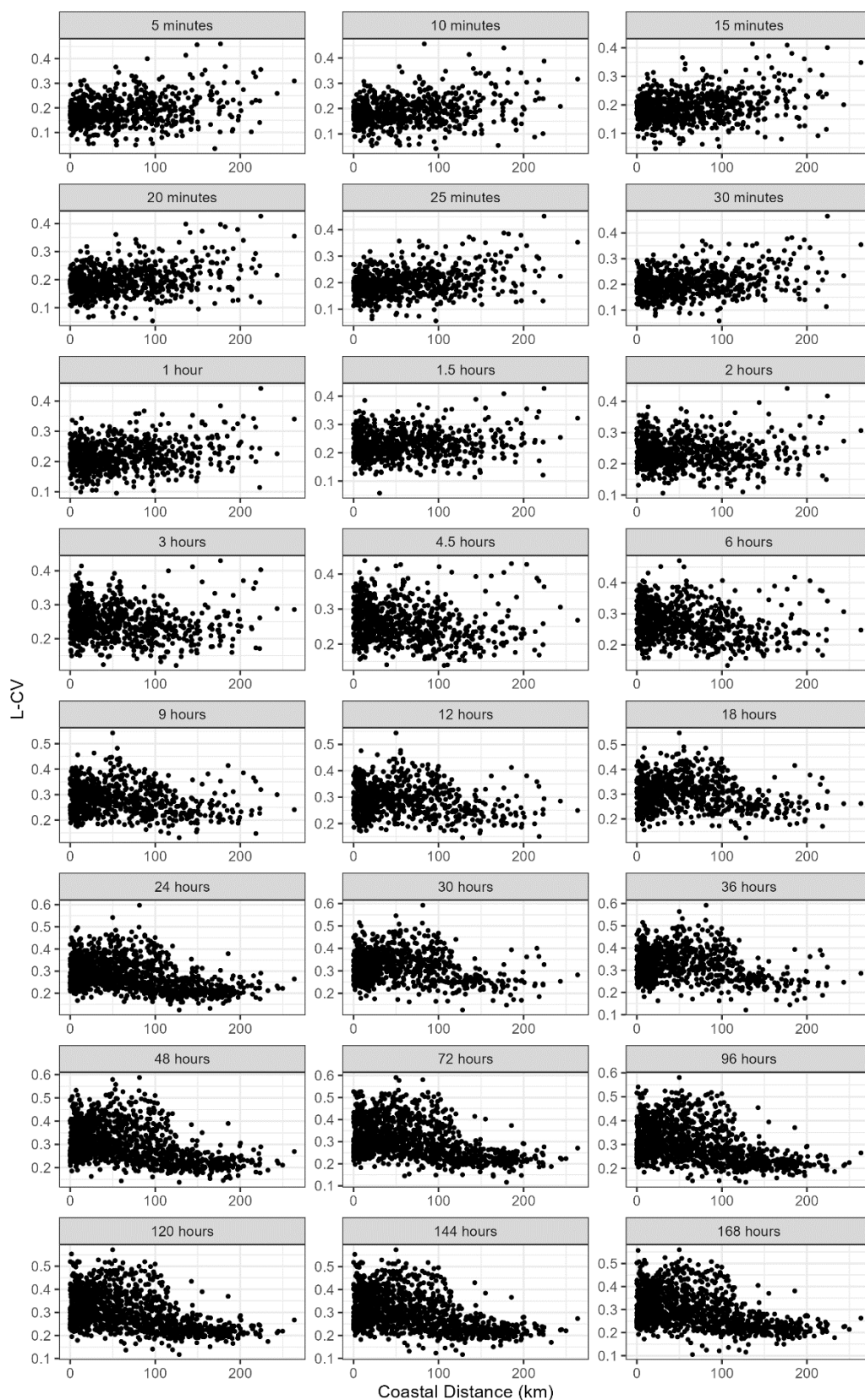


Figure A 6 Variation of L-CV with coastal distance

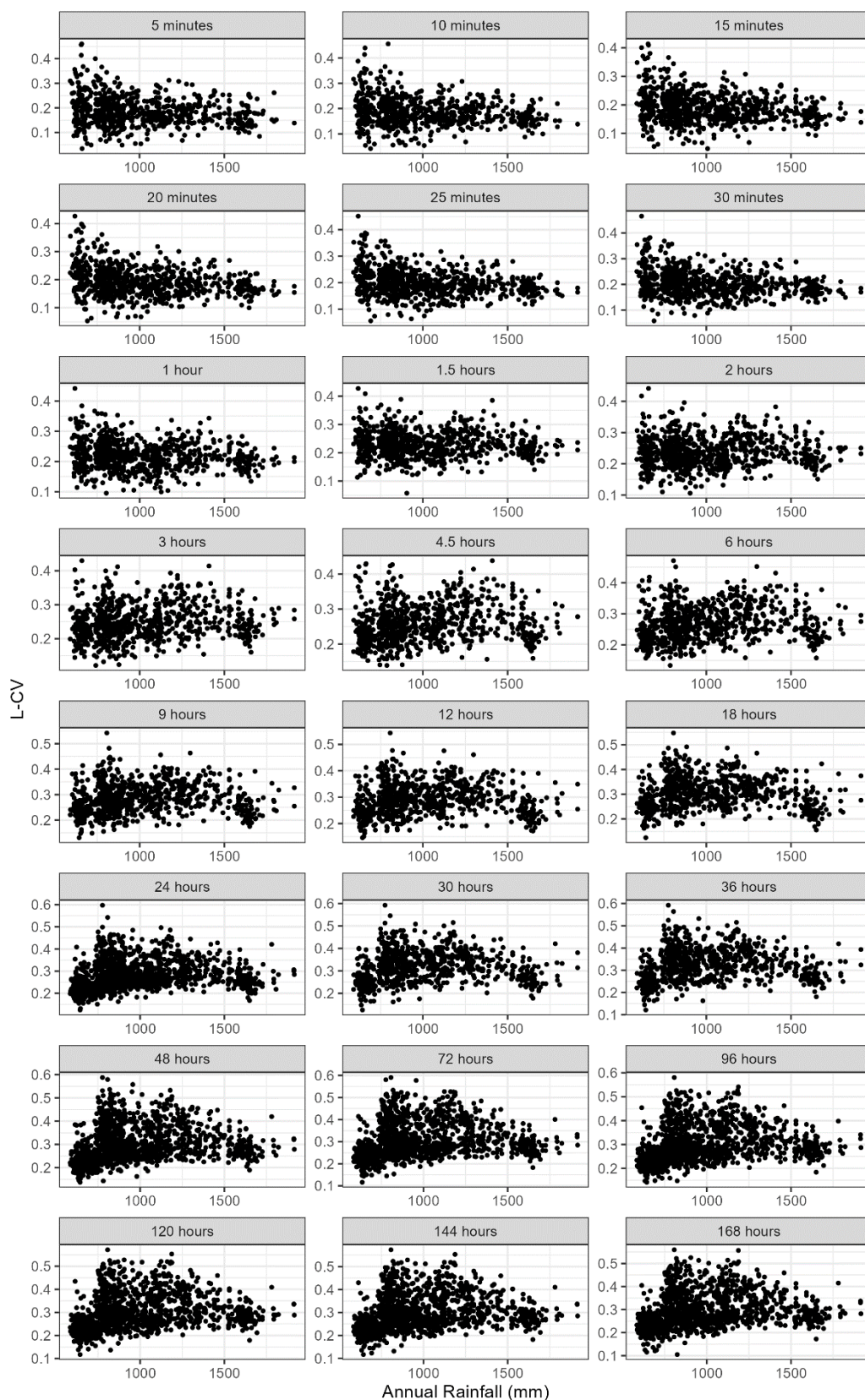


Figure A 7 Variation of L-CV with mean annual rainfalls

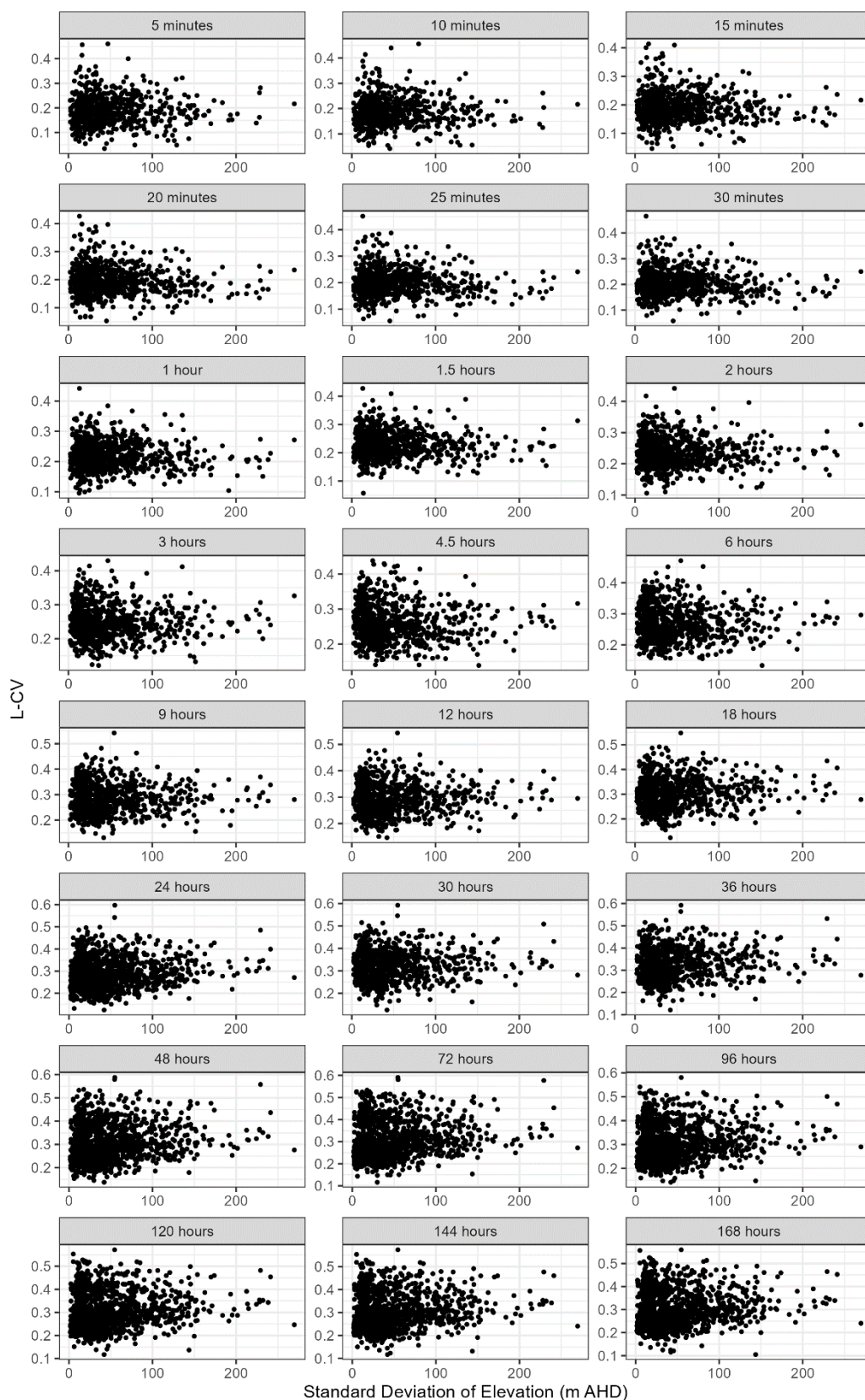


Figure A 8 Variation of L-CV with standard deviation of elevation

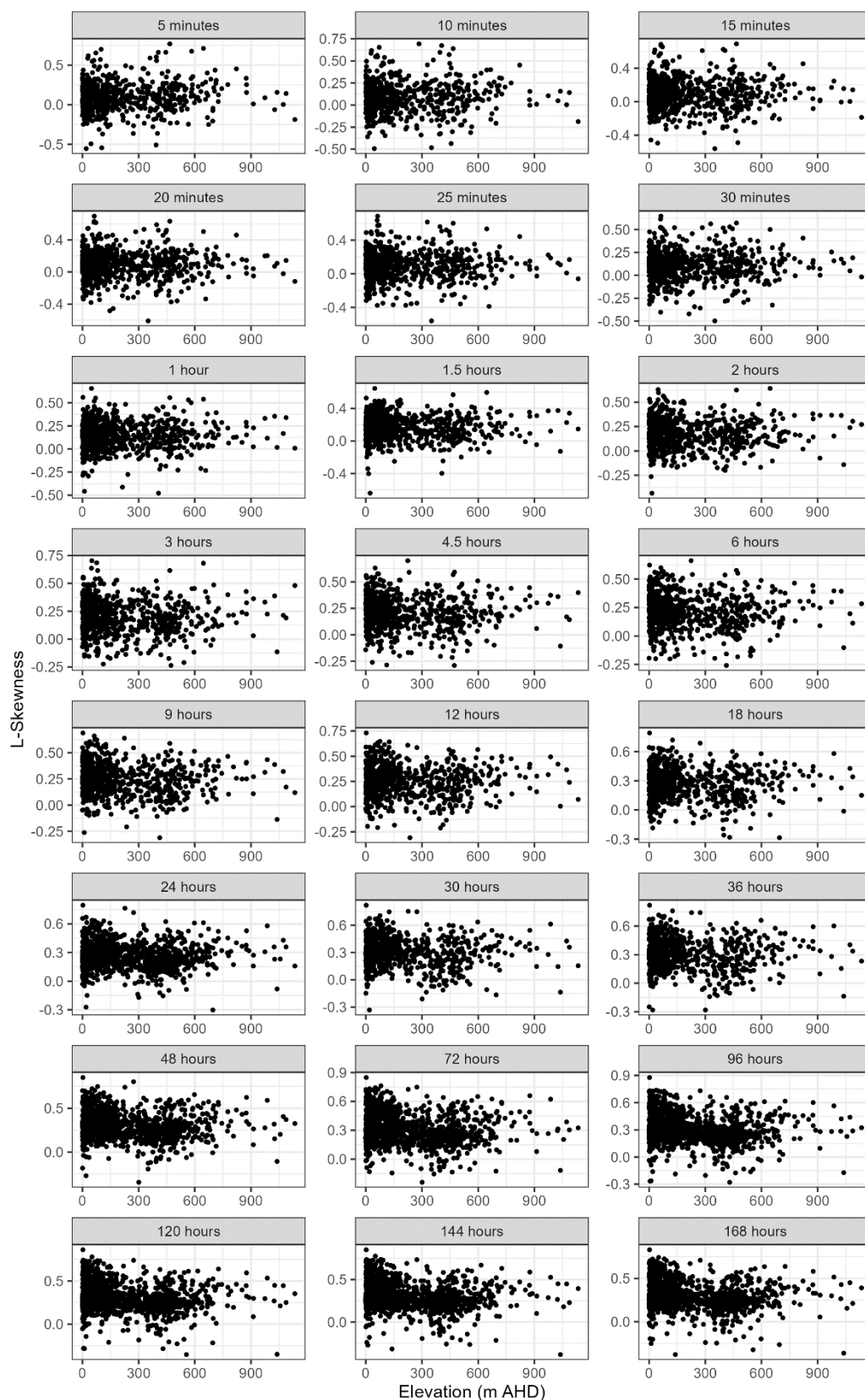


Figure A 9 Variation of L-Skew with elevation

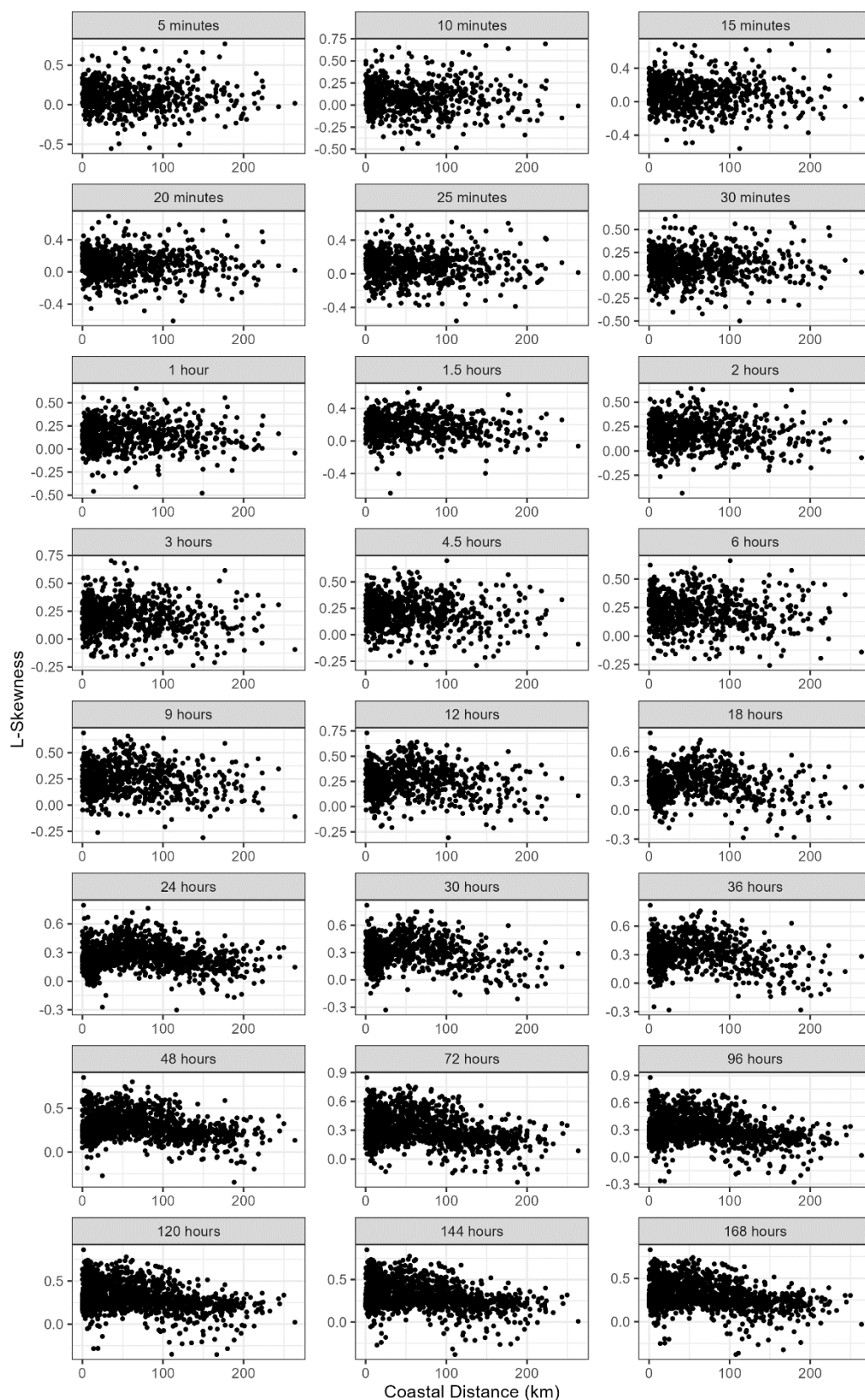


Figure A 10 Variation of L-Skew with coastal distance

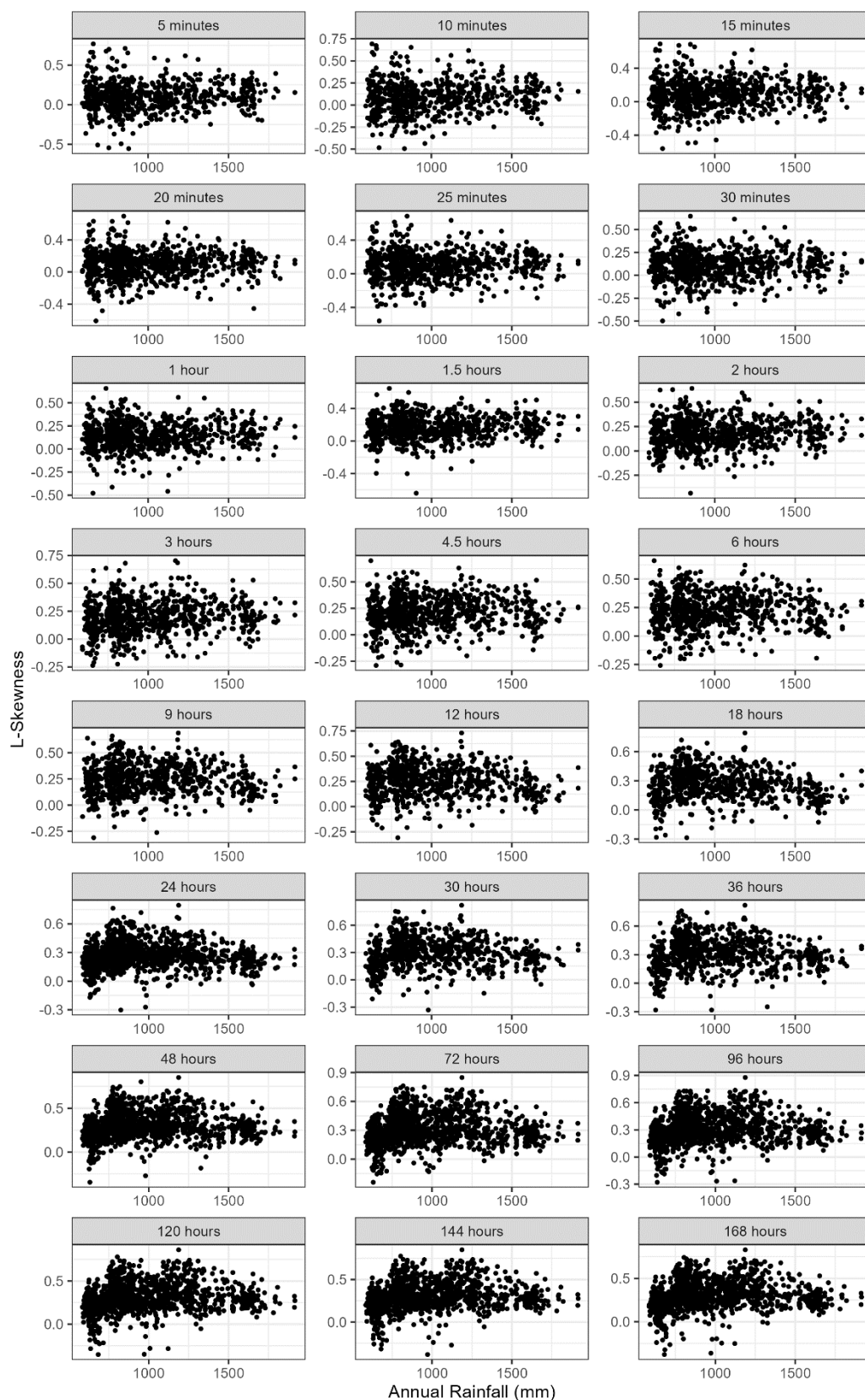


Figure A 11 Variation of L-Skew with mean annual rainfalls

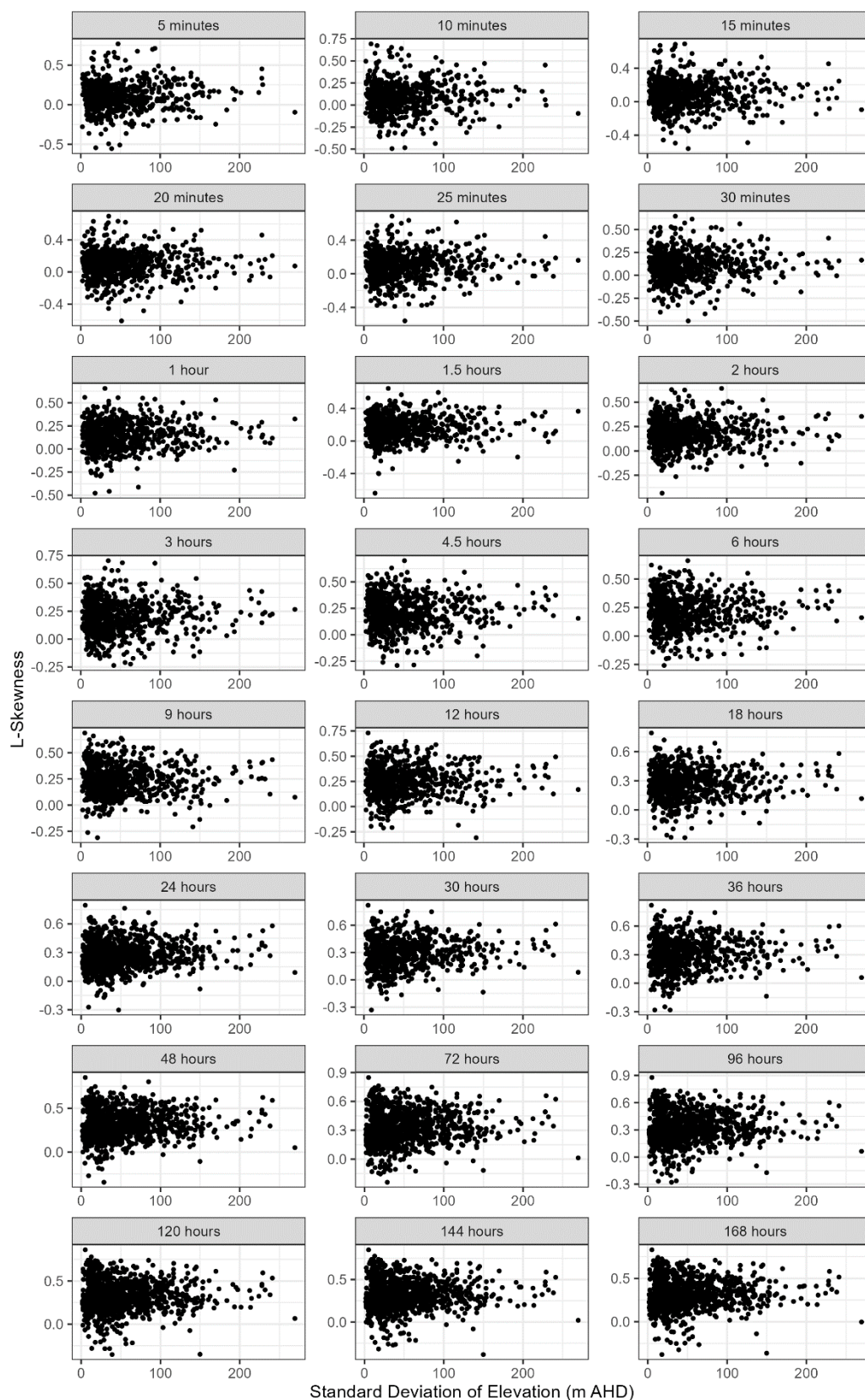


Figure A 12 Variation of L-Skew with standard deviation of elevation

Appendix B L1 (Index Rainfalls)

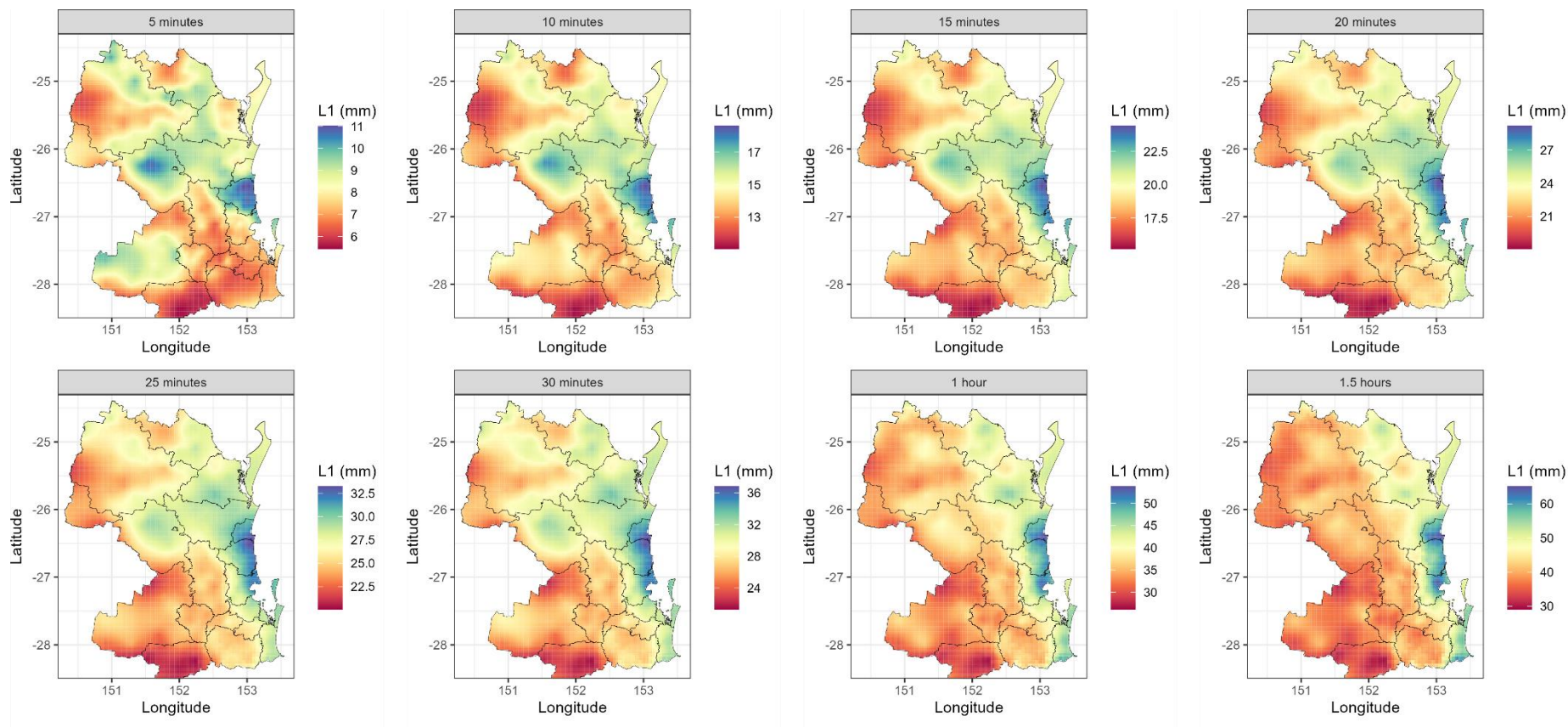


Figure B 1 Gridded L1 (Index Rainfall) for durations 5 minutes to 1.5 hours

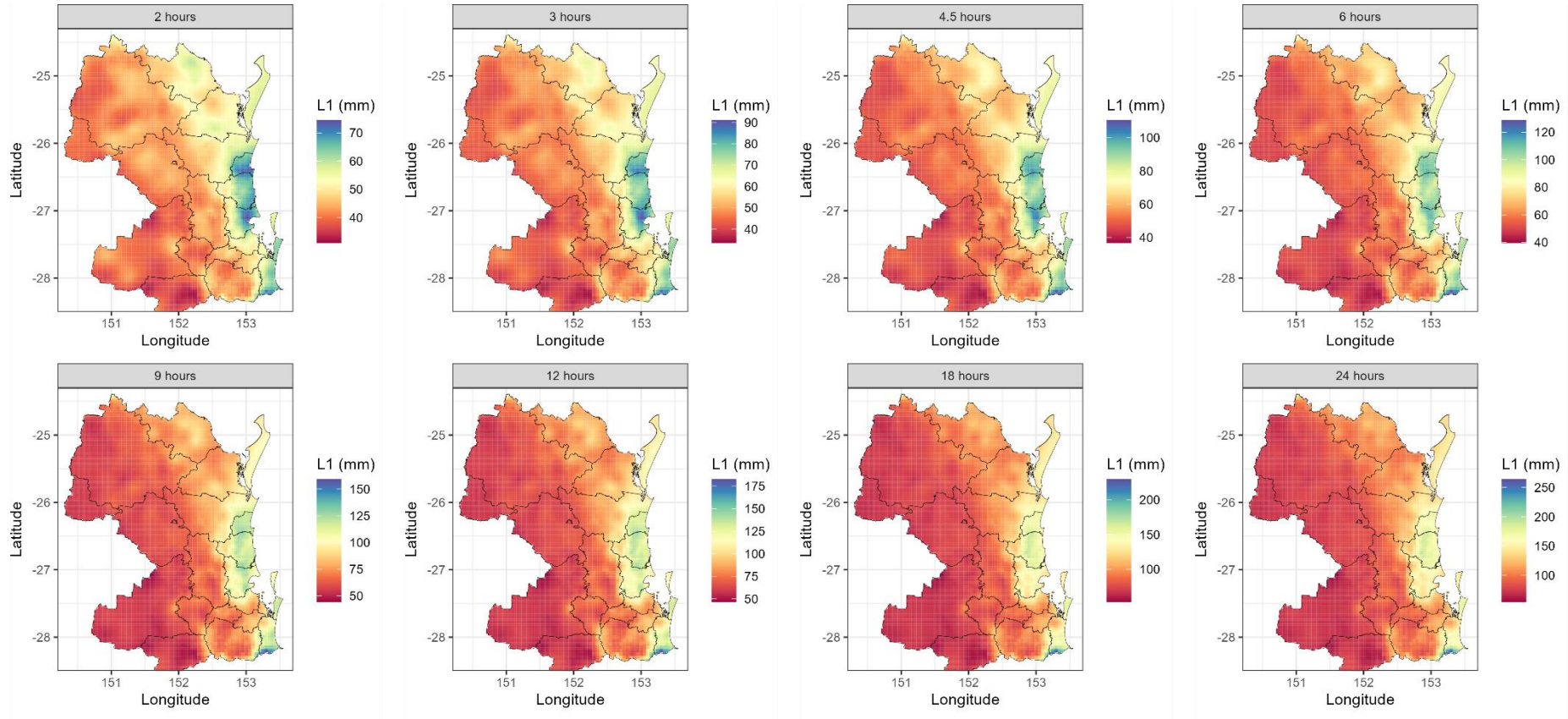


Figure B 2 Gridded L1 (Index Rainfall) for durations 2 hours to 24 hours

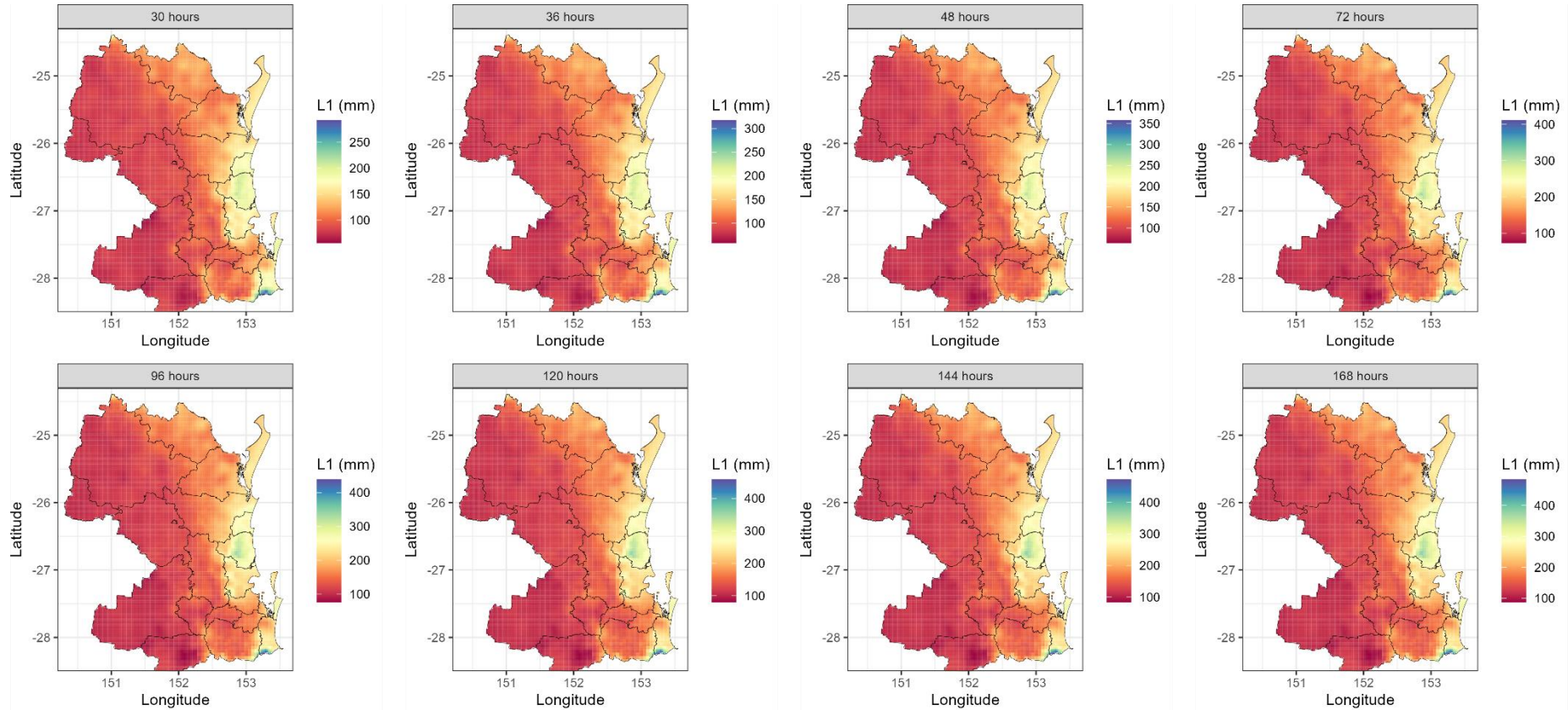


Figure B 3 Gridded L1 (Index Rainfall) for durations 30 hours to 168 hours

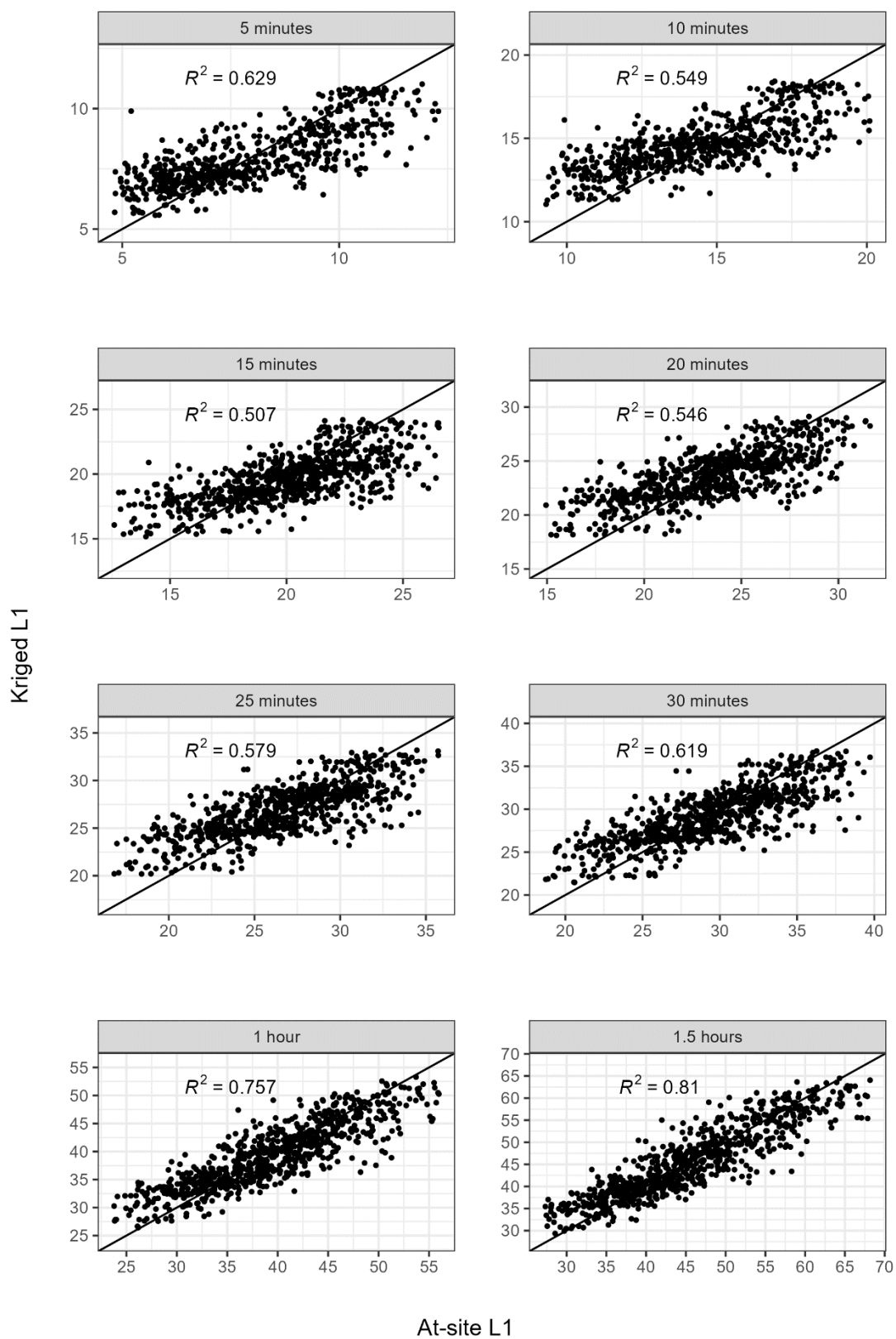


Figure B 4 Comparison of at-site and kriged L1 for durations 5 minutes to 1.5 hours

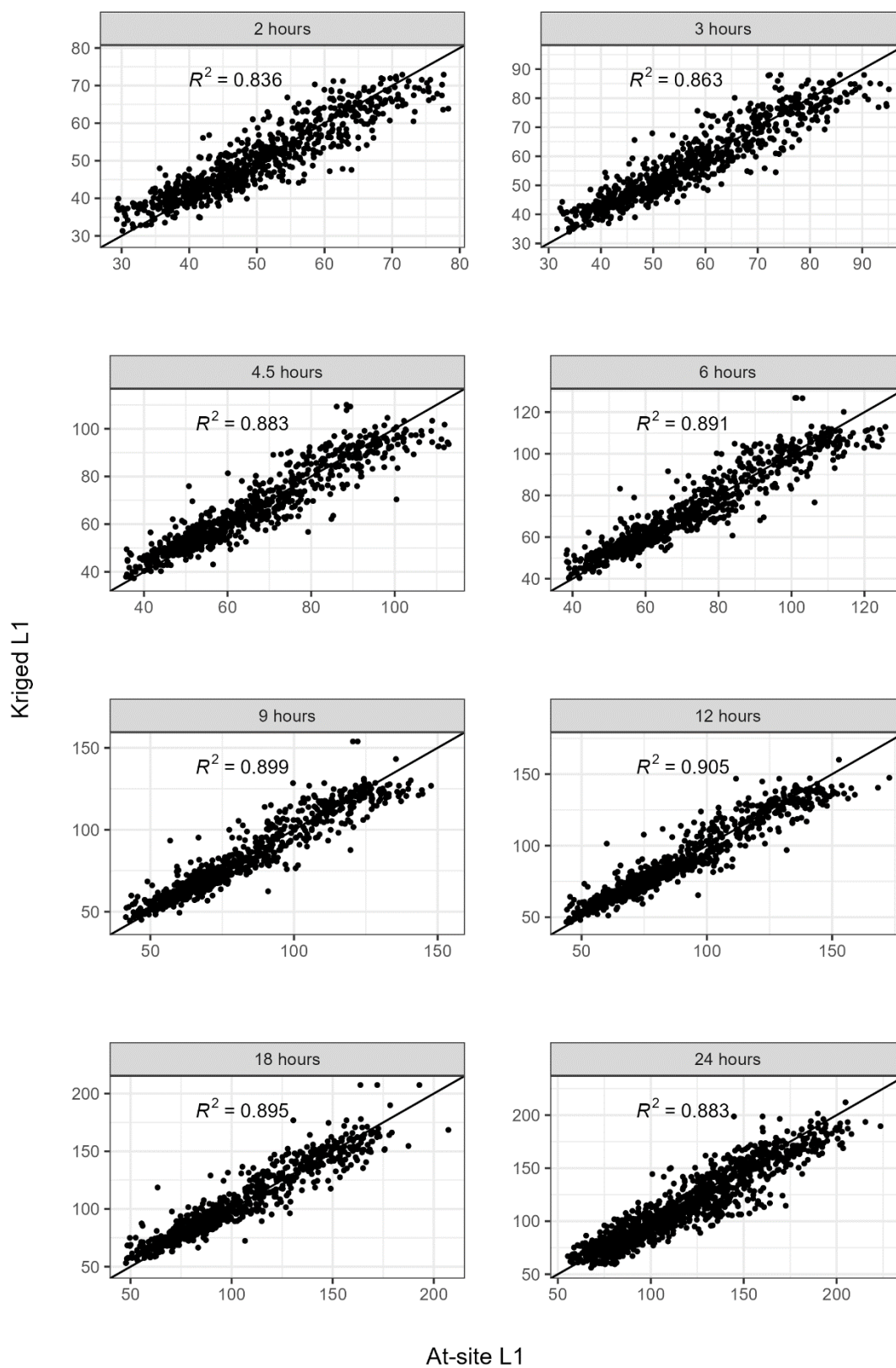


Figure B 5 Comparison of at-site and kriged L1 for durations 2 hours to 24 hours

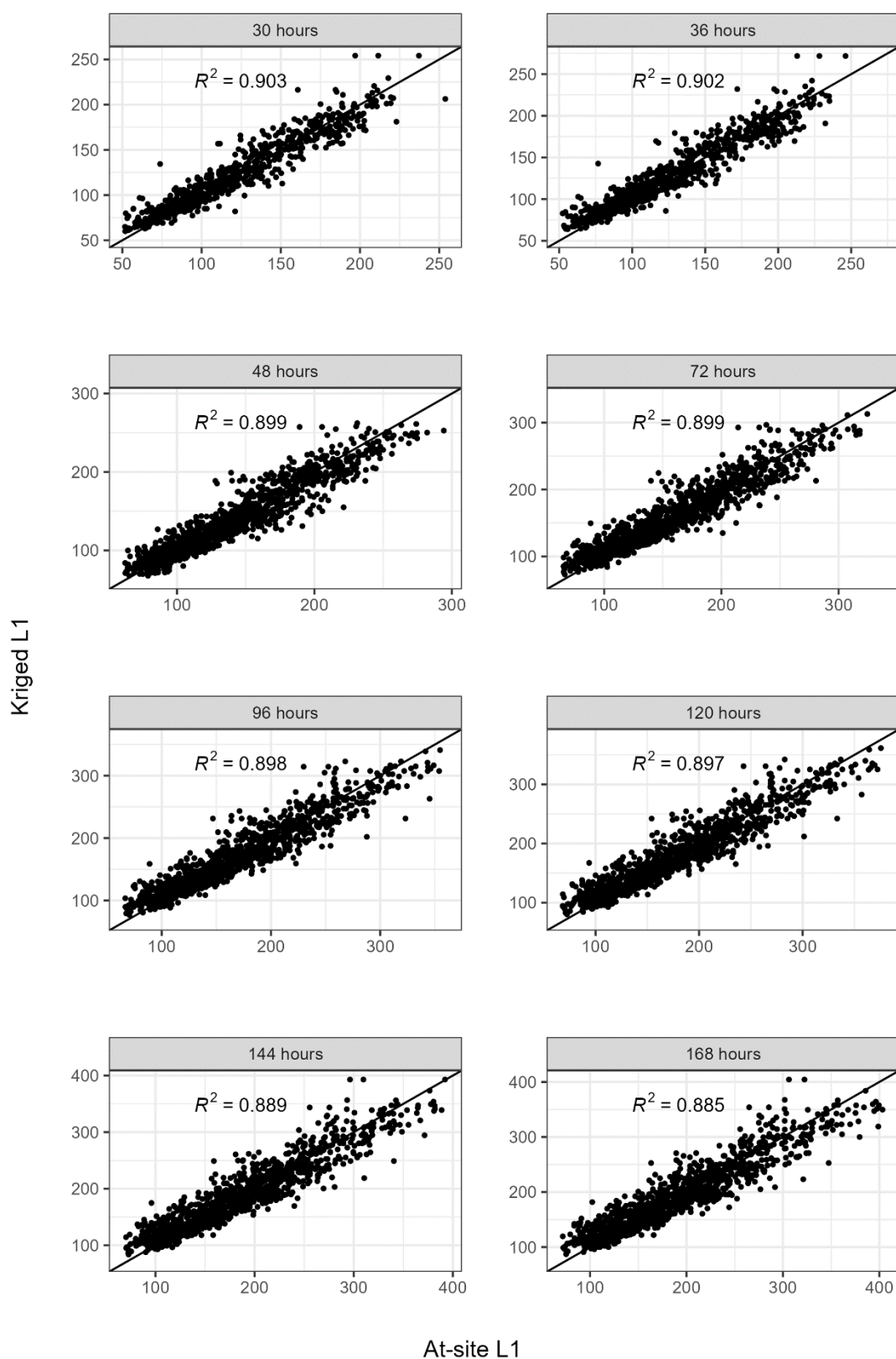
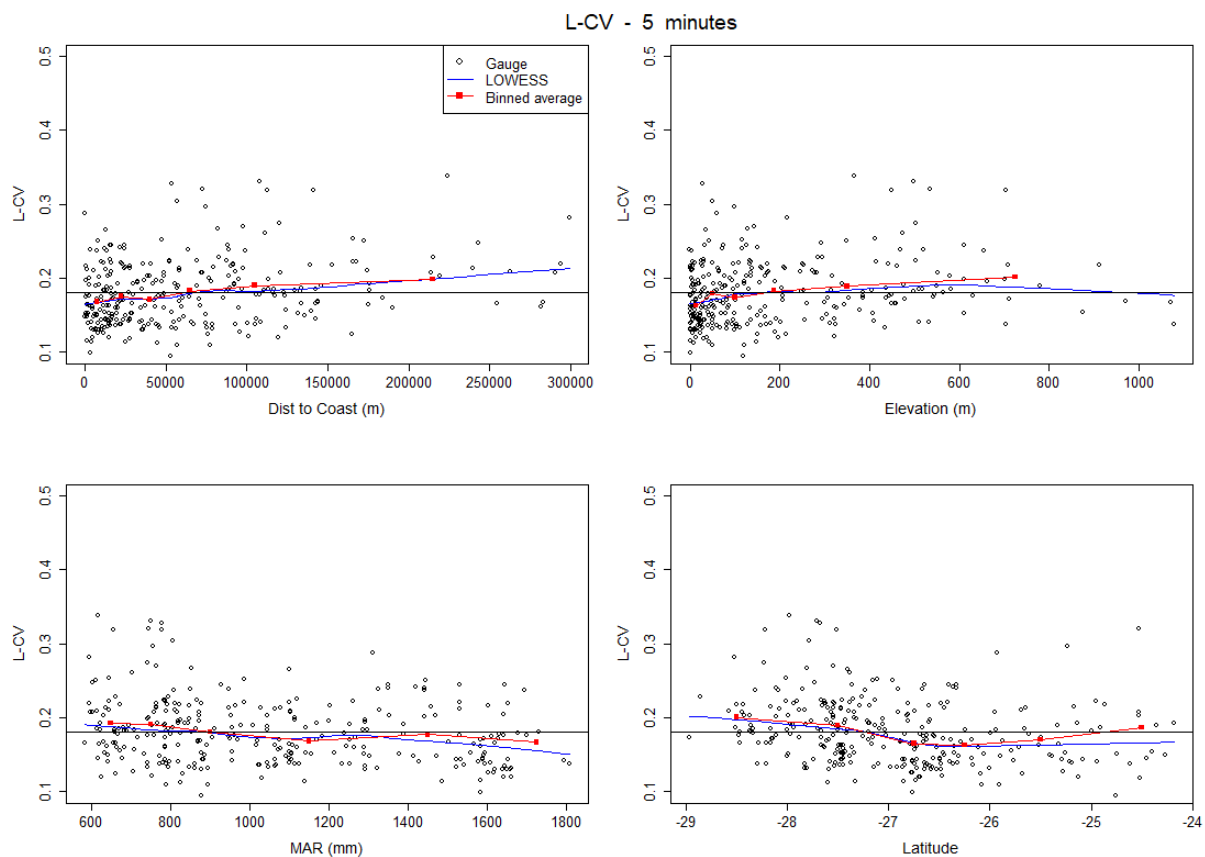
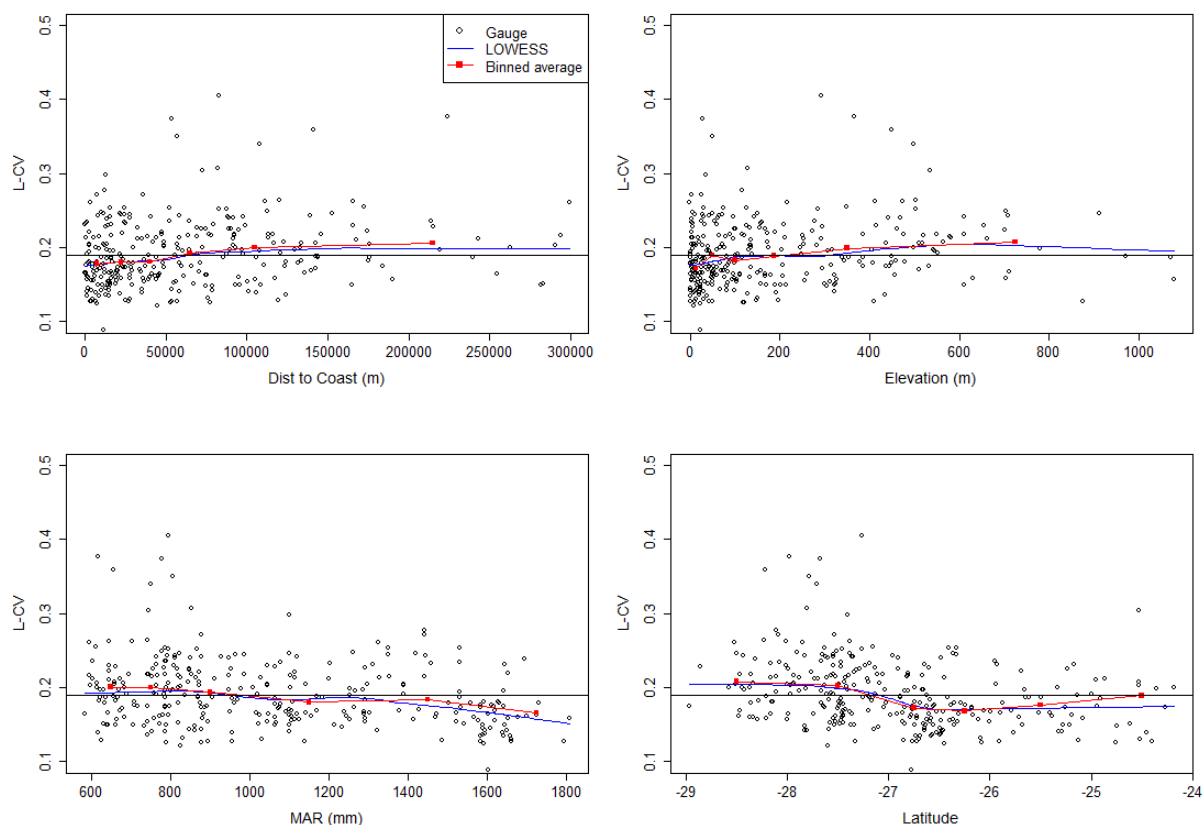


Figure B 6 Comparison of at-site and kriged L1 for durations 30 minutes to 168 hours

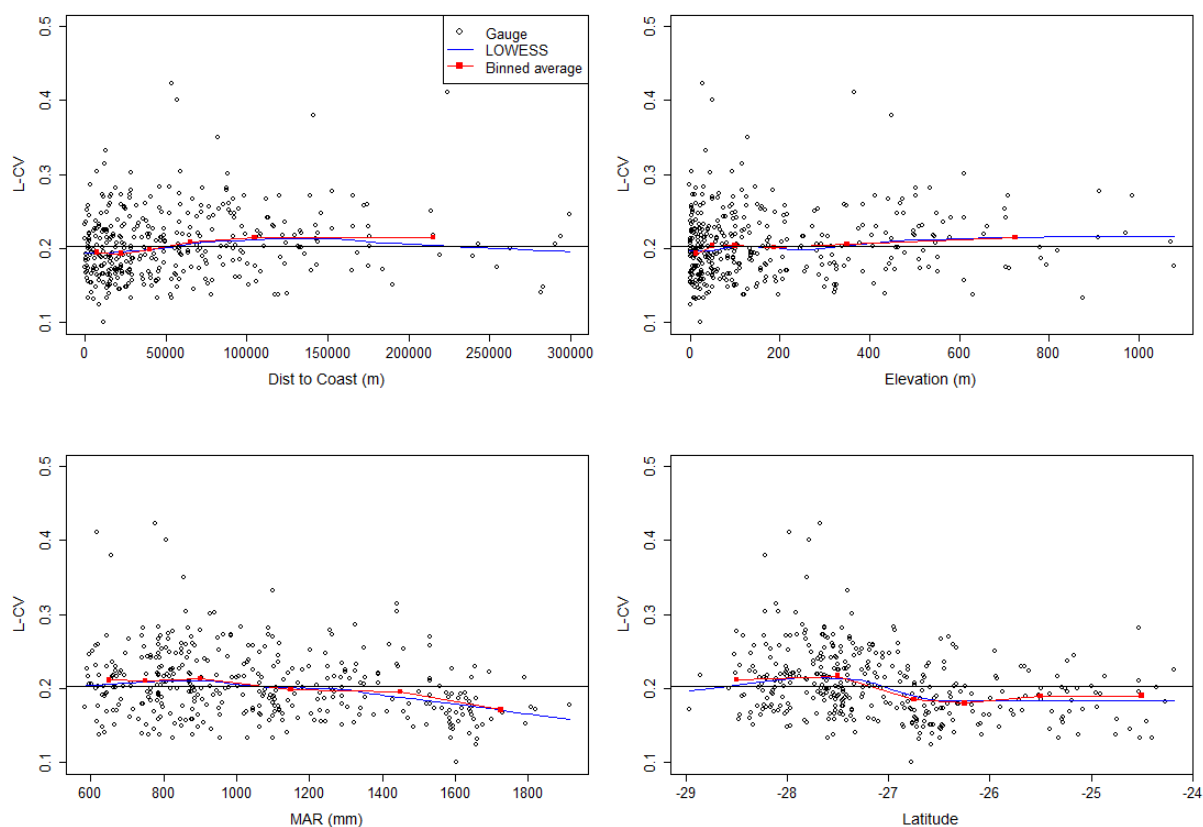
Appendix C L-CV and L-skewness vs physical attributes



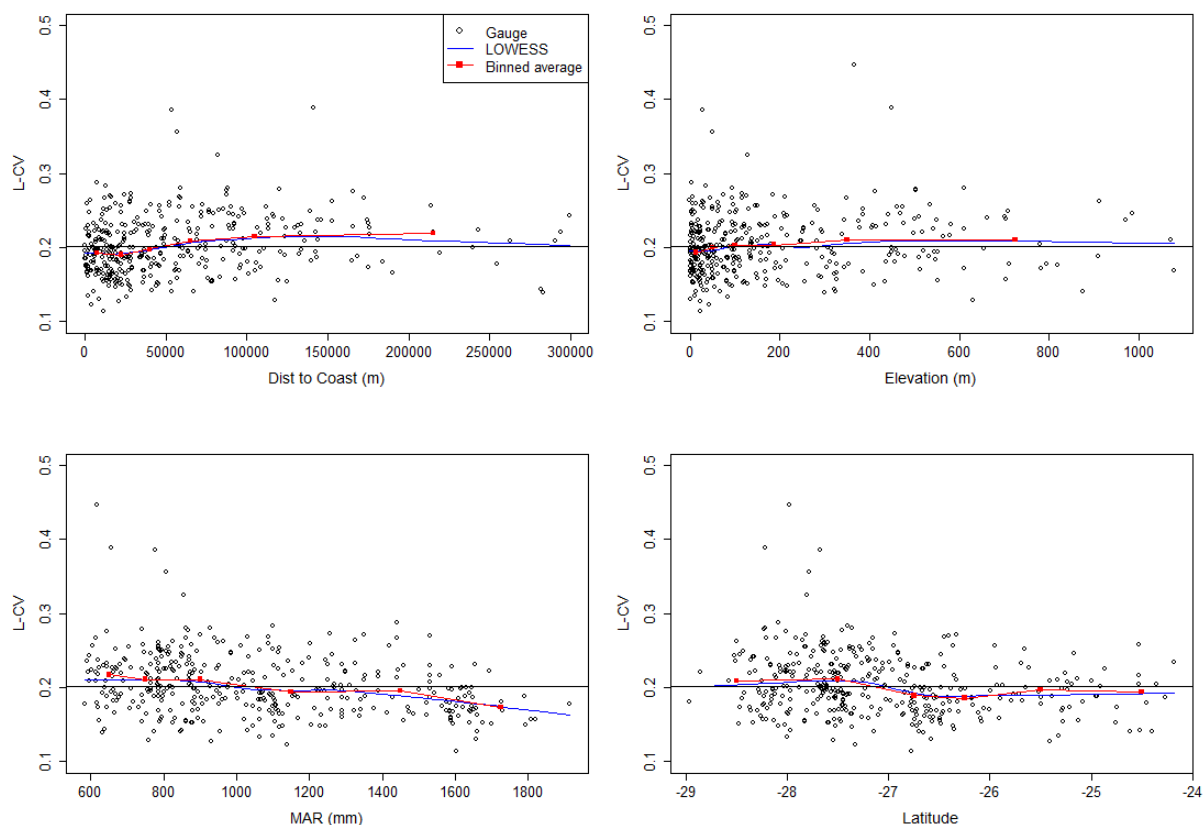
L-CV - 10 minutes



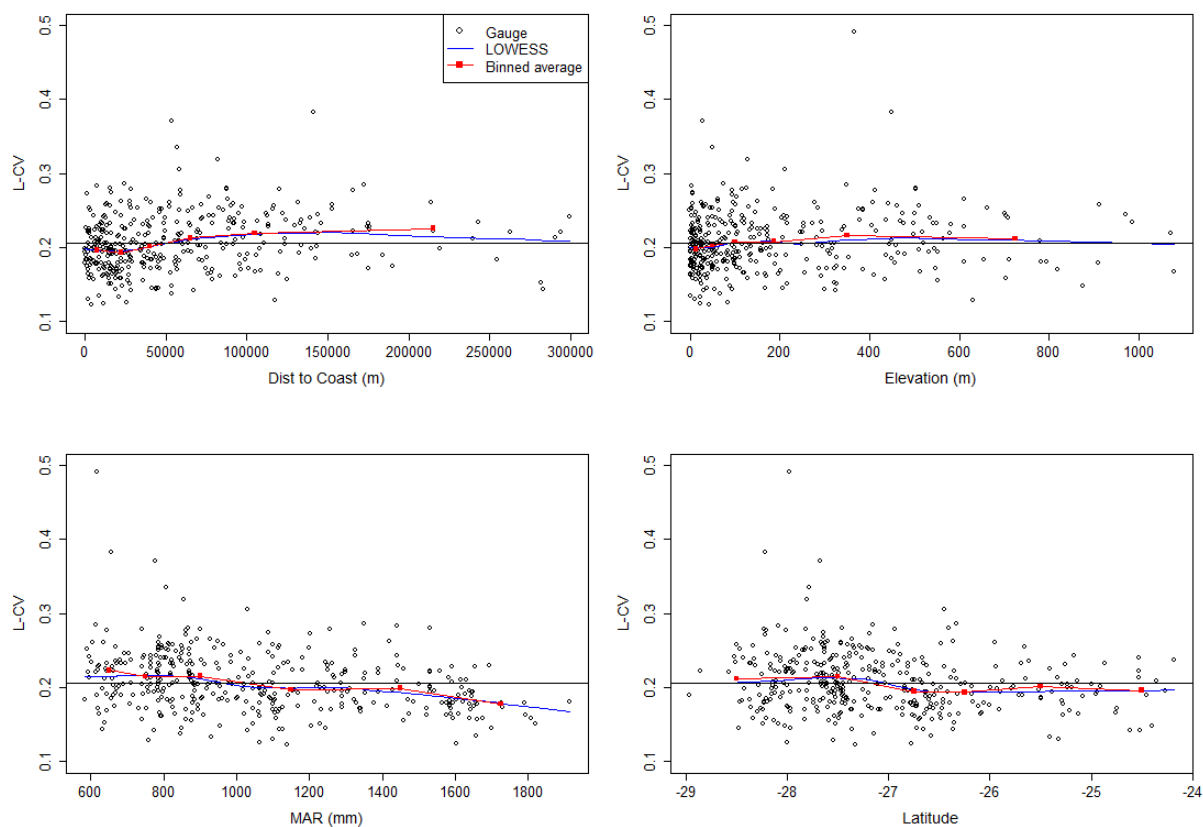
L-CV - 15 minutes



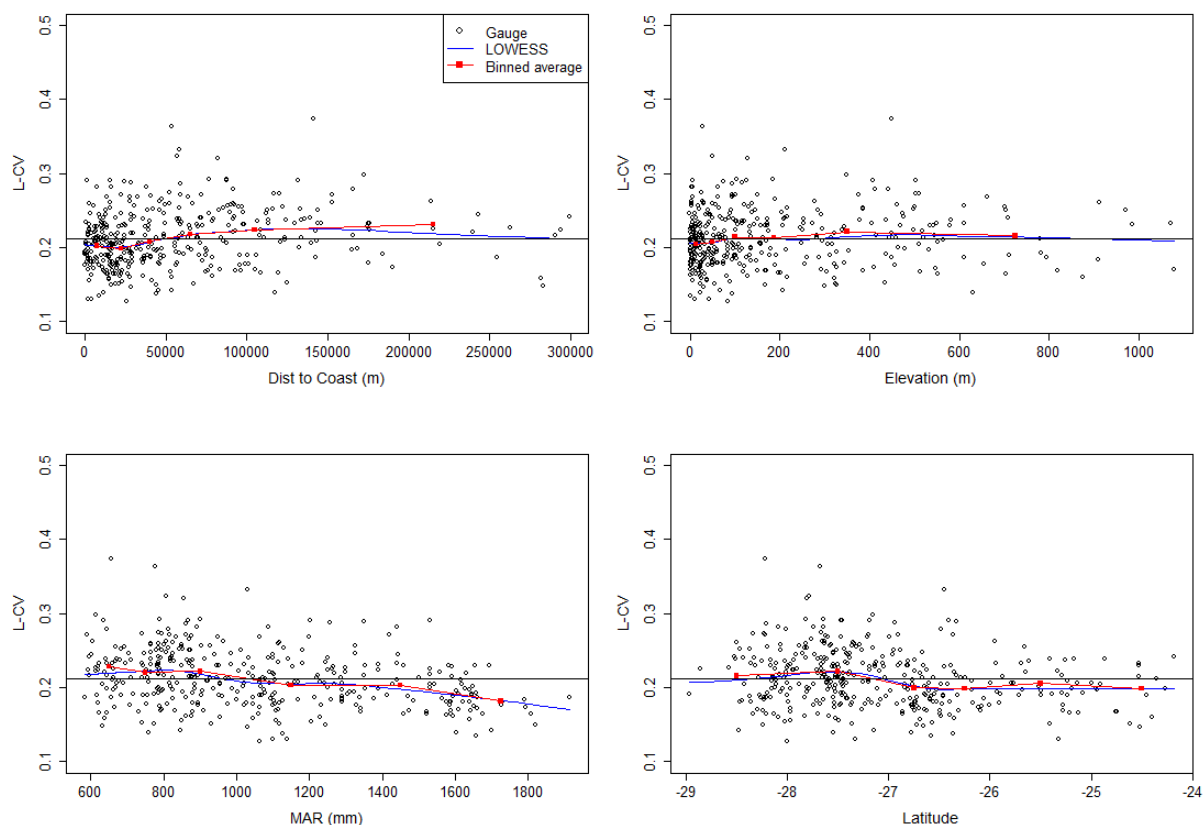
L-CV - 20 minutes



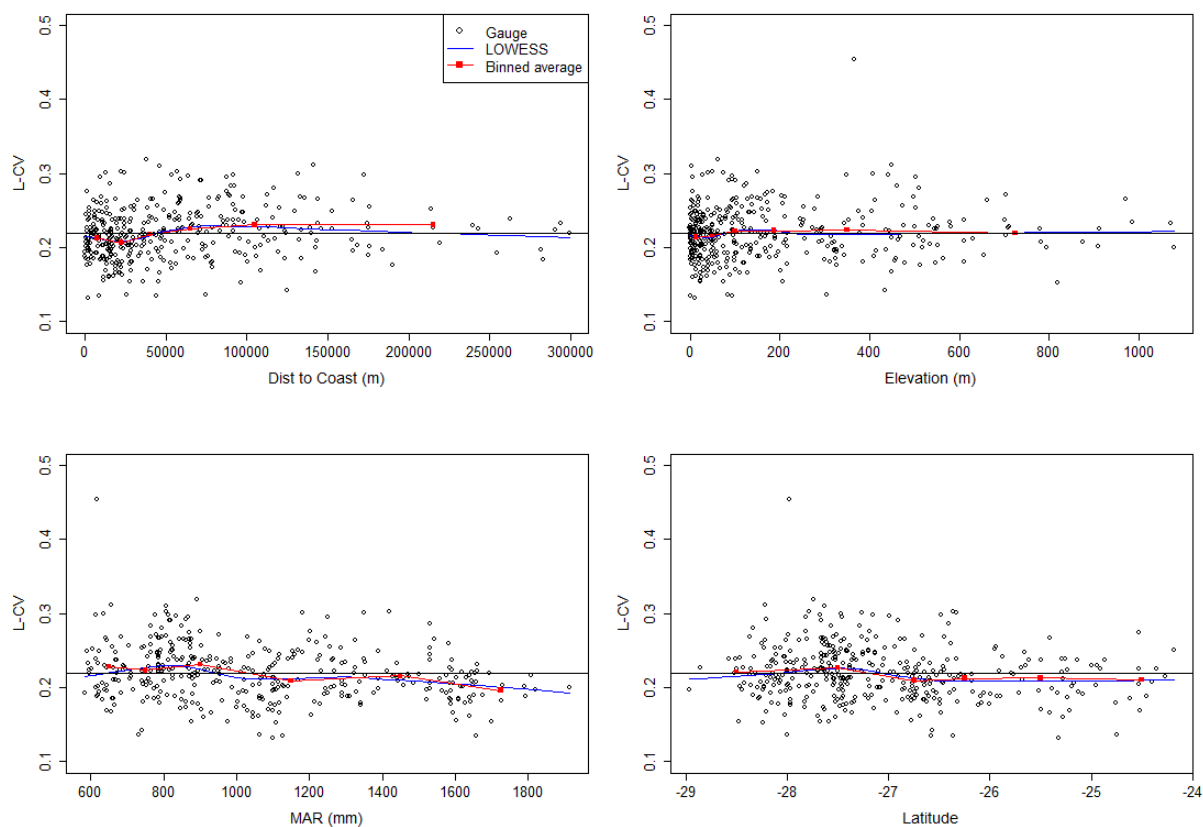
L-CV - 25 minutes



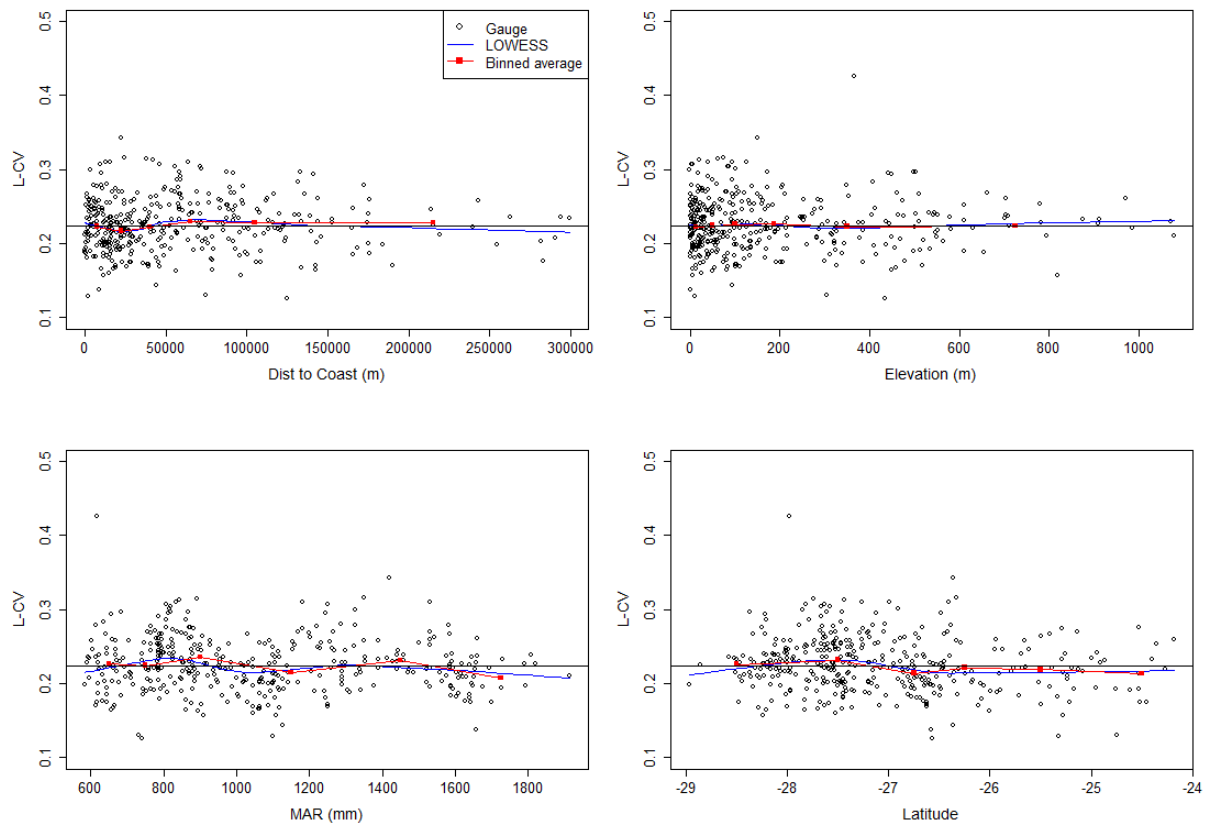
L-CV - 30 minutes



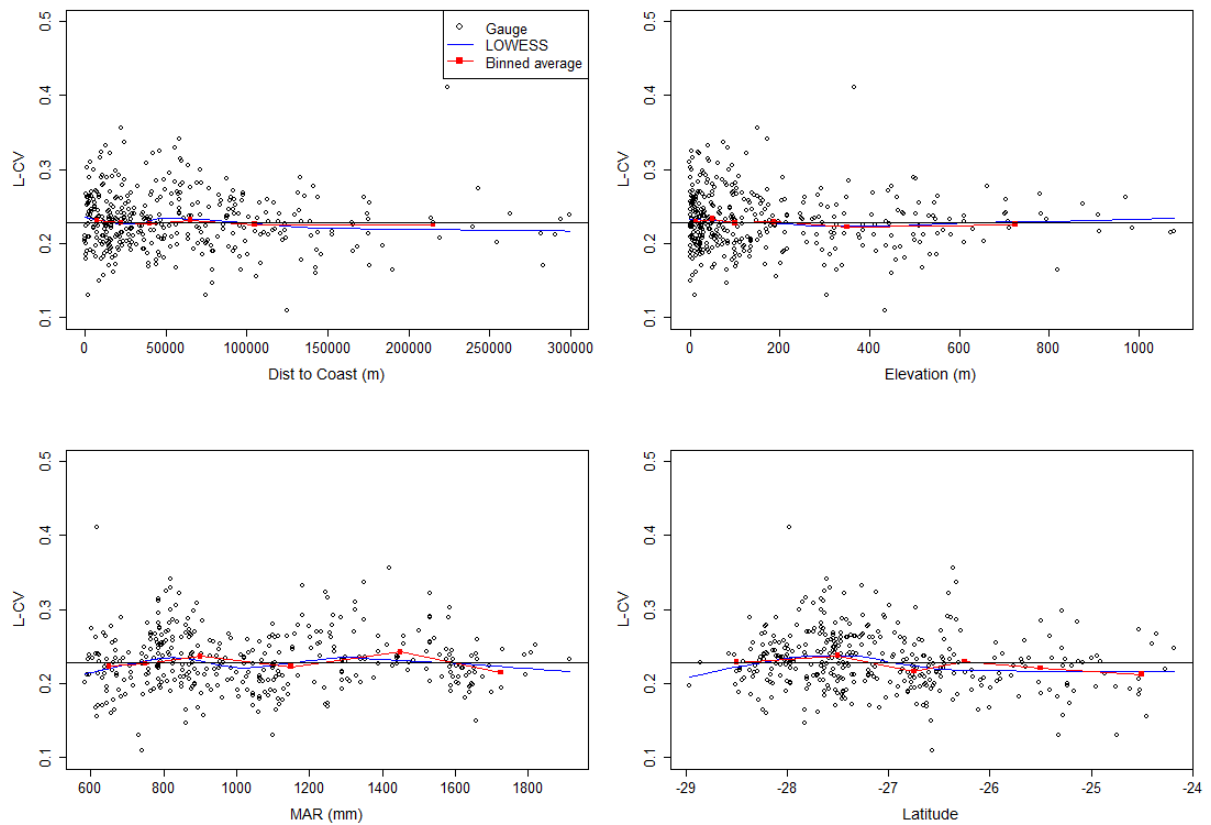
L-CV - 60 minutes



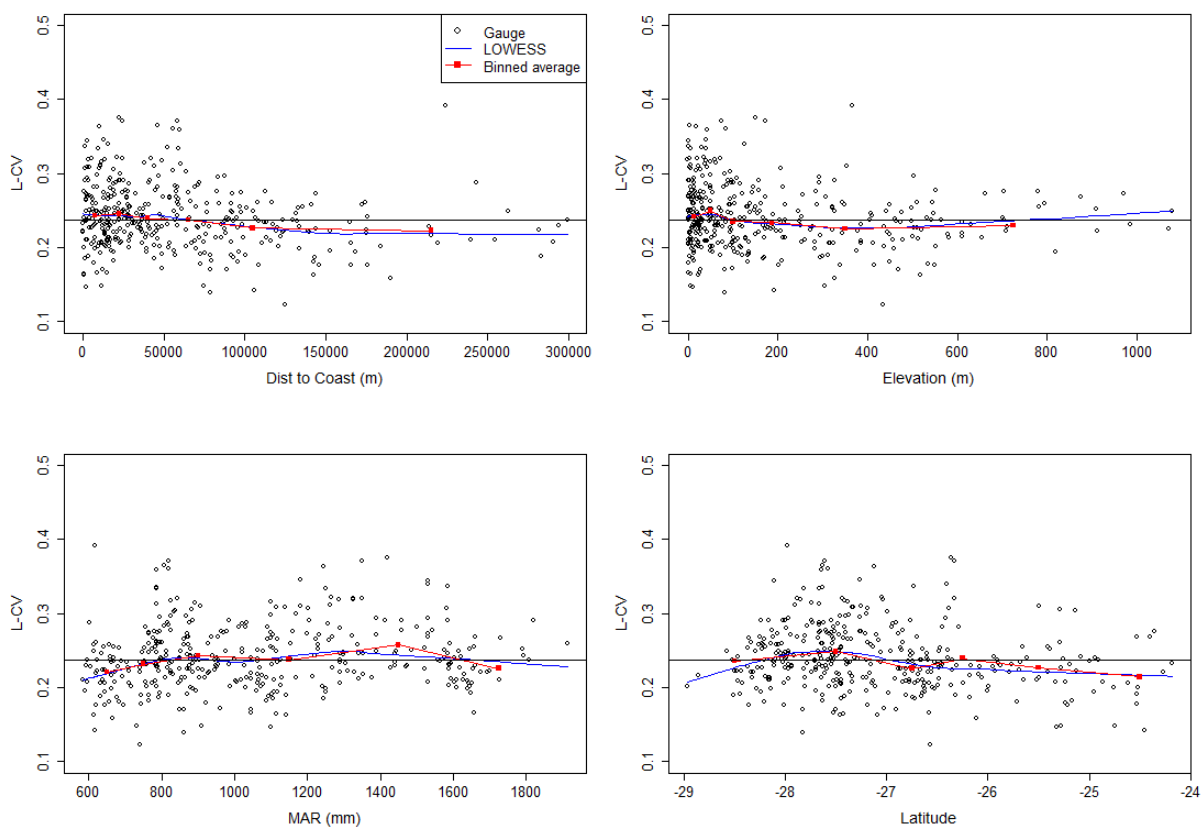
L-CV - 90 minutes



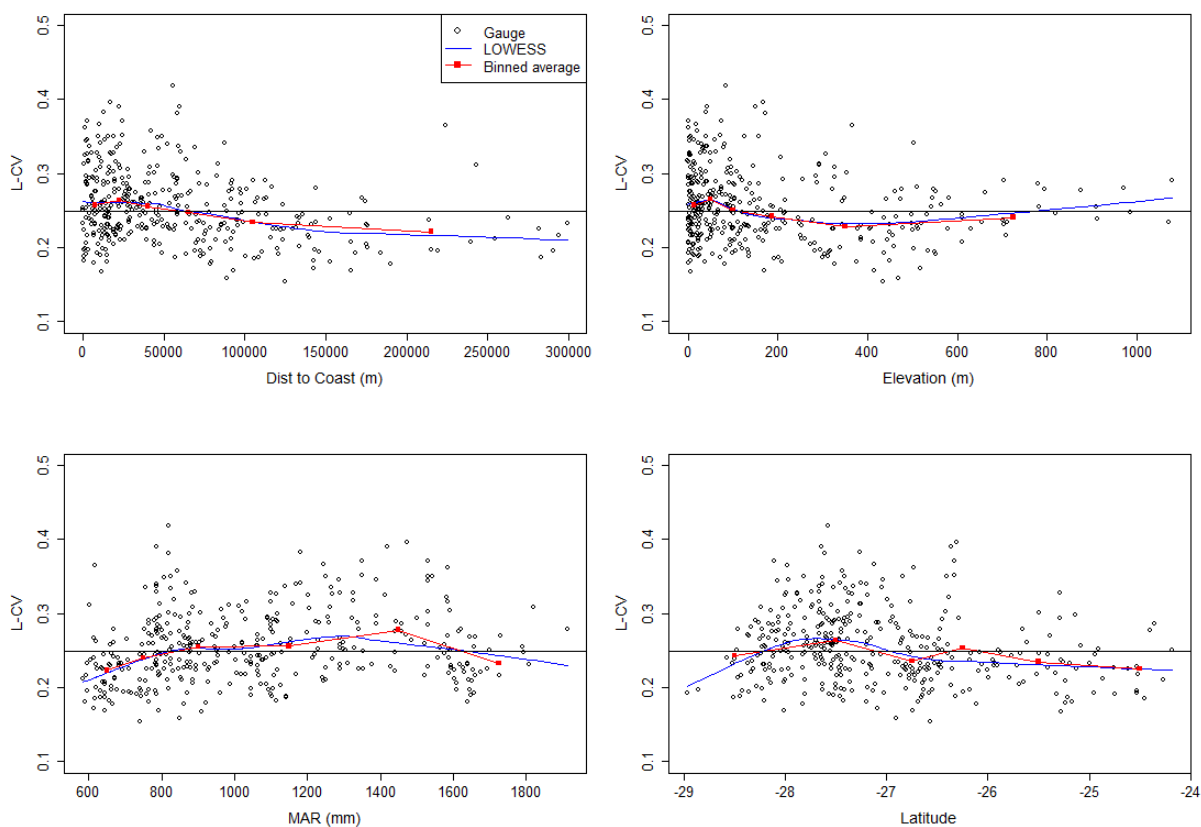
L-CV - 120 minutes



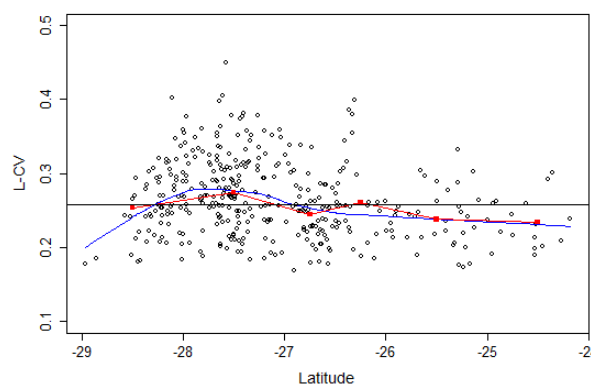
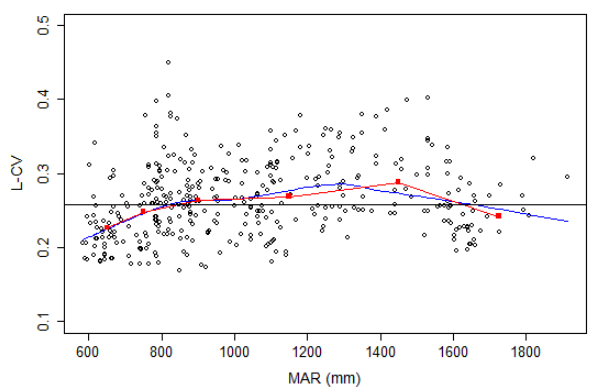
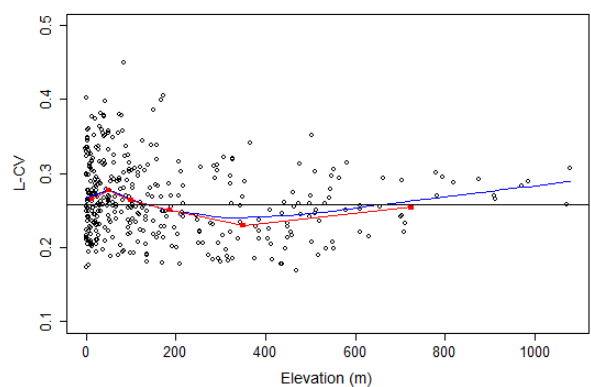
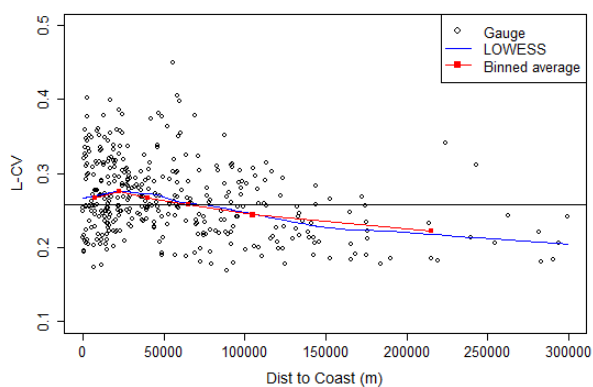
L-CV - 180 minutes



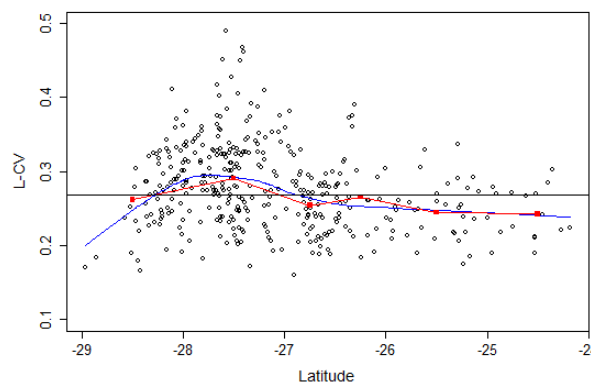
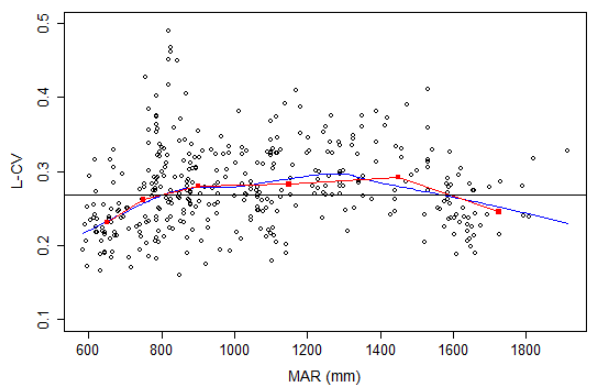
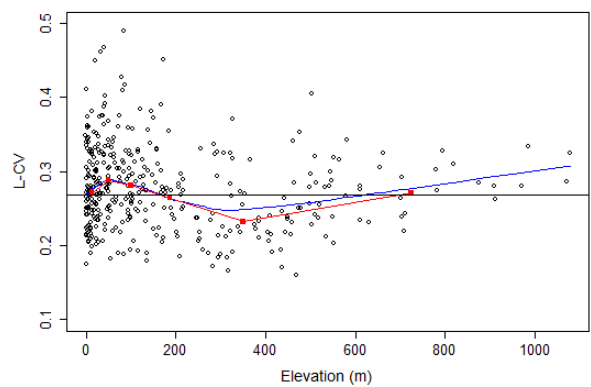
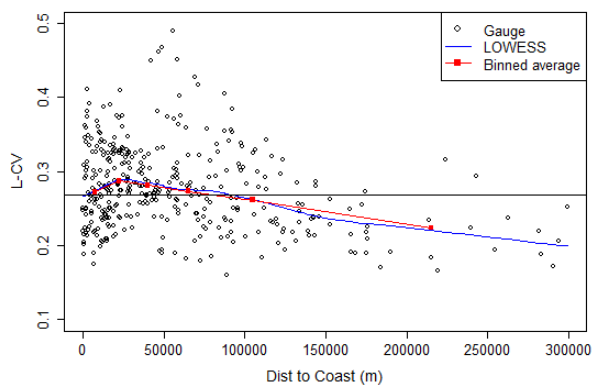
L-CV - 270 minutes



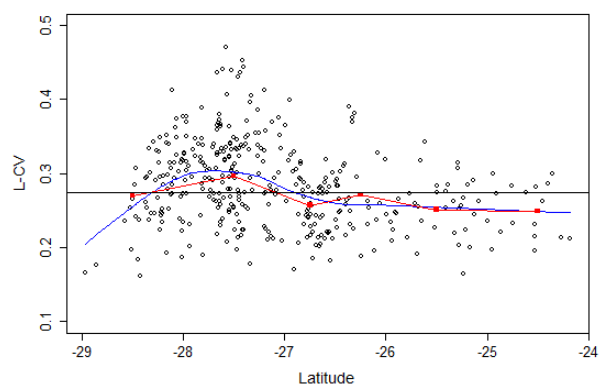
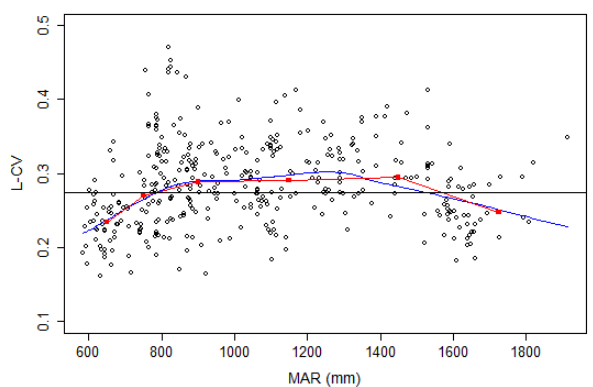
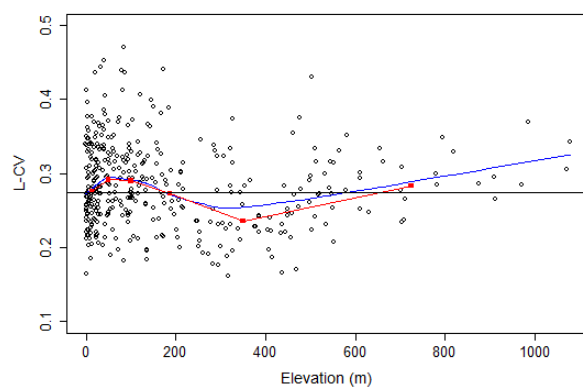
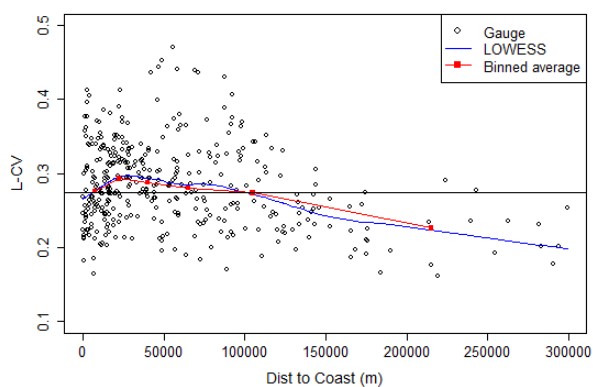
L-CV - 360 minutes



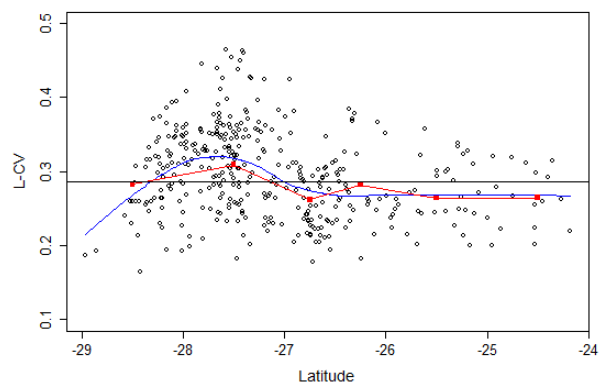
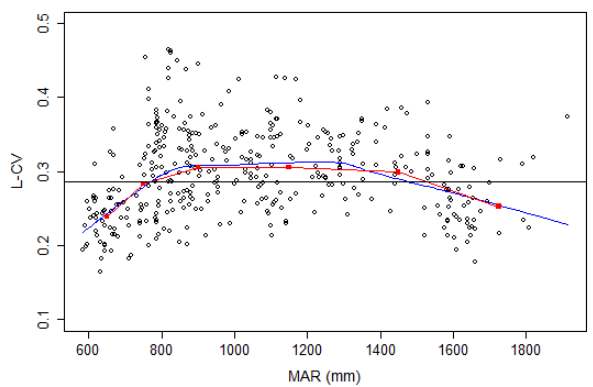
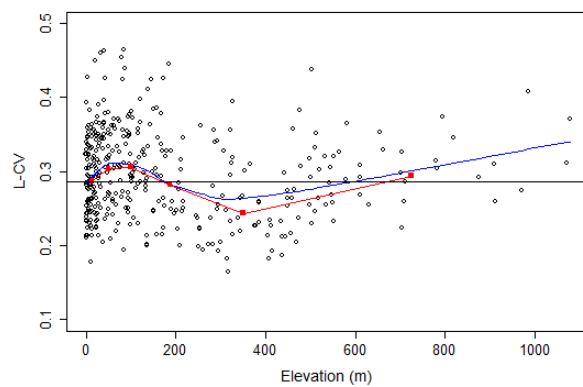
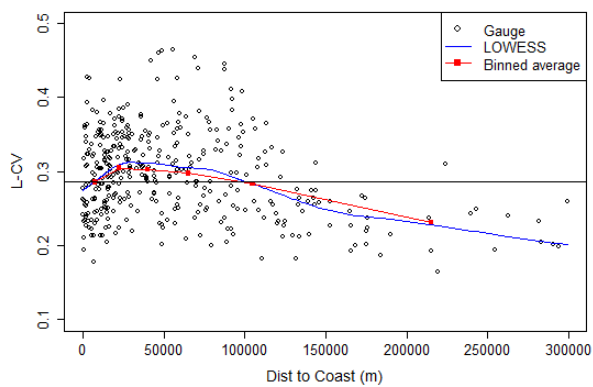
L-CV - 540 minutes



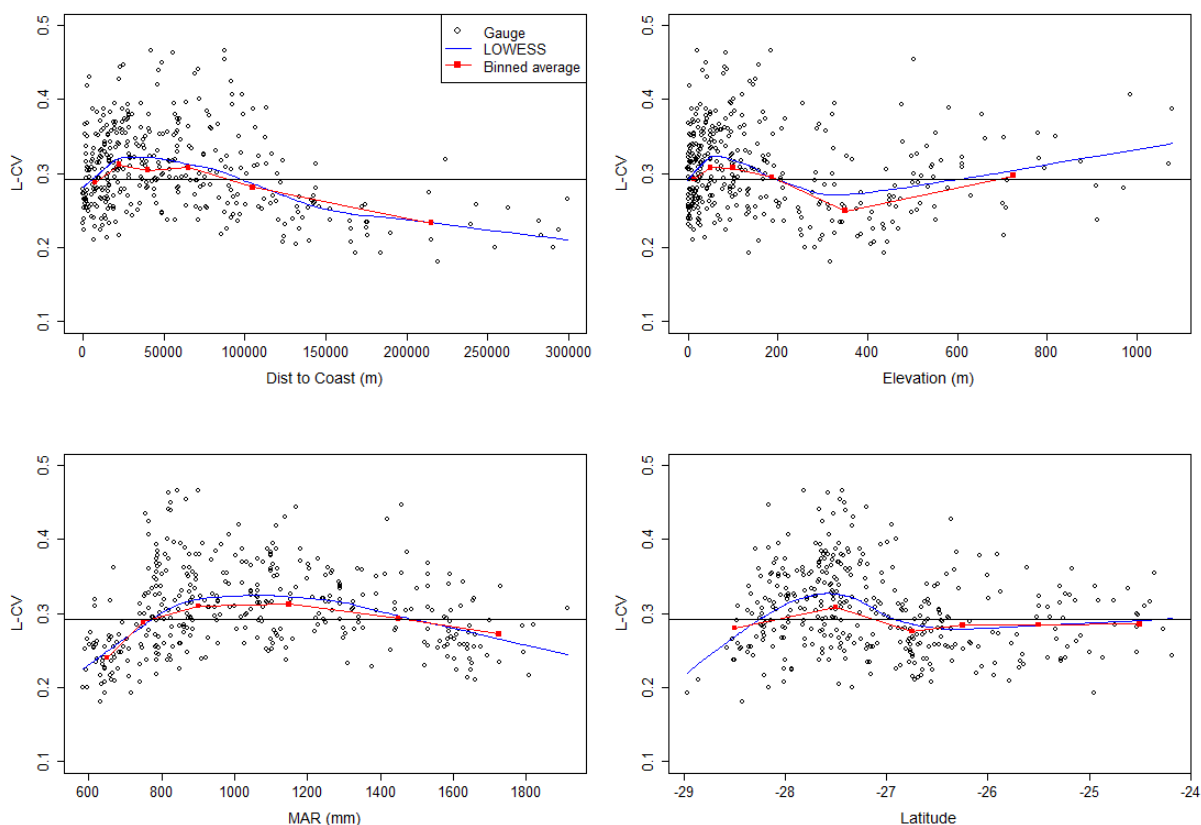
L-CV - 720 minutes



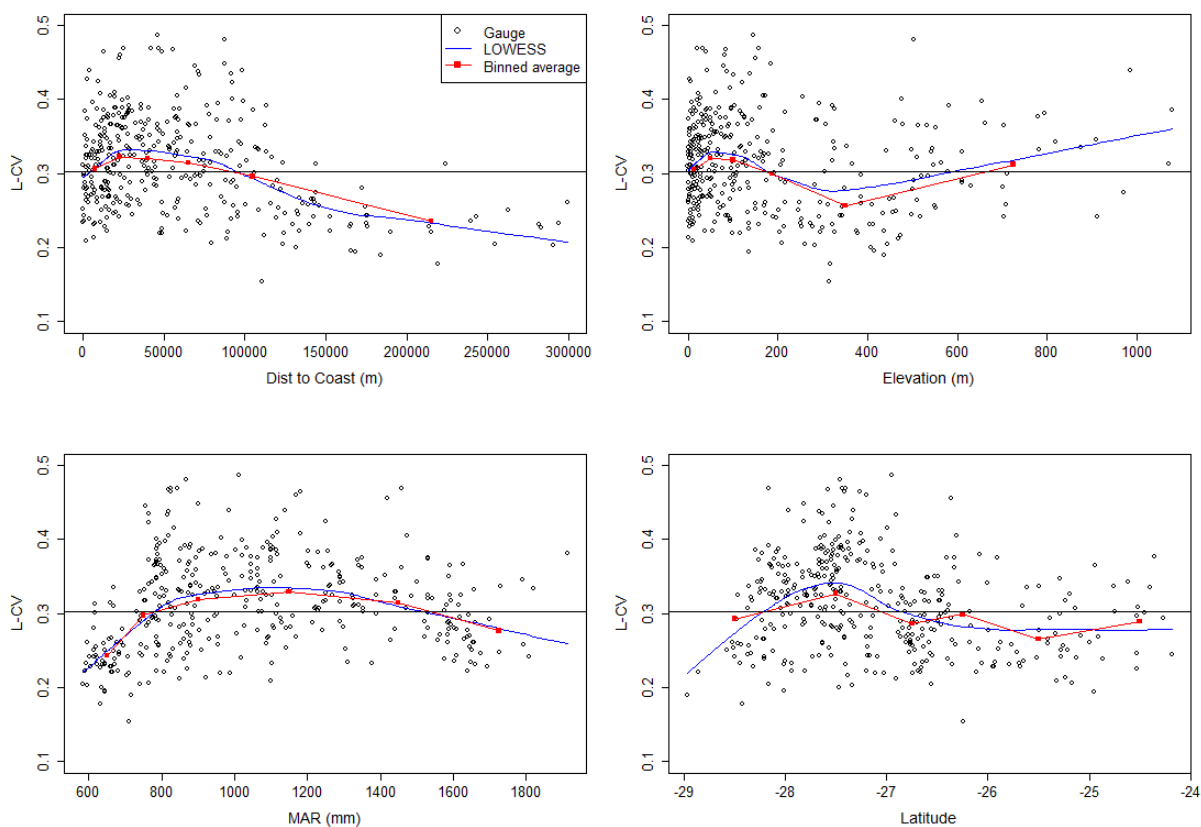
L-CV - 1080 minutes



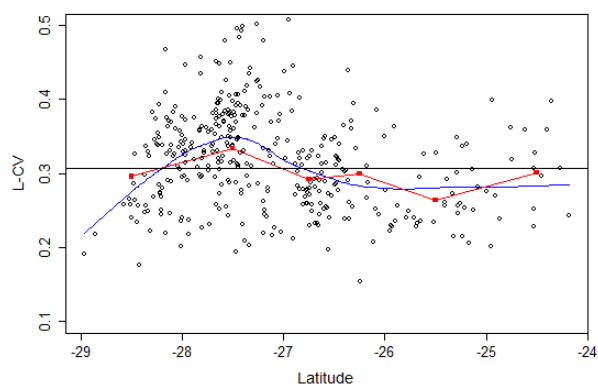
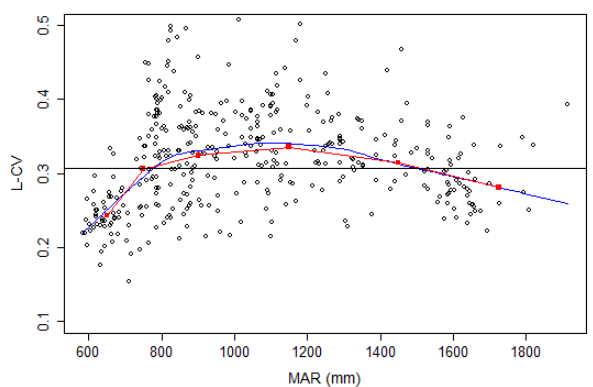
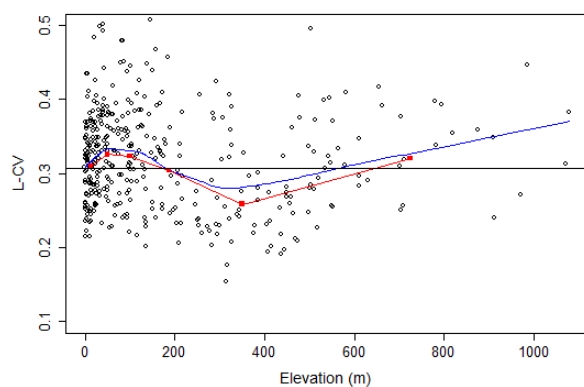
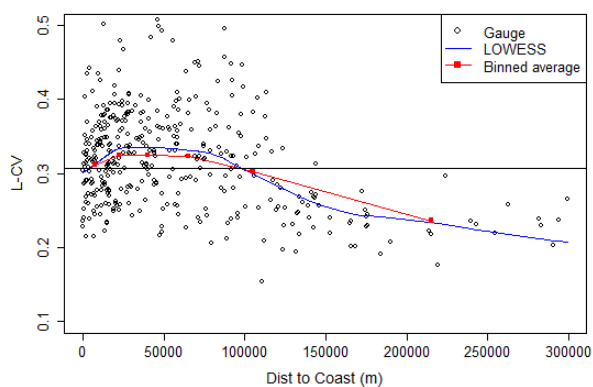
L-CV - 1440 minutes



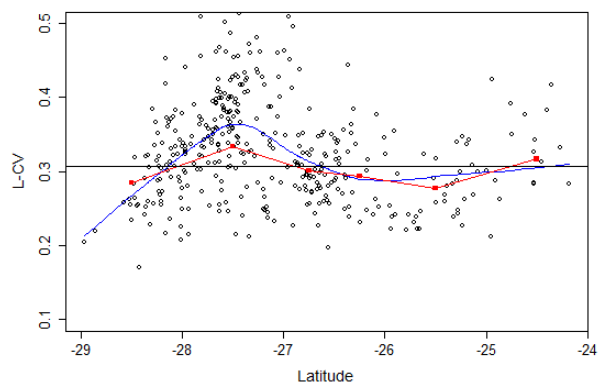
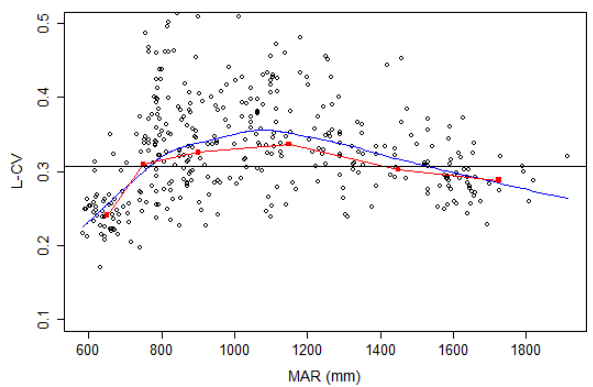
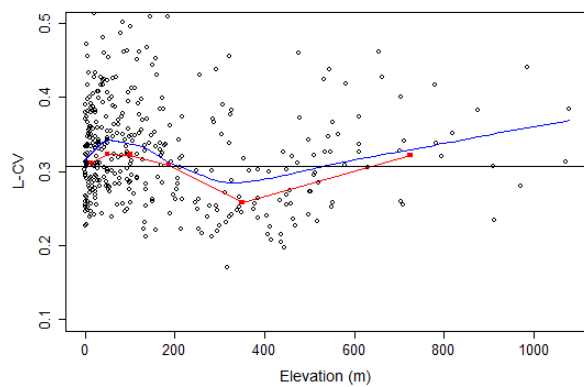
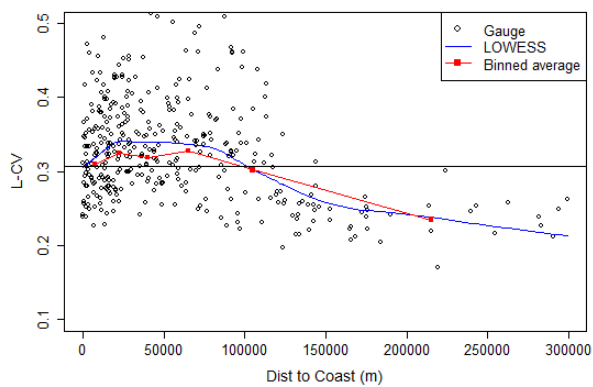
L-CV - 1800 minutes



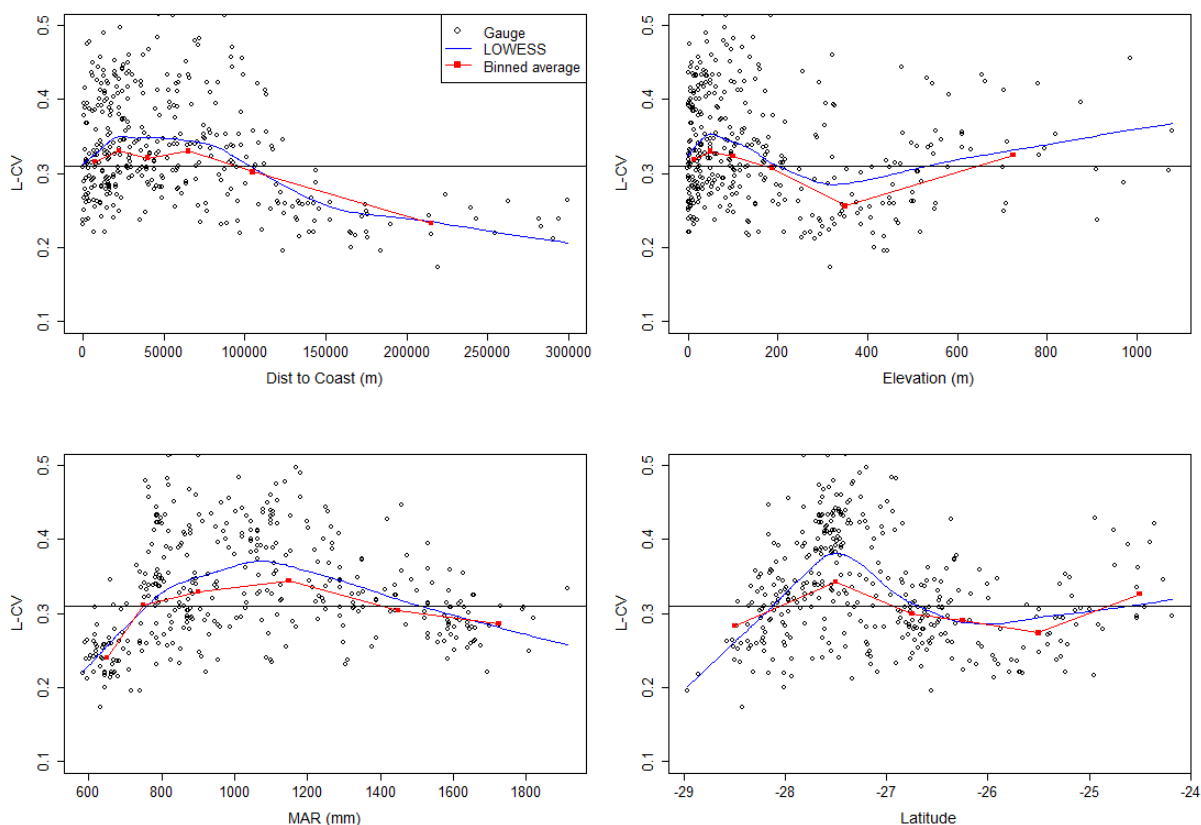
L-CV - 2160 minutes



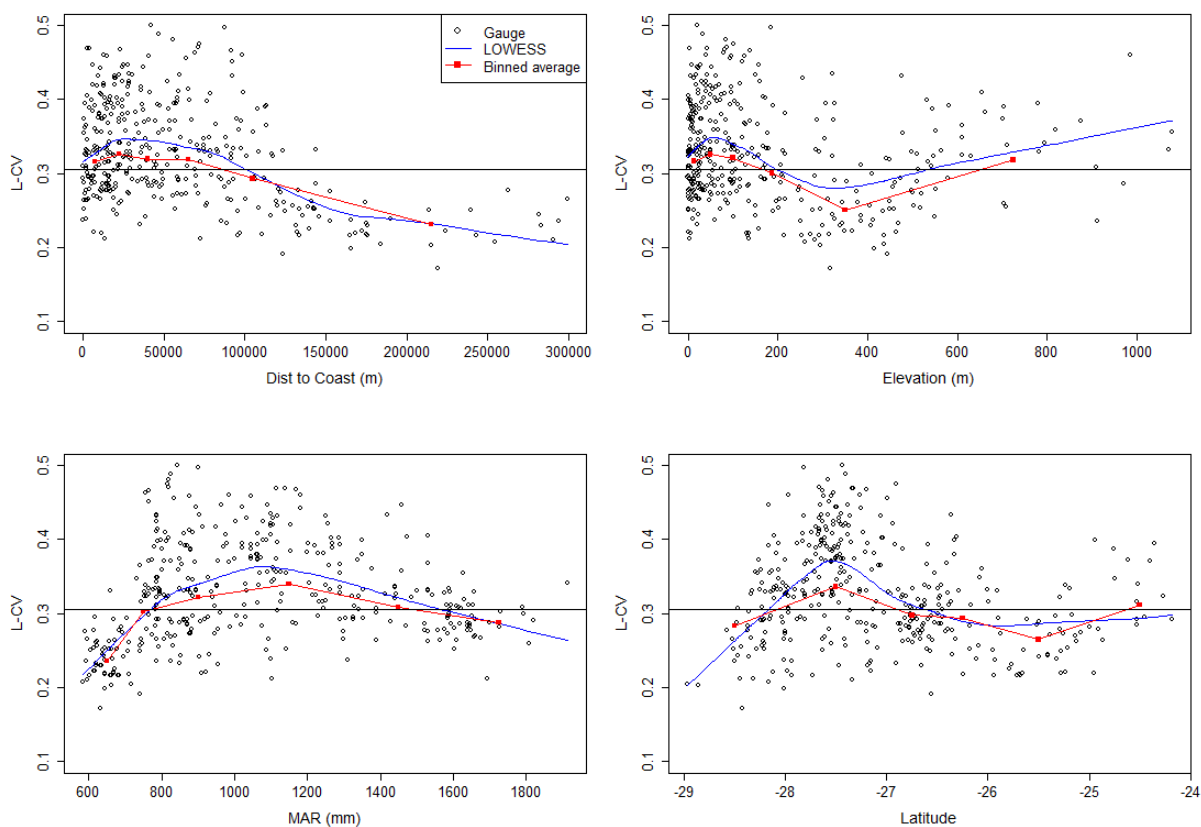
L-CV - 2880 minutes



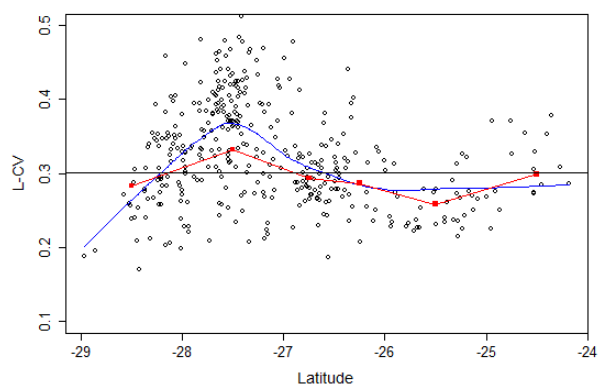
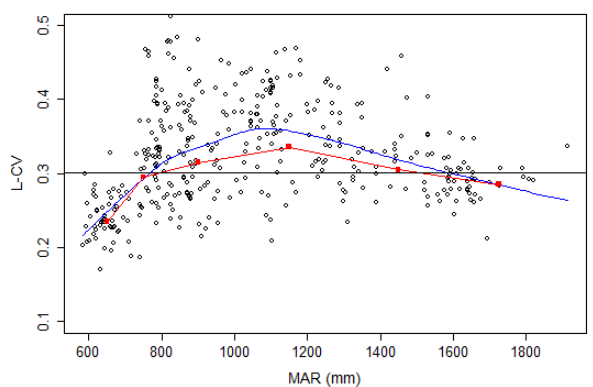
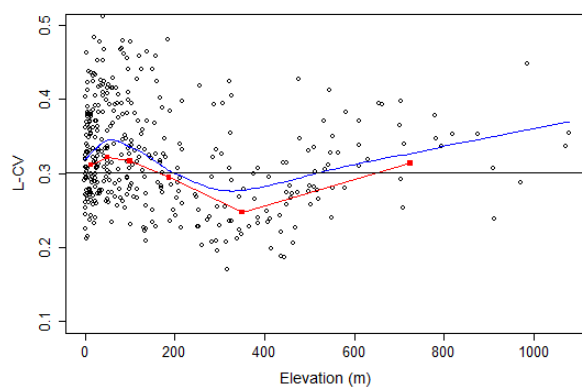
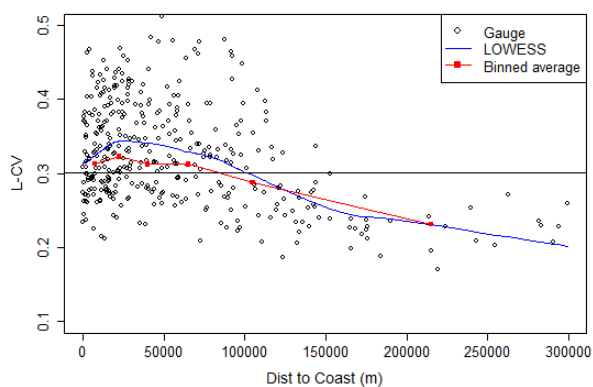
L-CV - 4320 minutes



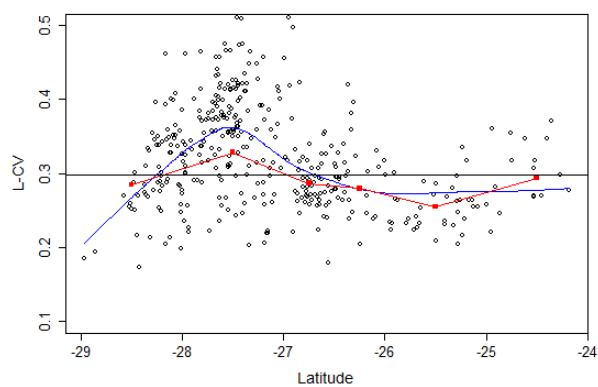
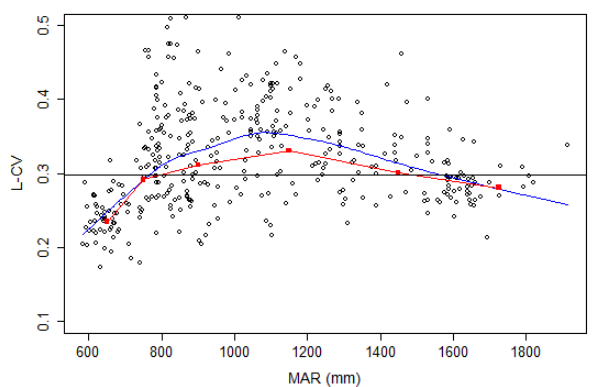
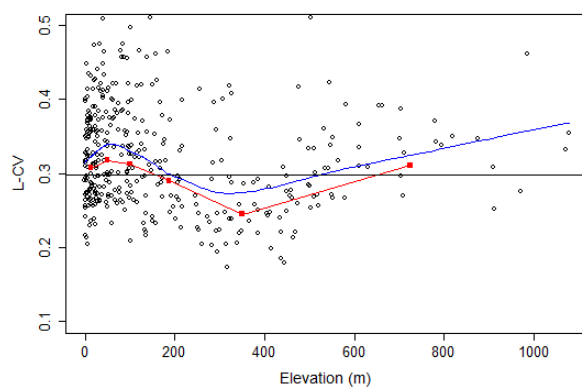
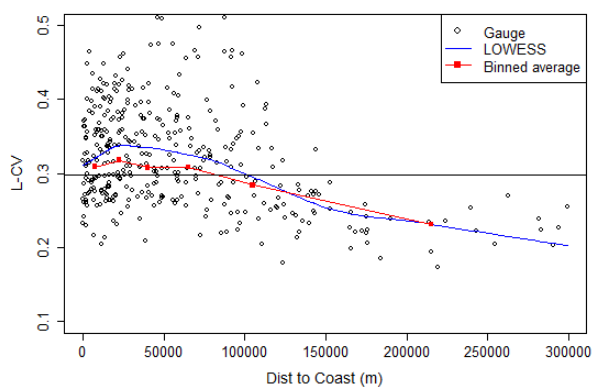
L-CV - 5760 minutes



L-CV - 7200 minutes



L-CV - 8640 minutes



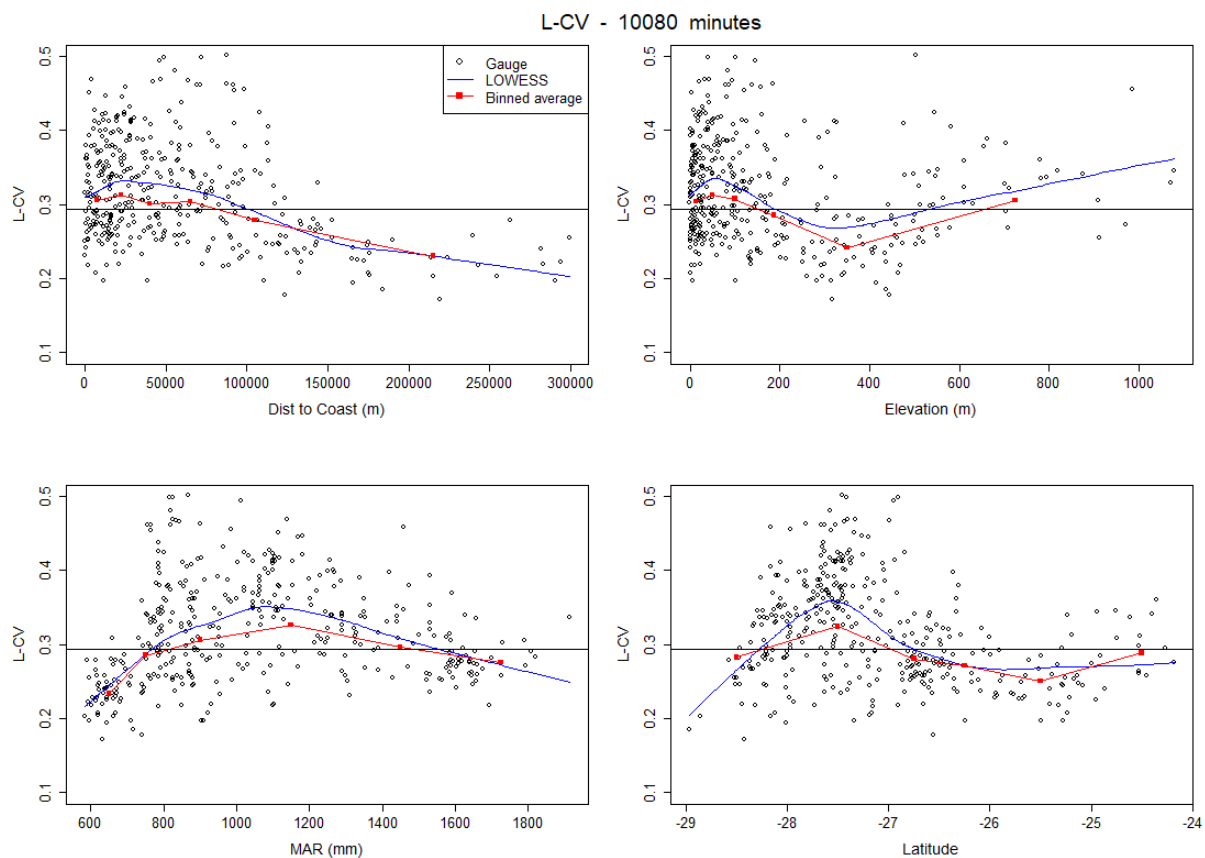
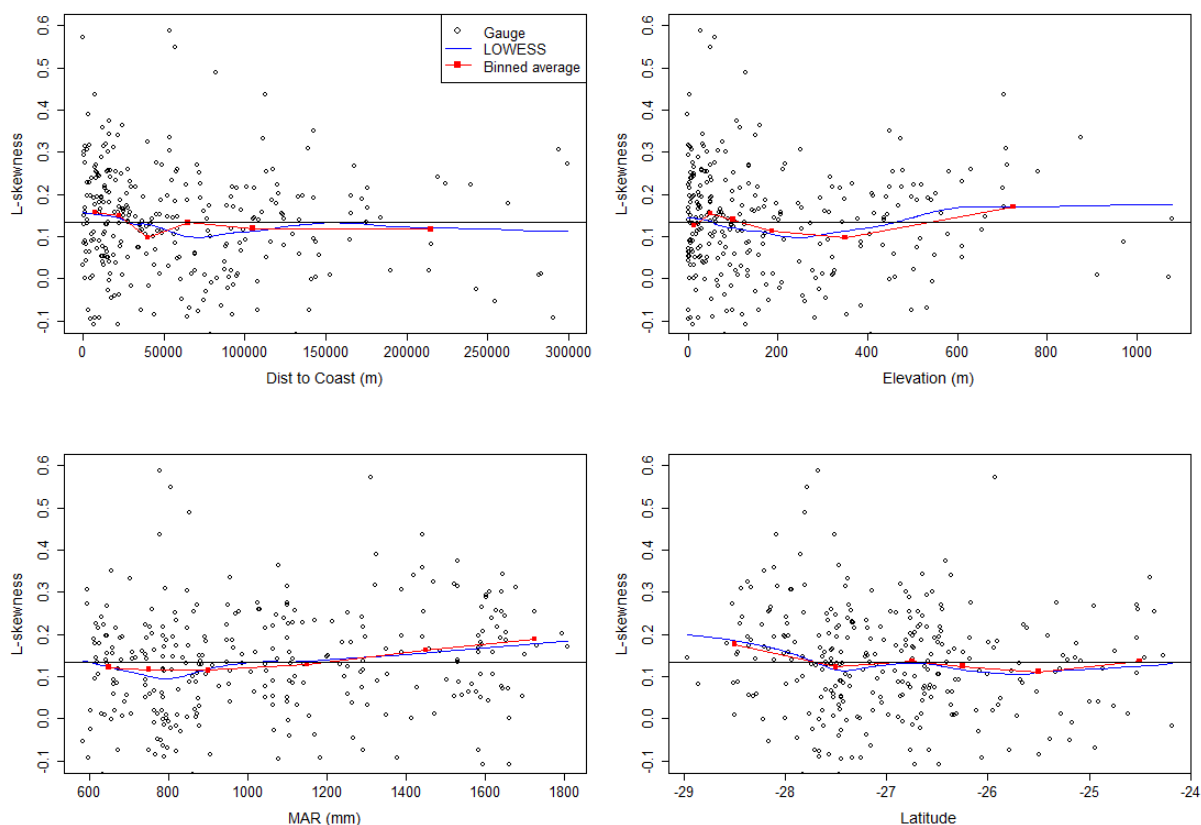
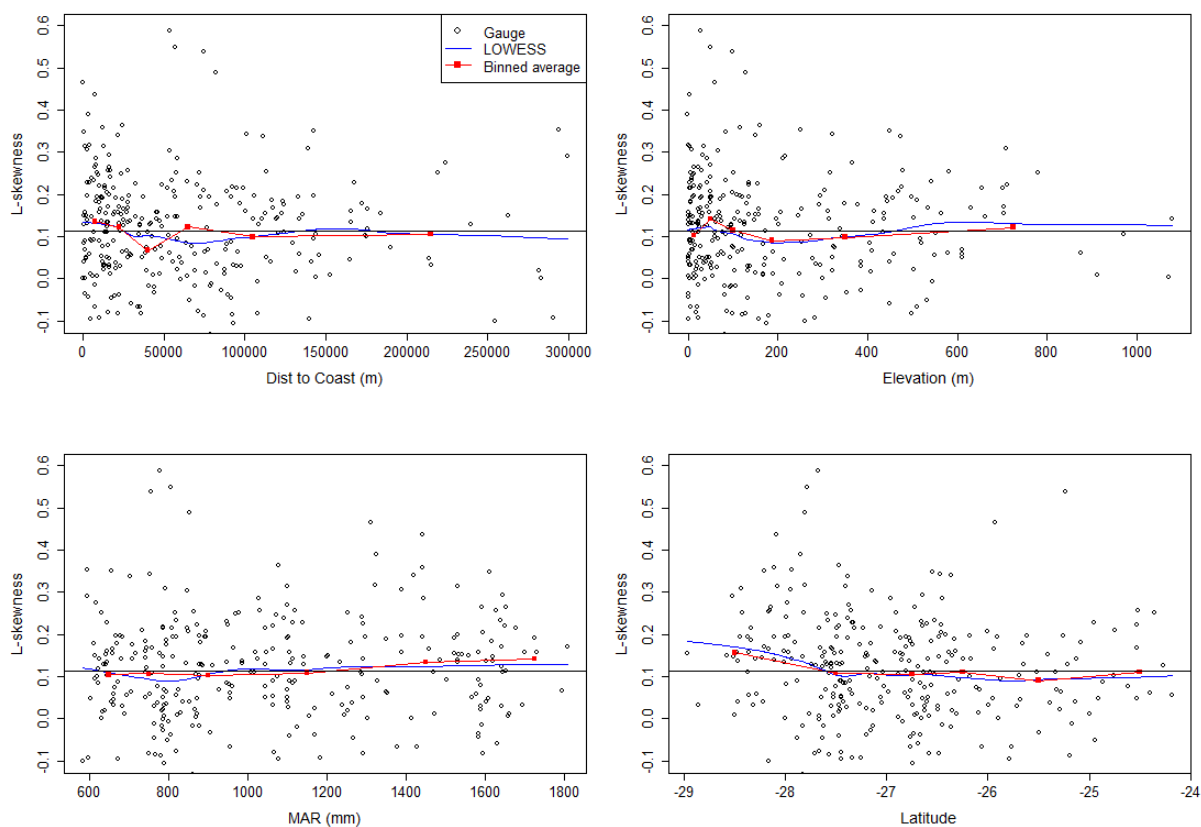


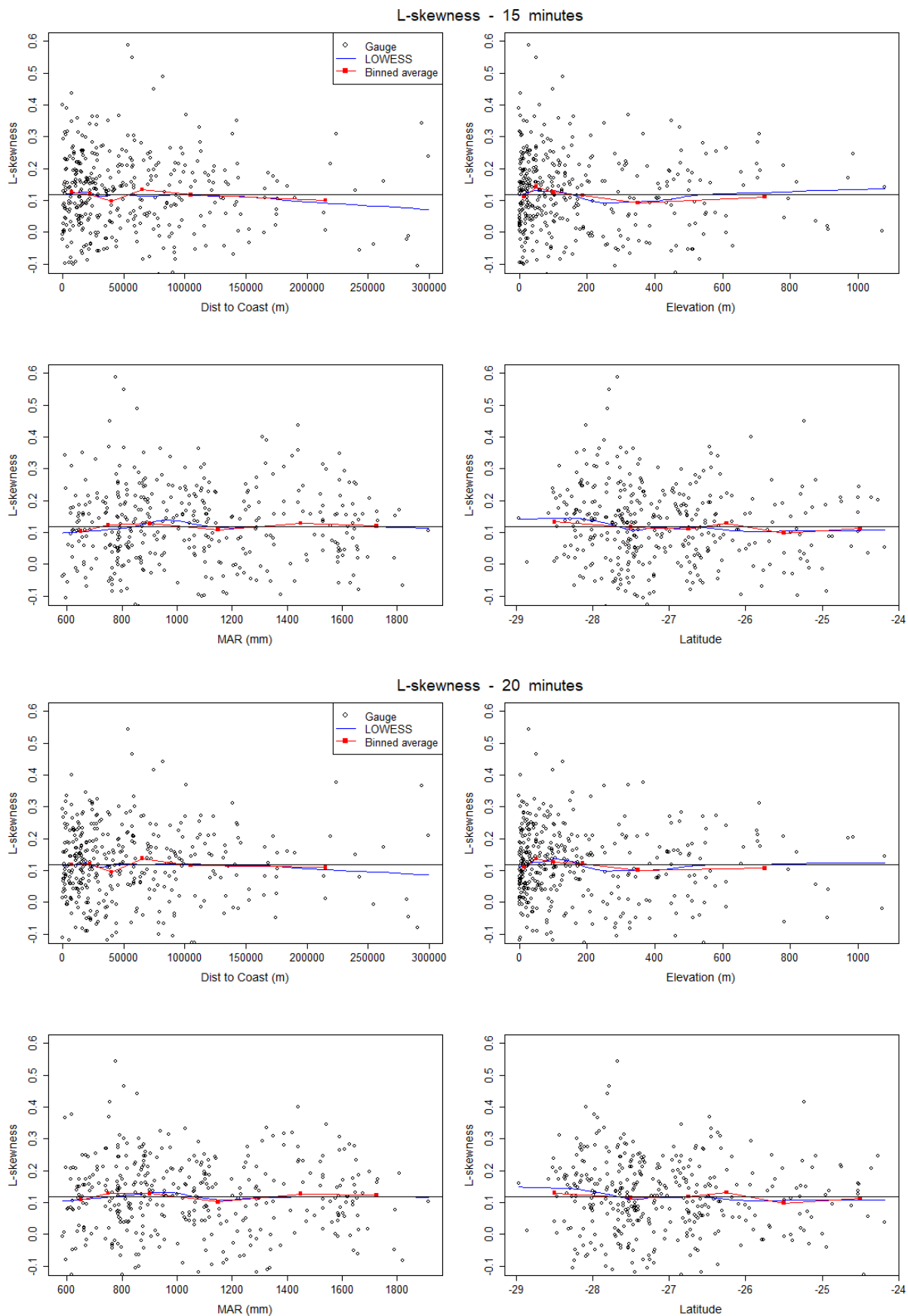
Figure C 1: L-CV versus physical gauge attributes for all durations

L-skewness - 5 minutes

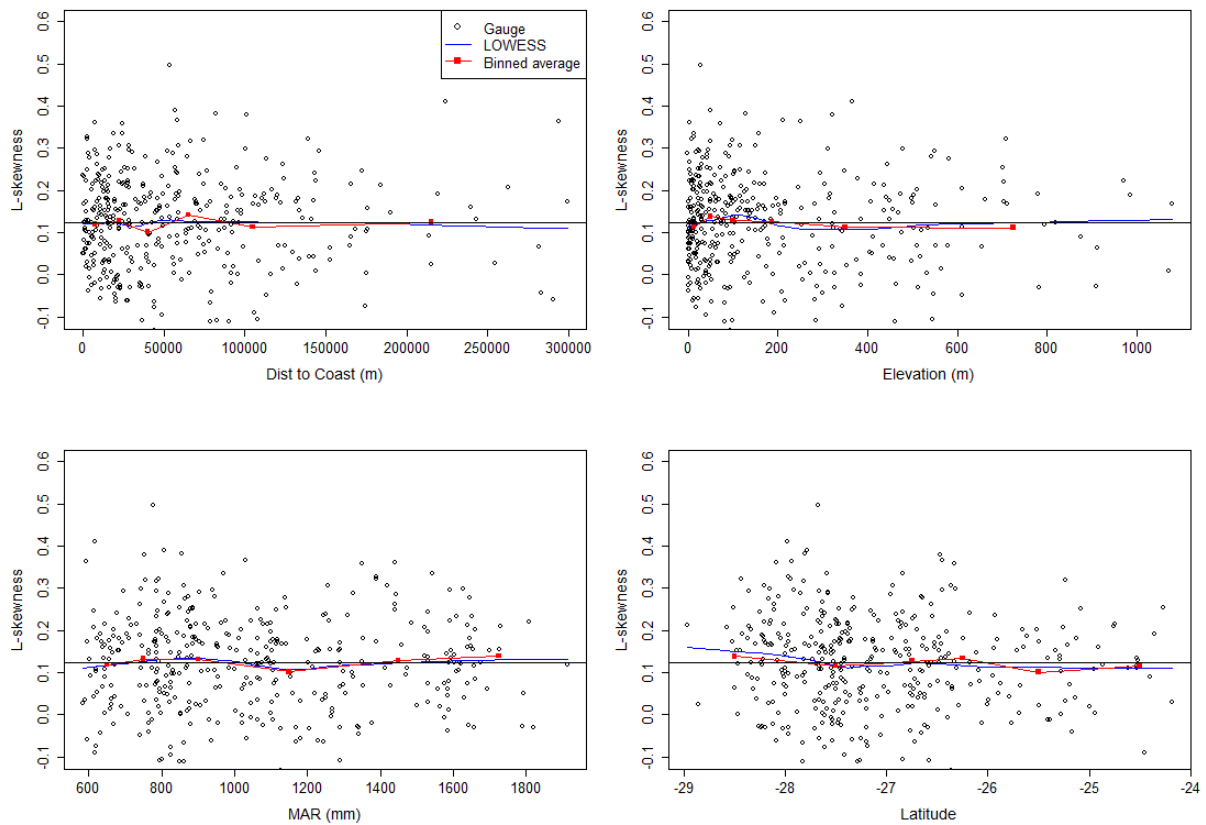


L-skewness - 10 minutes

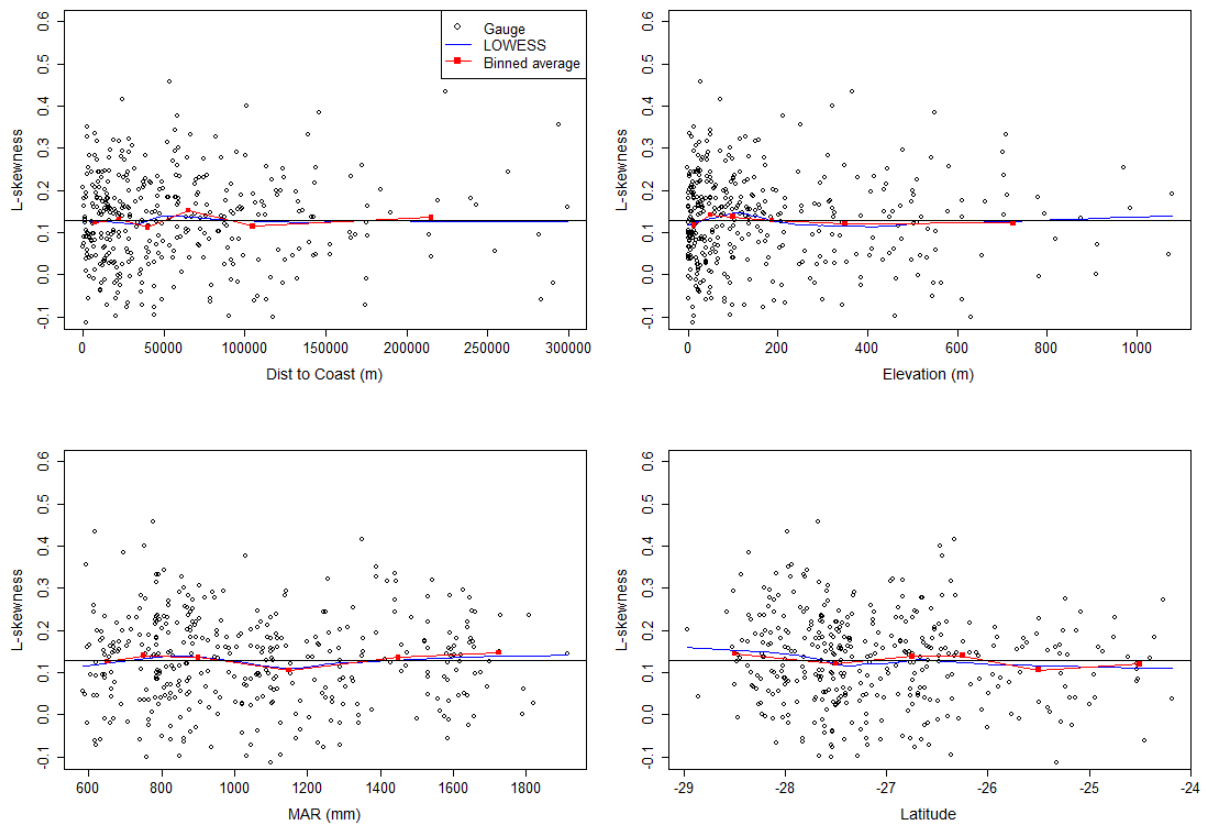


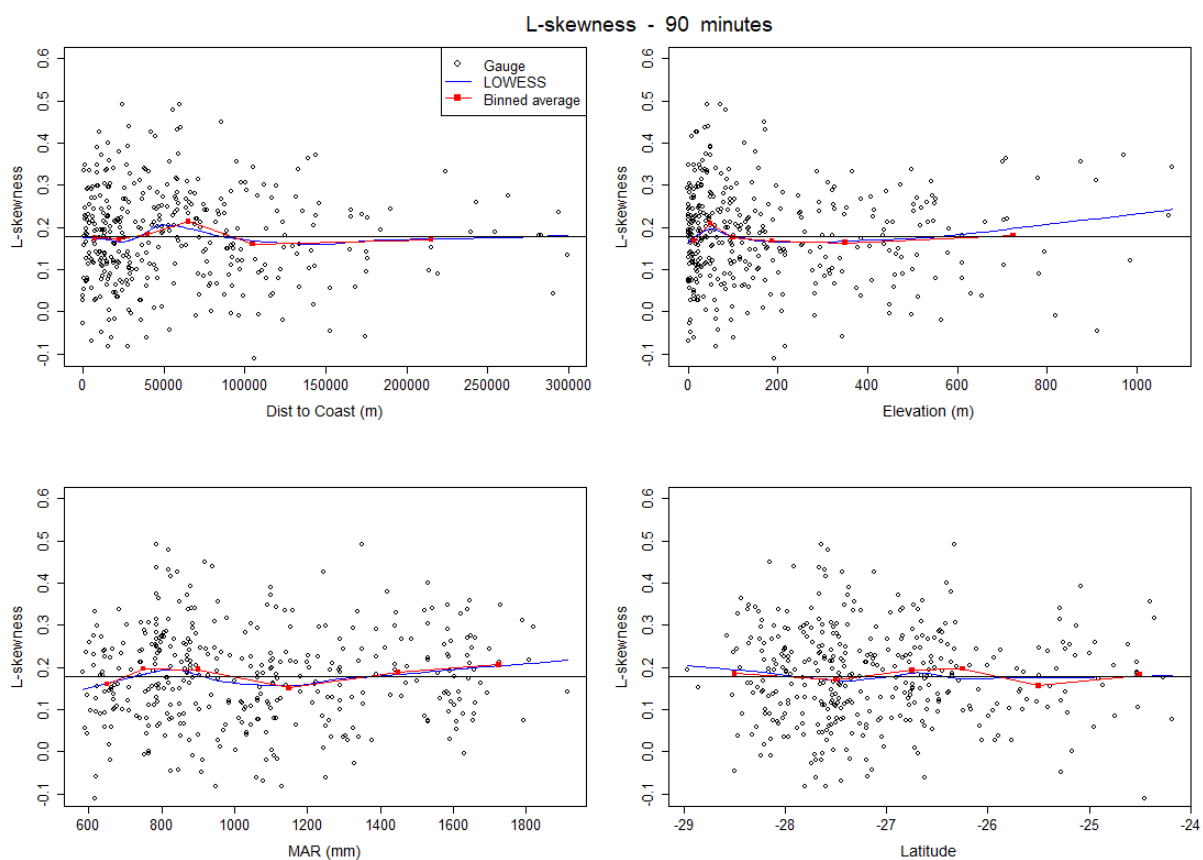
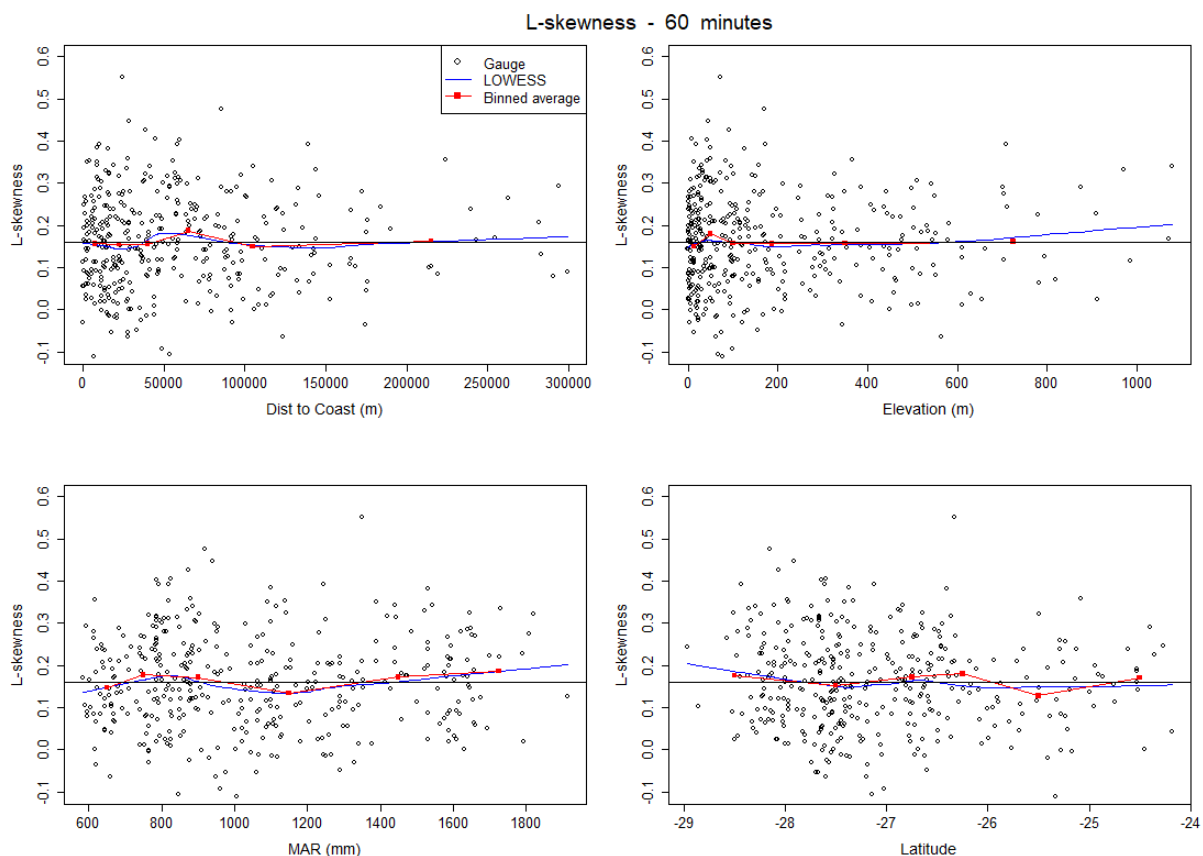


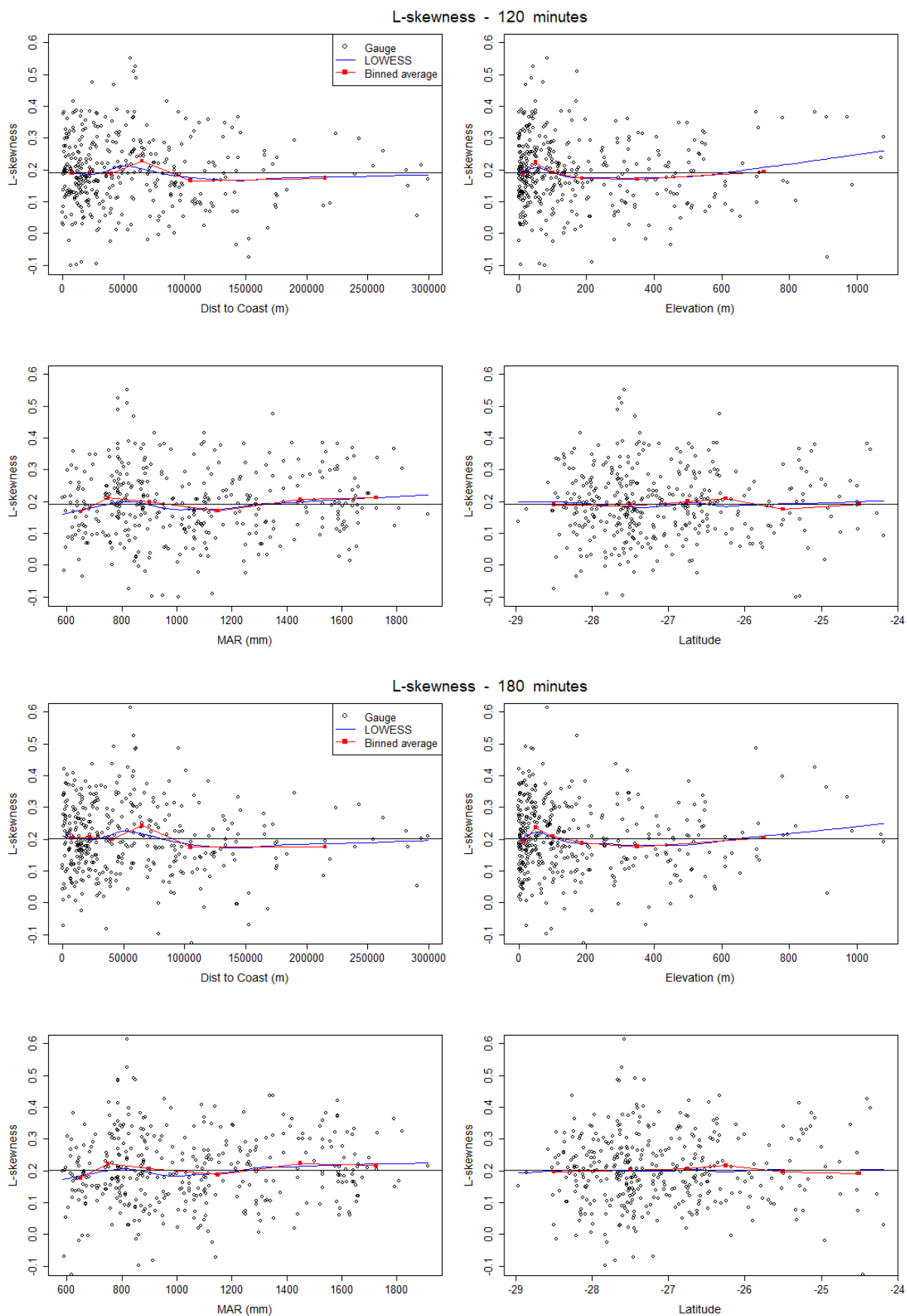
L-skewness - 25 minutes

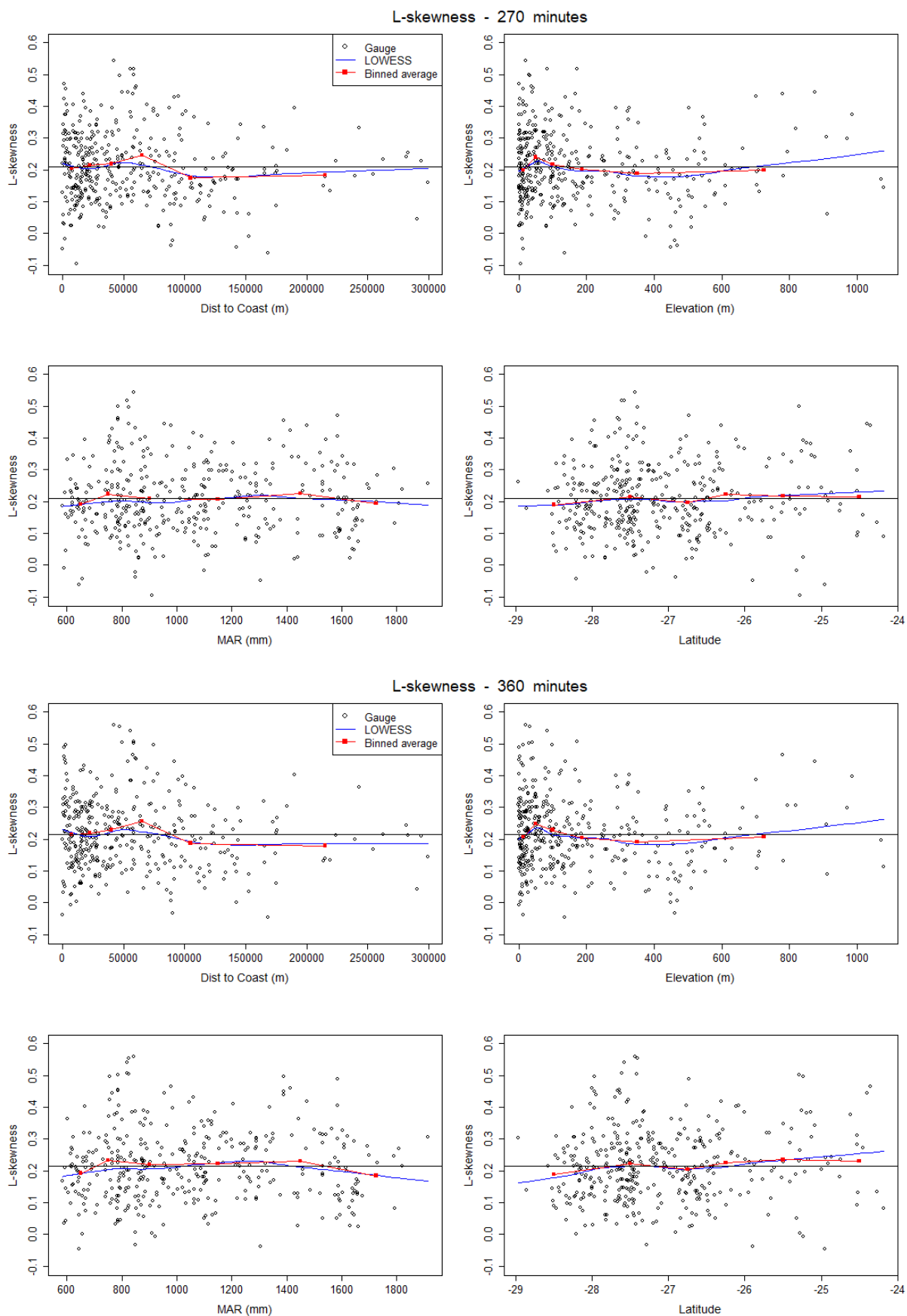


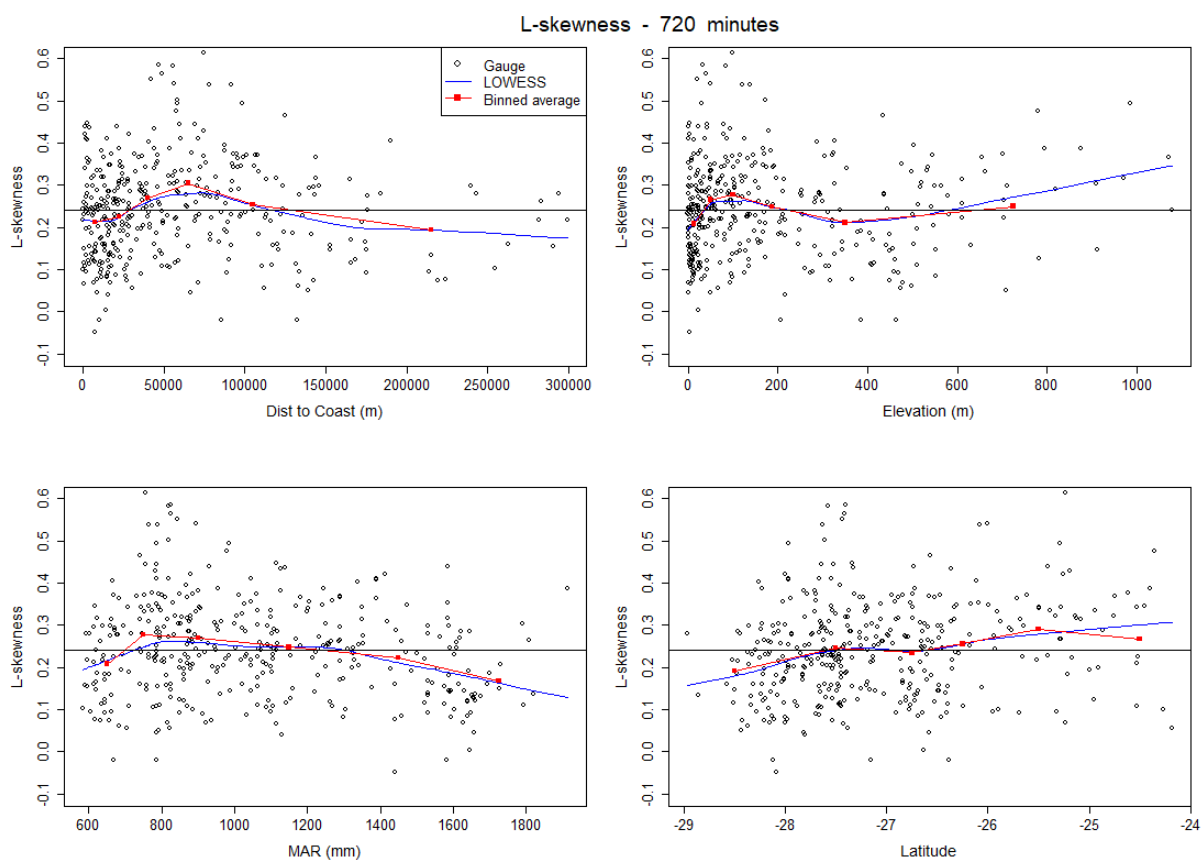
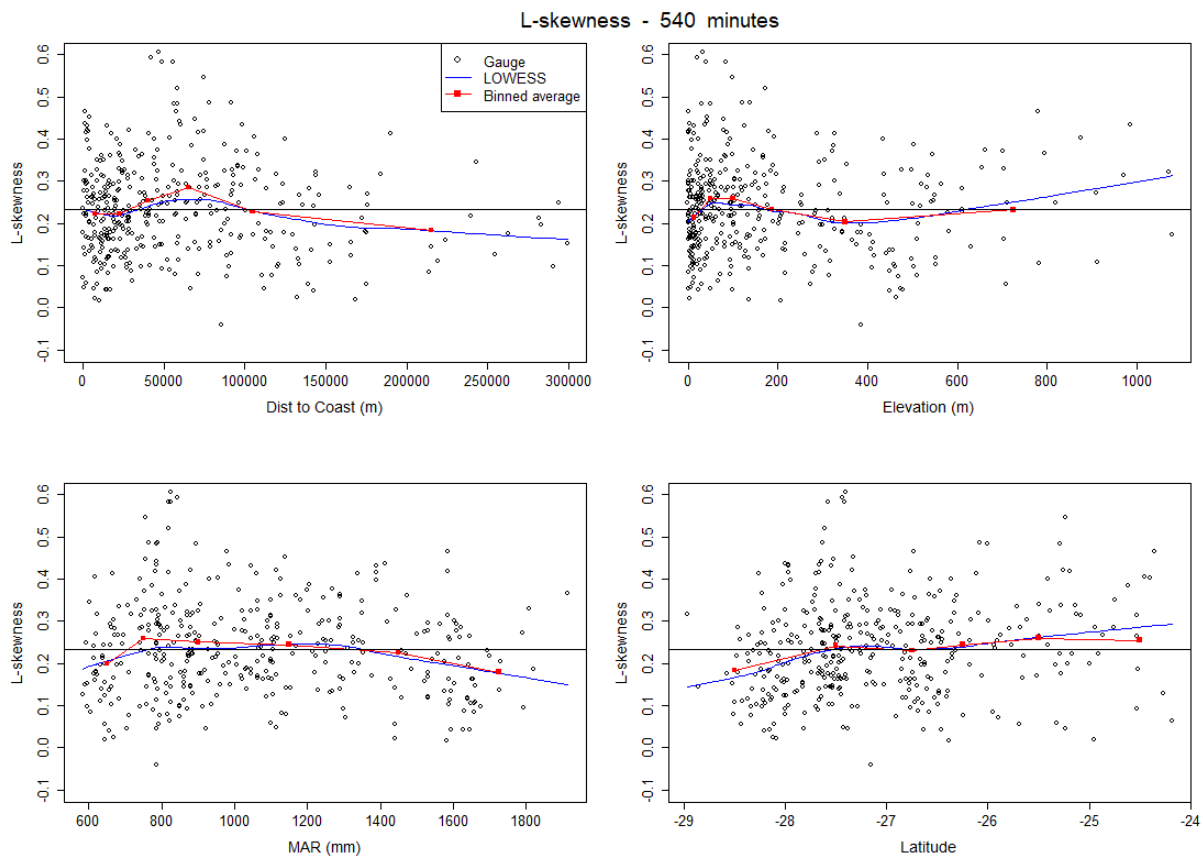
L-skewness - 30 minutes



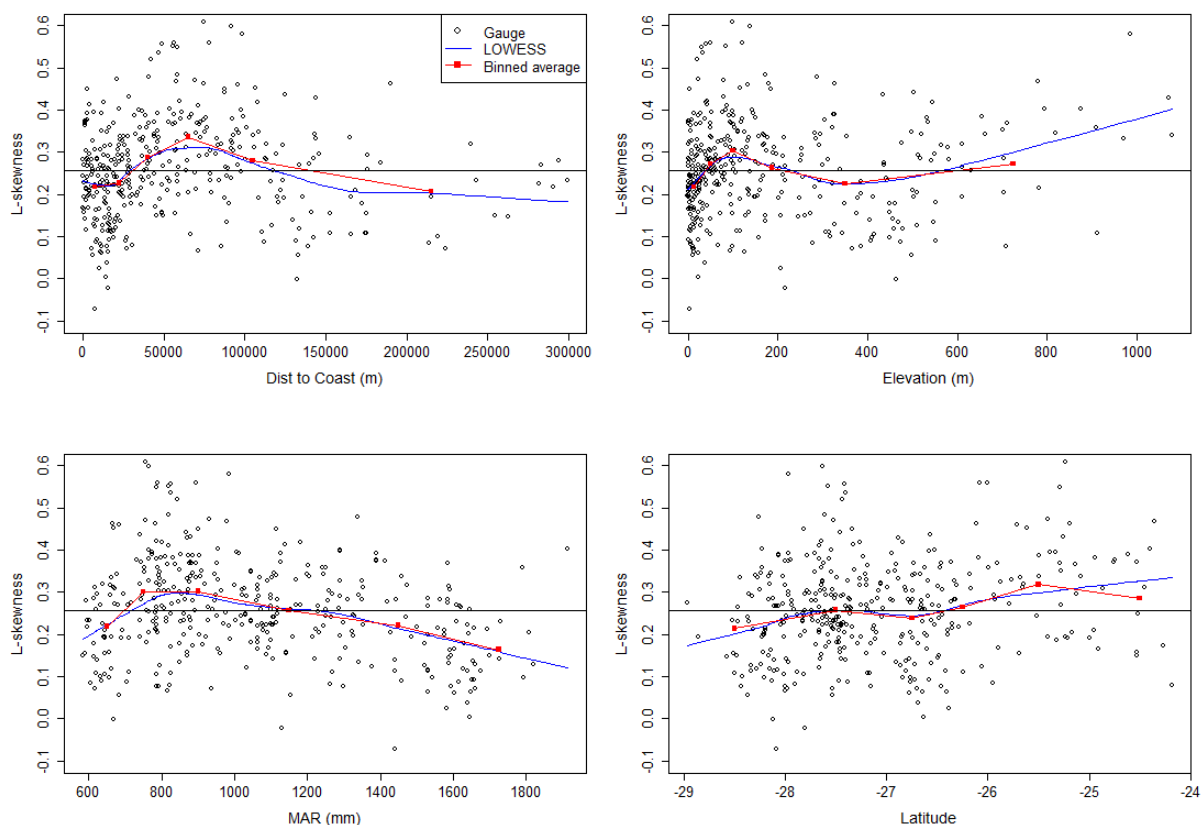




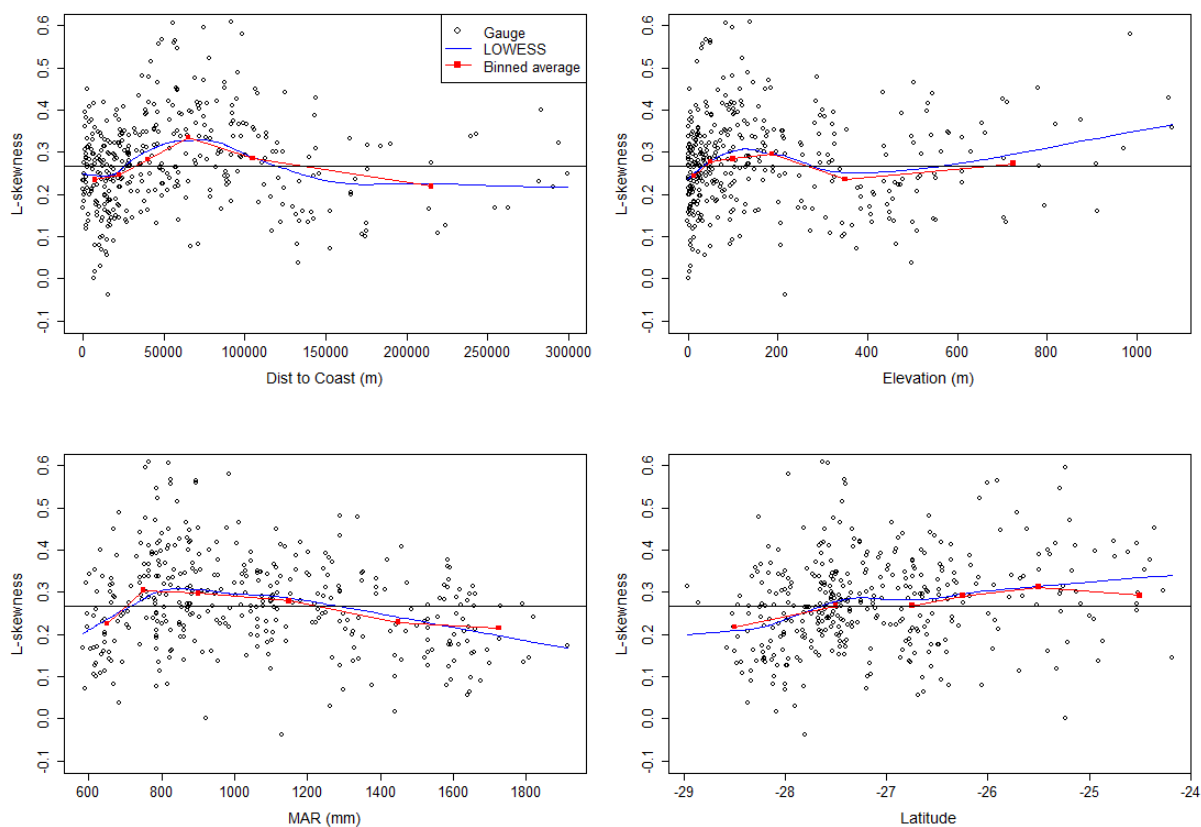


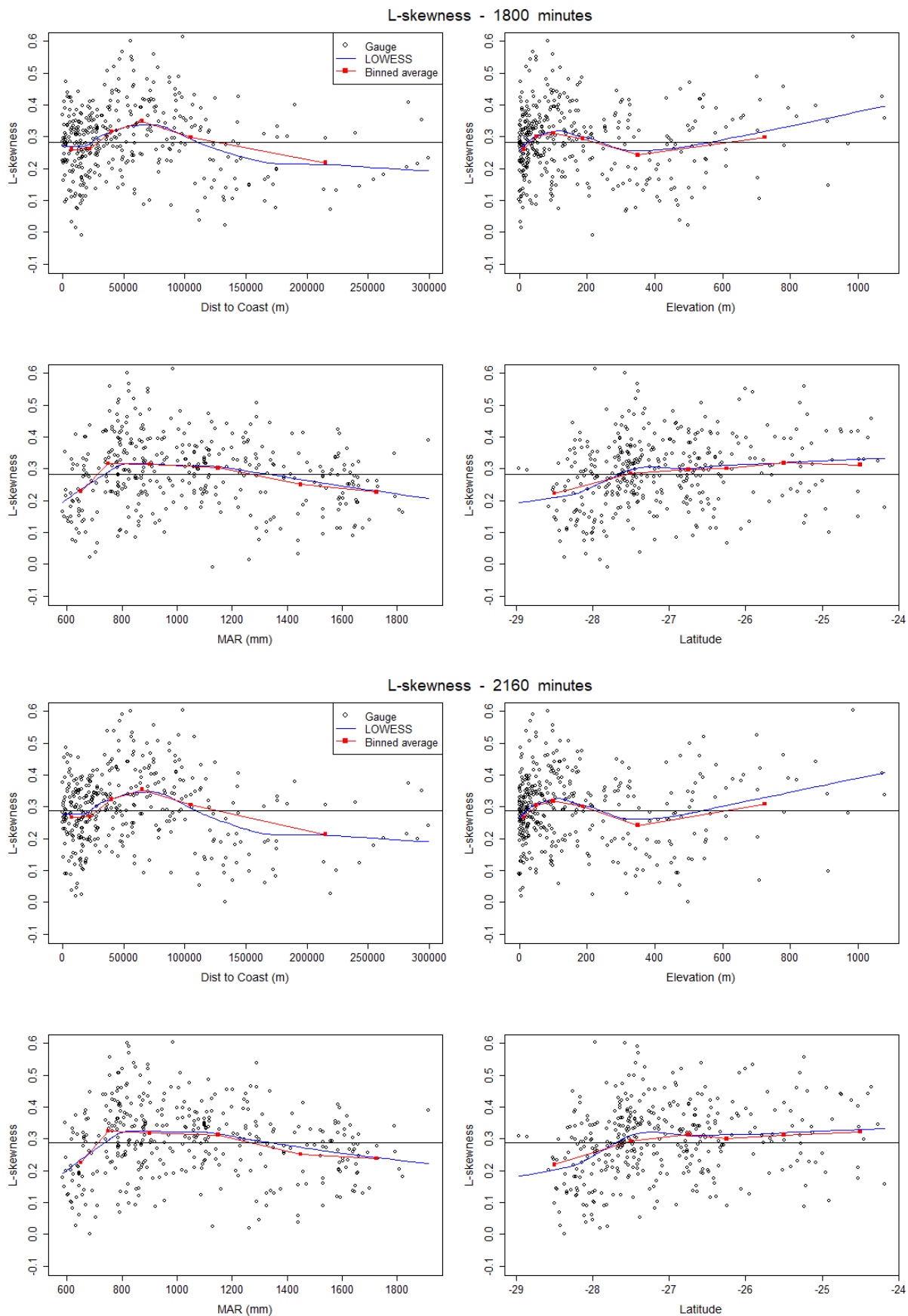


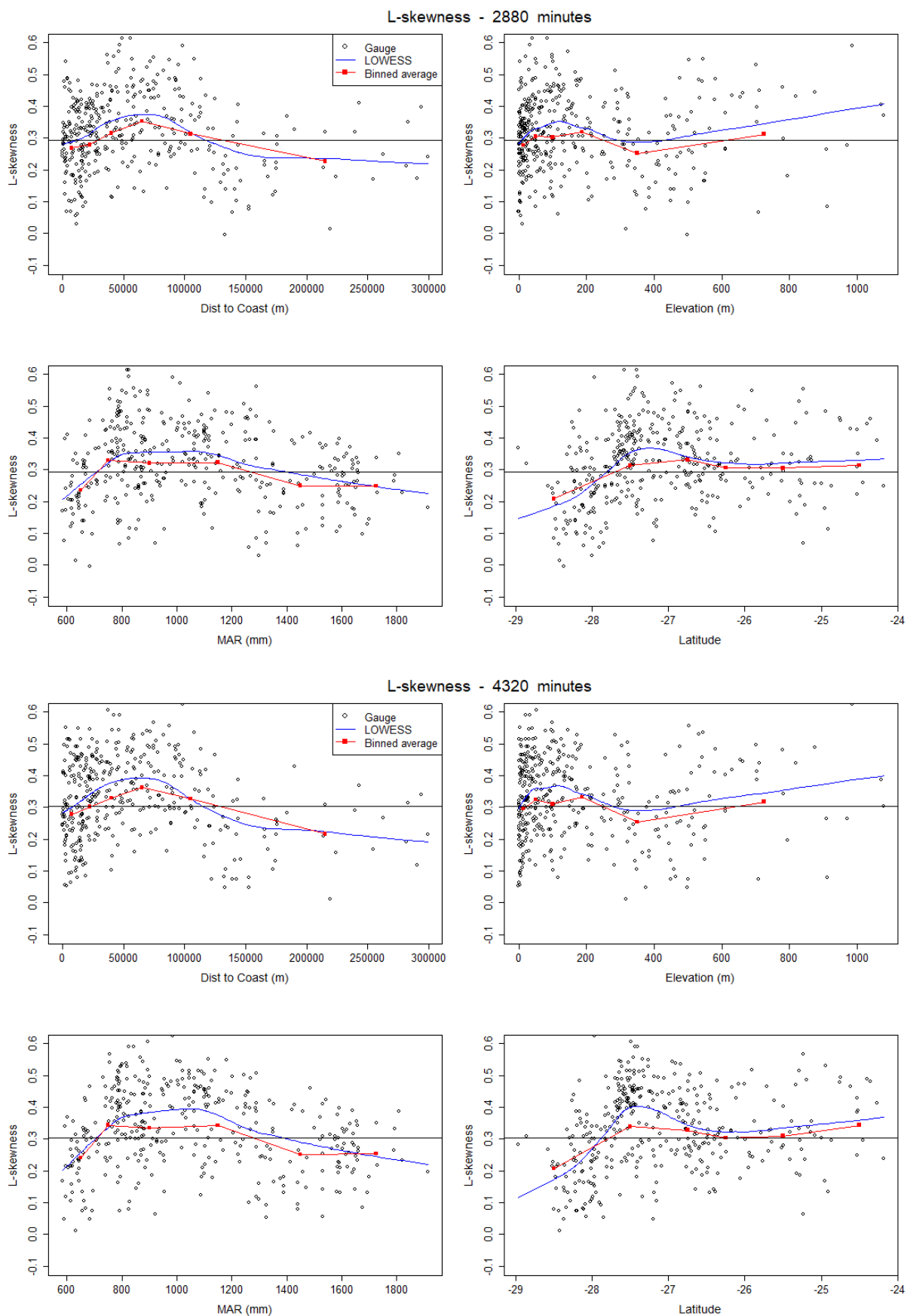
L-skewness - 1080 minutes

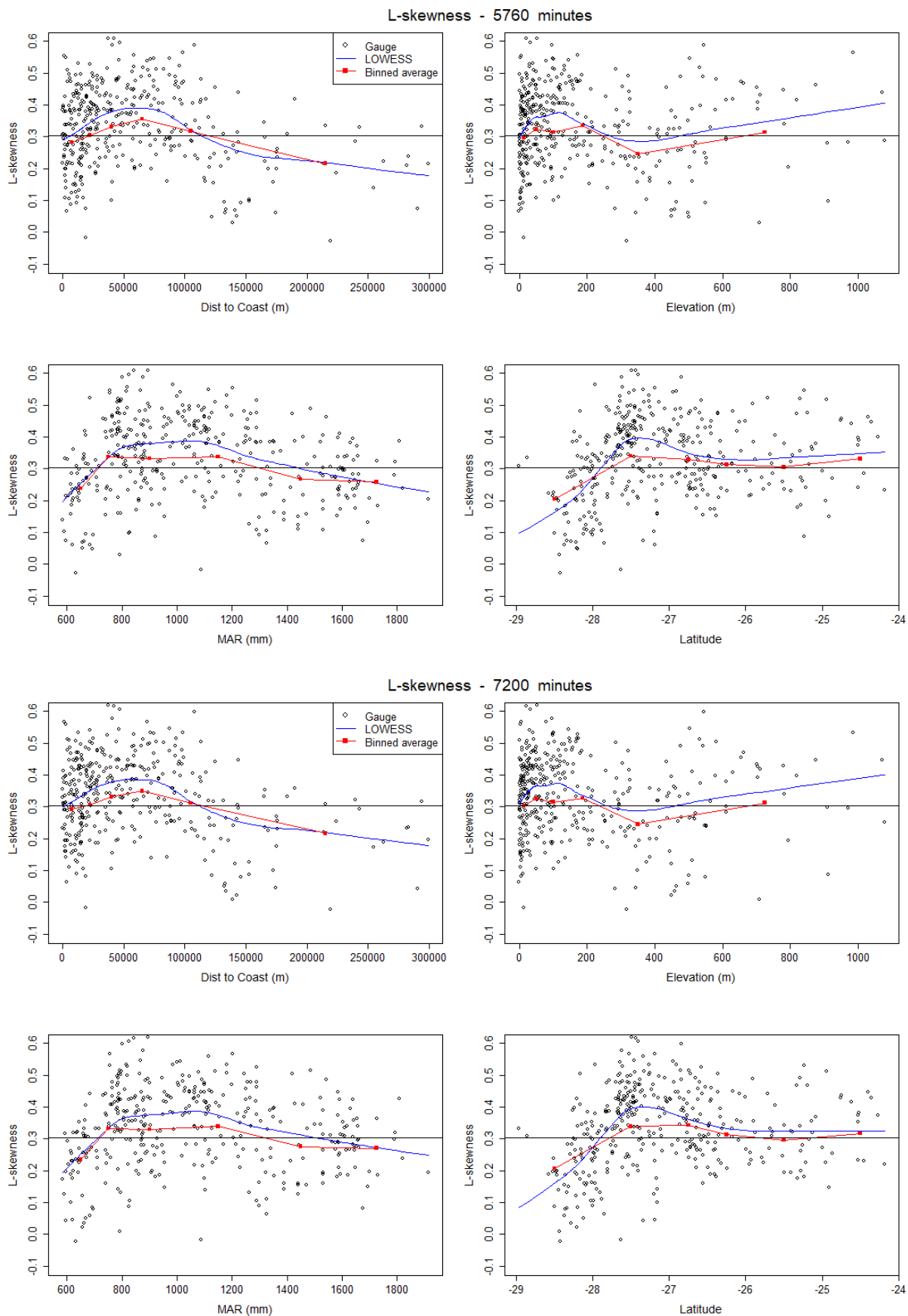


L-skewness - 1440 minutes









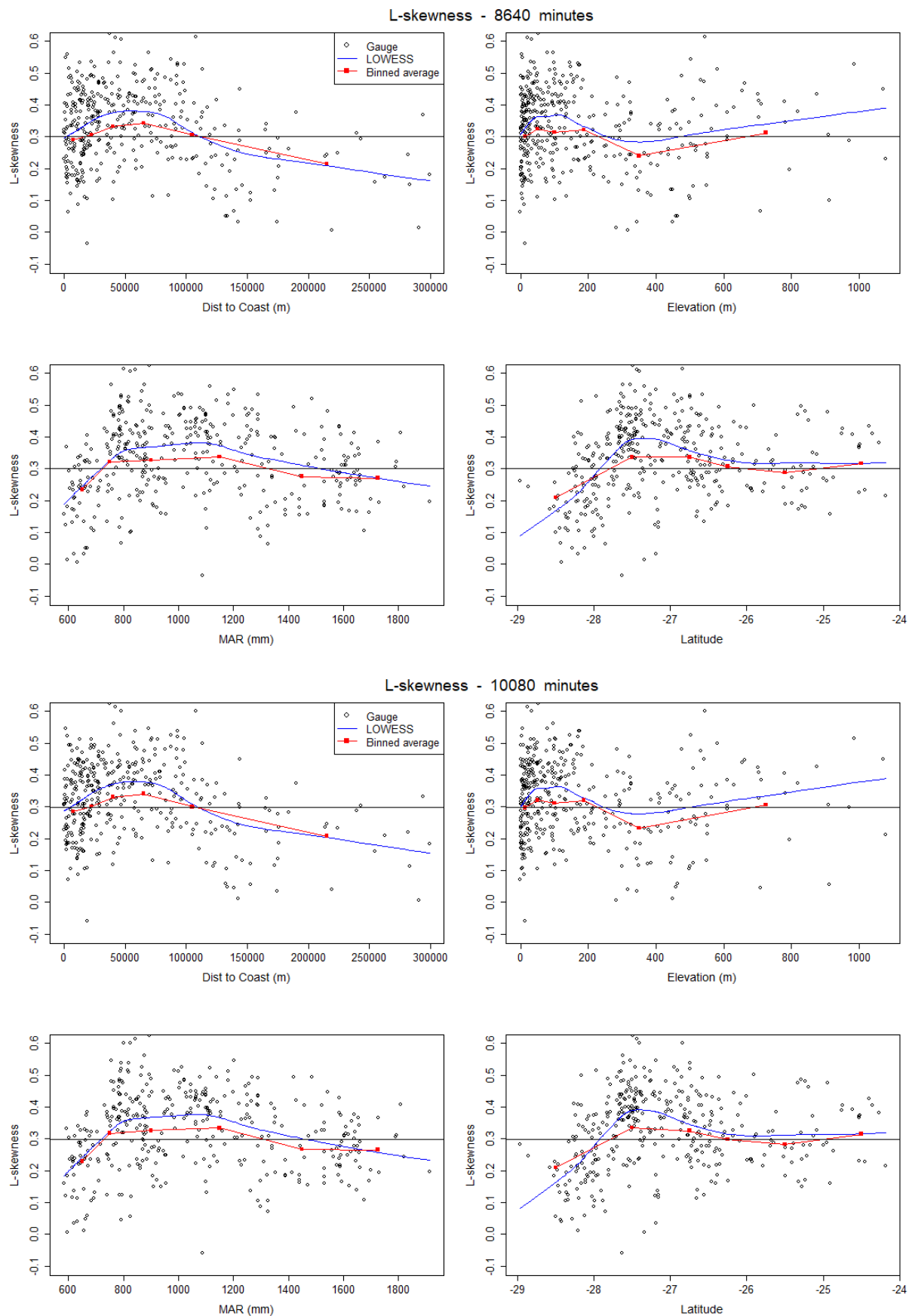


Figure C 2: L-skewness versus physical gauge attributes for all durations

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Appendix D Use of physical distance in Region of Influence approach

For durations 48 hours and longer L-CV and L-skewness were regionalised by pooling of nearby sites. 500 years of data were pooled from the nearby sites. In this study, the nearby sites were defined based on physical distance only – meaning that the pooling of L-moment ratios was carried out by accumulating the L-moment ratios of the (physically) closest sites until 500 years of record were accumulated. However, it was noted that ARR (2016) and LIMB (2021) studies have used a “transformed distance” approach to define the nearby sites when pooling L-CV and L-skewness. The decision to use physical distance in this study was made based on the following investigation during an early iteration of the regionalisation approach which considered using region of influence pooling for all durations. This investigation is presented here, and is considered relevant to the final regionalisation approach.

Effective (or transformed) distance can be expressed as:

$$D = w_1V_1 + w_2V_2 + w_3V_3$$

where, **D** refers to the transformed distance. **V₁**, **V₂** and **V₃** are variables used to define transformed distance. **w₁**, **w₂** and **w₃** are the respective weights for the variables.

In the LIMB (2021) study, the transformed distance was defined based on weighted distance, weighted elevation and weighted standard deviation of elevation. The weights were optimised by matching the at-site L-moments to the pooled L-moments (based on the coefficient of determination (**R²**) between at-site and pooled L-moments).

A similar approach was carried out in this study using multiple combinations of variables. We find that this approach did not have significant improvement to the **R²** compared to only pooling based on physical distance. This was because optimising (changing) the weights to match the at-site L-moments to the pooled L-moments, often resulted in pooling the same sites, regardless of what the variables used to define the nearby stations – meaning that there will be only one combination of nearby sites that would result in pooled L-moment ratios that is closest to the at-site value.

Figure D1 presents the **R²** between the at-site L-moment ratios and pooled L-moment ratios, estimated based on different equations (variables) used to define the transformed distance. The weights were optimised by selecting the combination of weights that provided the highest **R²** considering all durations (see Appendix C for all the results). The median **R²** value for all different equations used for the transformed distance (including the physical distance-only method) was around 0.3. However, it is worth noting that for this assessment, the L-CV value at the site of interest was excluded when pooling. When gridding L-moment ratios, all sites were included (resulting in slightly higher **R²**).

It was also noted that the optimised weights for physical distance were significantly higher than the weights given for other variables. The optimised weights for the physical distance were at least 9 times higher than the other weights in our study. Similarly, in the LIMB (2022) study, the weight given to the physical distance was 17 times higher than the weight given to the elevation.

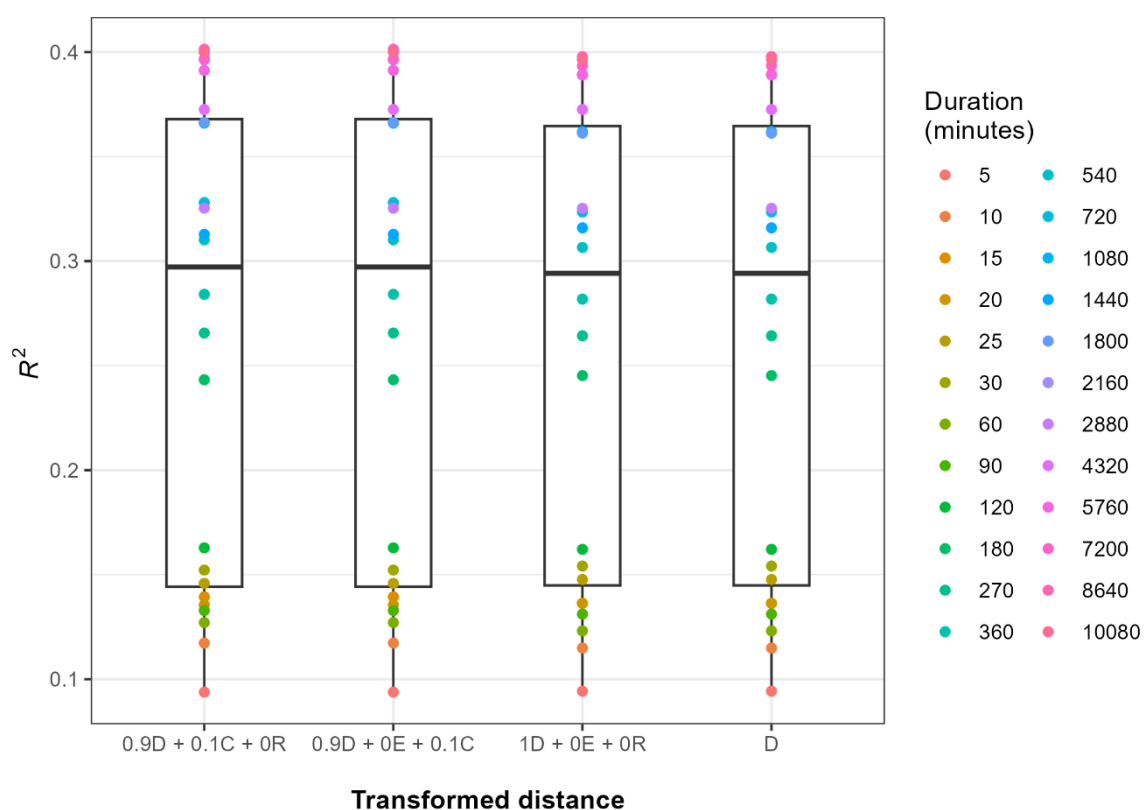
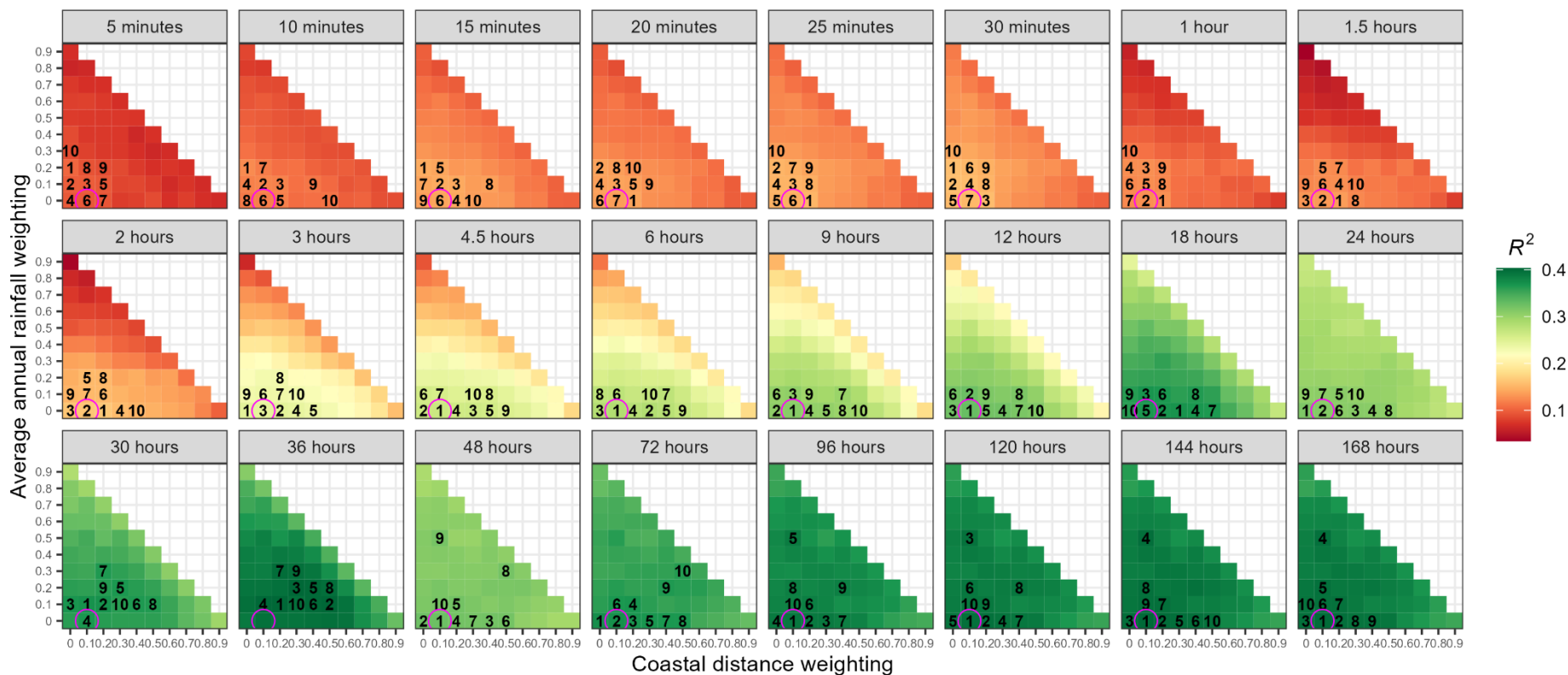


Figure D 1 R^2 between the at-site L-CV and pooled L-CV estimated based on different transformed distances. D - physical distance, C - Distance to coast, E – Elevation and R – Mean annual rainfalls.

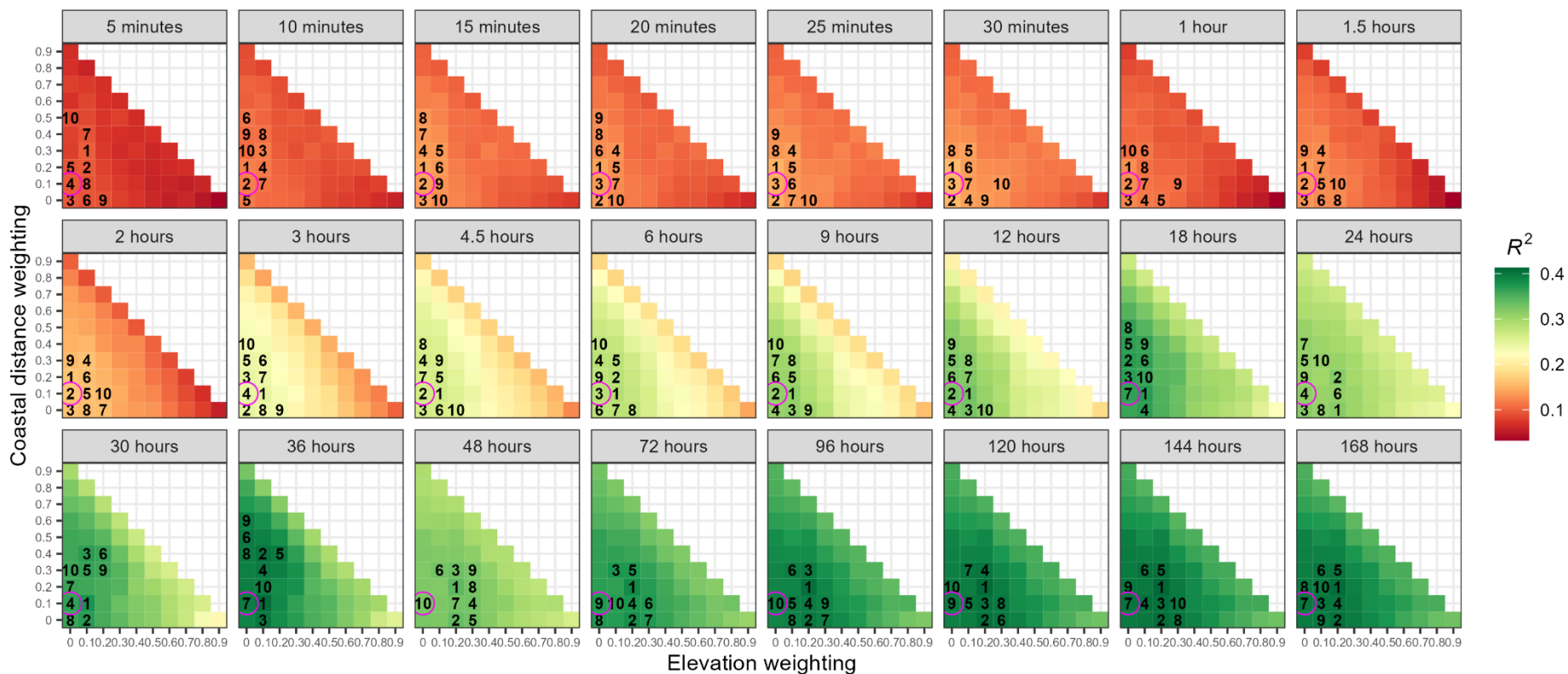
Overall, the transformed distance (or different variable used in the transformed distance) did not show a considerable improvement in the R^2 compared to only using physical distance to define the nearby stations. Therefore, only physical distance was used to pool L-CV in this study.



Notes:

- The transformed distance was estimated based on the physical distance, distance to the coast and mean annual rainfall.
- Physical distance weight = 1- Coastal distance weight – mean annual rainfall weight
- The top 10 performing combinations of weights are numbered in the figure for all durations. Among them, the best-performing combinations (optimum weights) considering all durations are circled in pink.

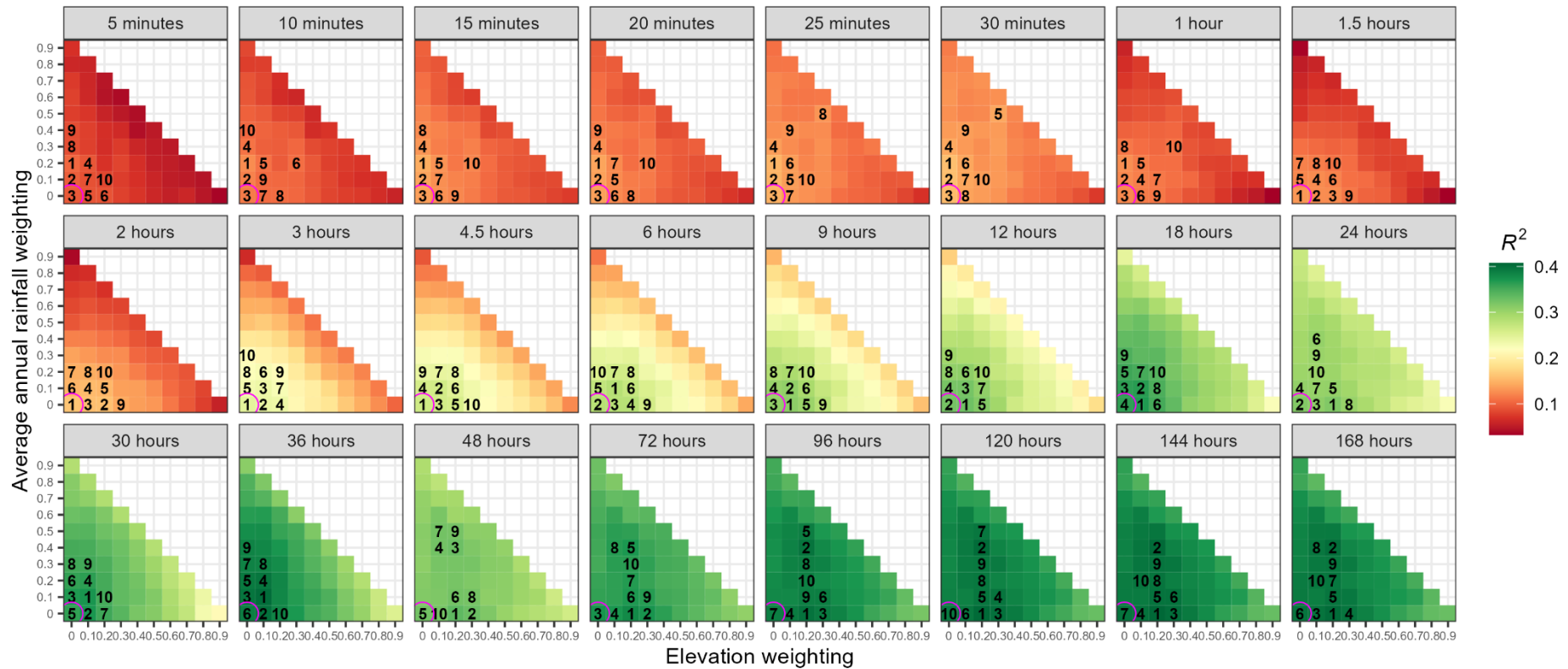
Figure D 2 R^2 values for different combinations of weighting. The transformed distance was estimated based on the physical distance, distance to the coast and mean annual rainfall.



Notes:

- The transformed distance was estimated based on the physical distance, elevation and distance to the coast.
- Physical distance weight = 1- Elevation weight - Coastal distance weight
- The top 10 performing combinations of weights are numbered in the figure for all durations. Among them, the best-performing combinations (optimum weights) considering all durations are circled in pink.

Figure D 3 R^2 values for different combinations of weighting. The transformed distance was estimated based on the physical distance, elevation and distance to the coast



Notes:

- The transformed distance was estimated based on the physical distance, elevation and mean annual rainfall.
- Physical distance weight = 1- Elevation weight – Mean annual rainfall weight
- The top 10 performing combinations of weights are numbered in the figure for all durations. Among them, the best-performing combinations (optimum weights) considering all durations are circled in pink.

Figure D 4 R^2 values for different combinations of weighting. The transformed distance was estimated based on the physical distance, elevation and mean annual rainfall

Appendix E Regionalised L-CV and L-skewness

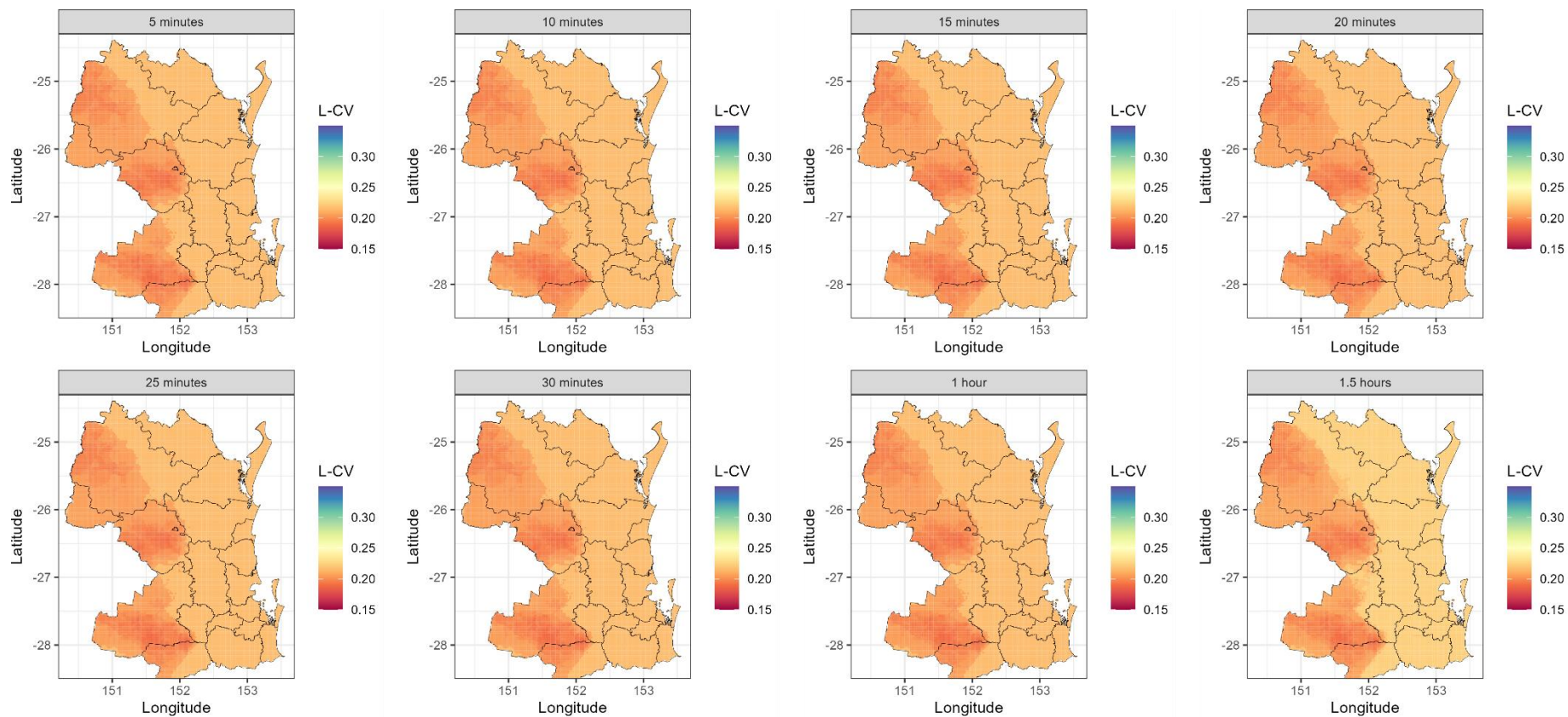


Figure D 1 Gridded L-CV for durations 5 minutes to 1.5 hours

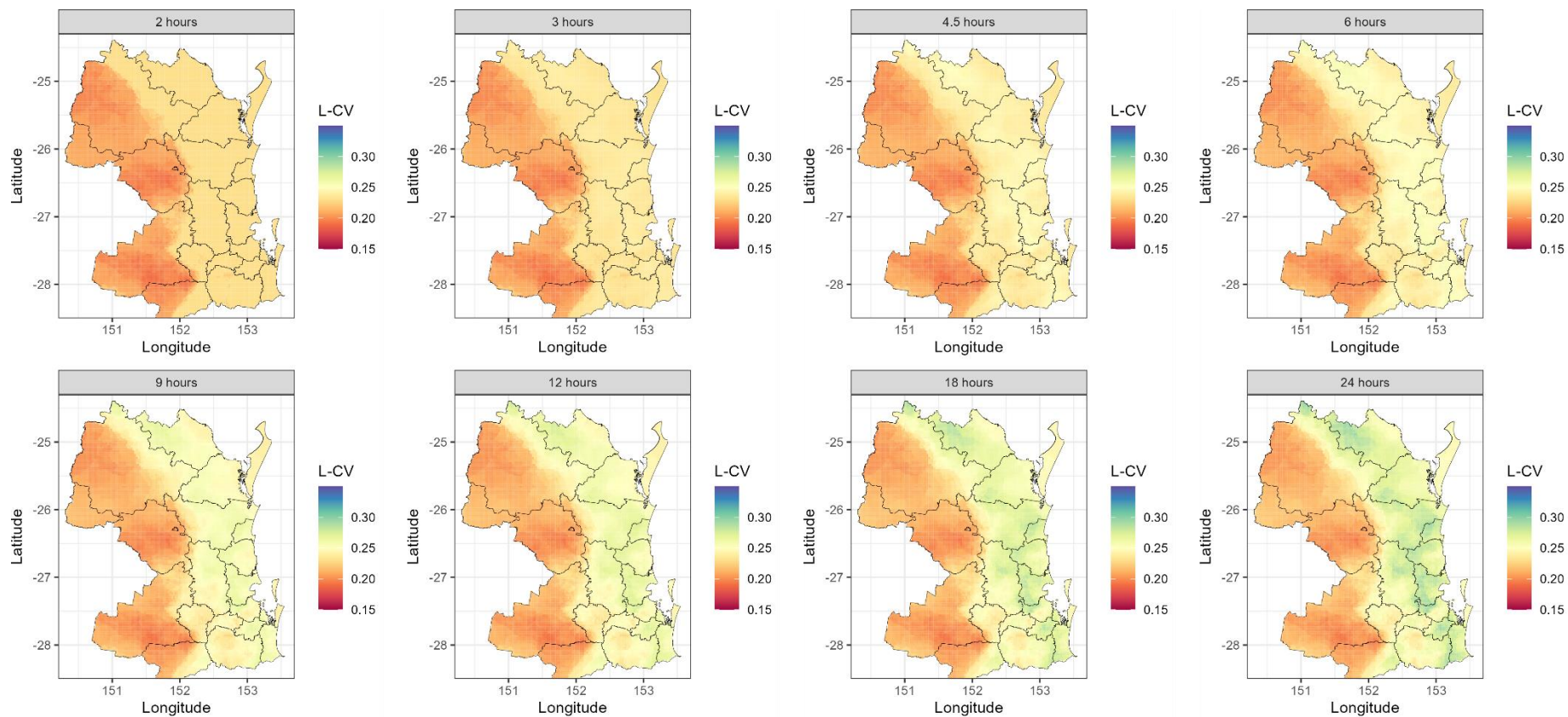


Figure D 2 Gridded L-CV for durations 2 hours to 24 hours

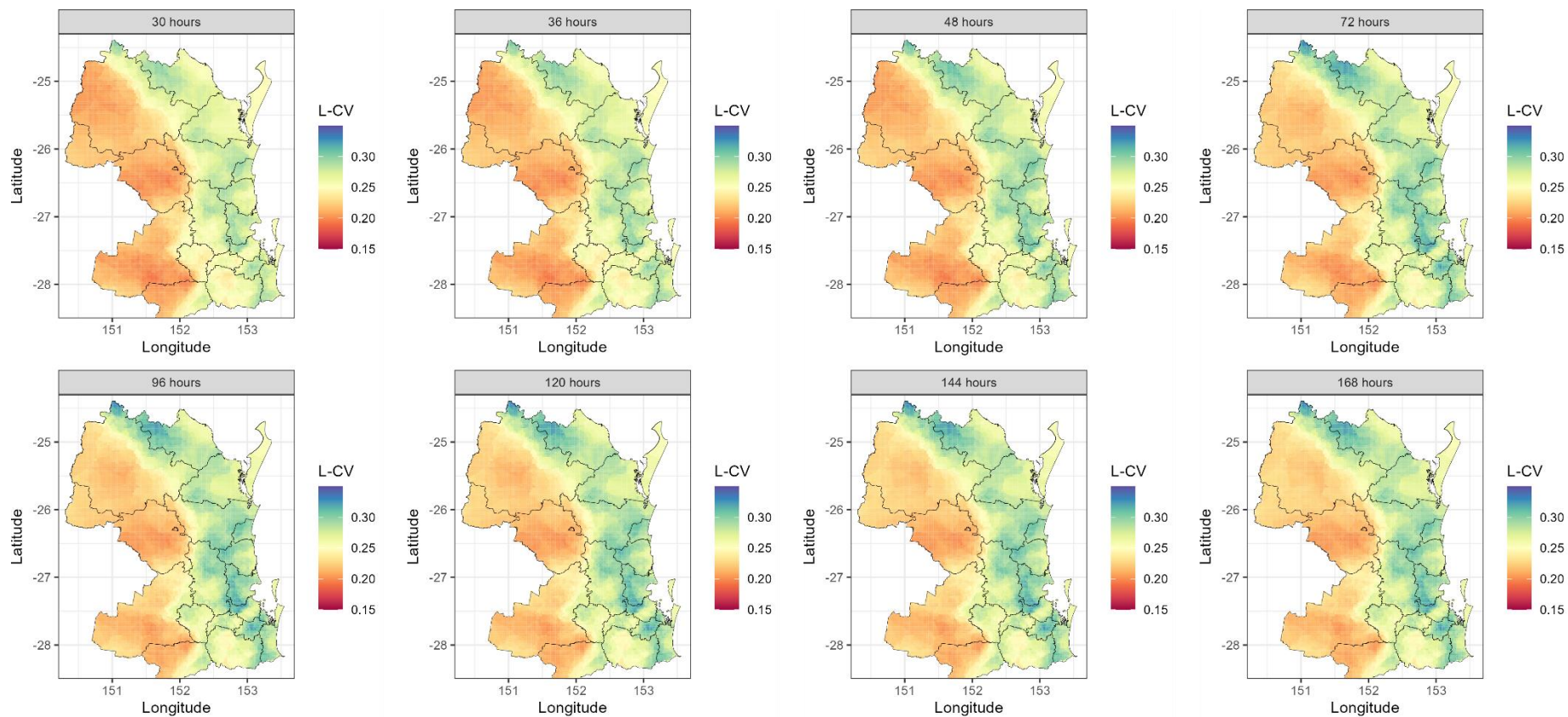


Figure D 3 Gridded L-CV for durations 30 hours to 168 hours

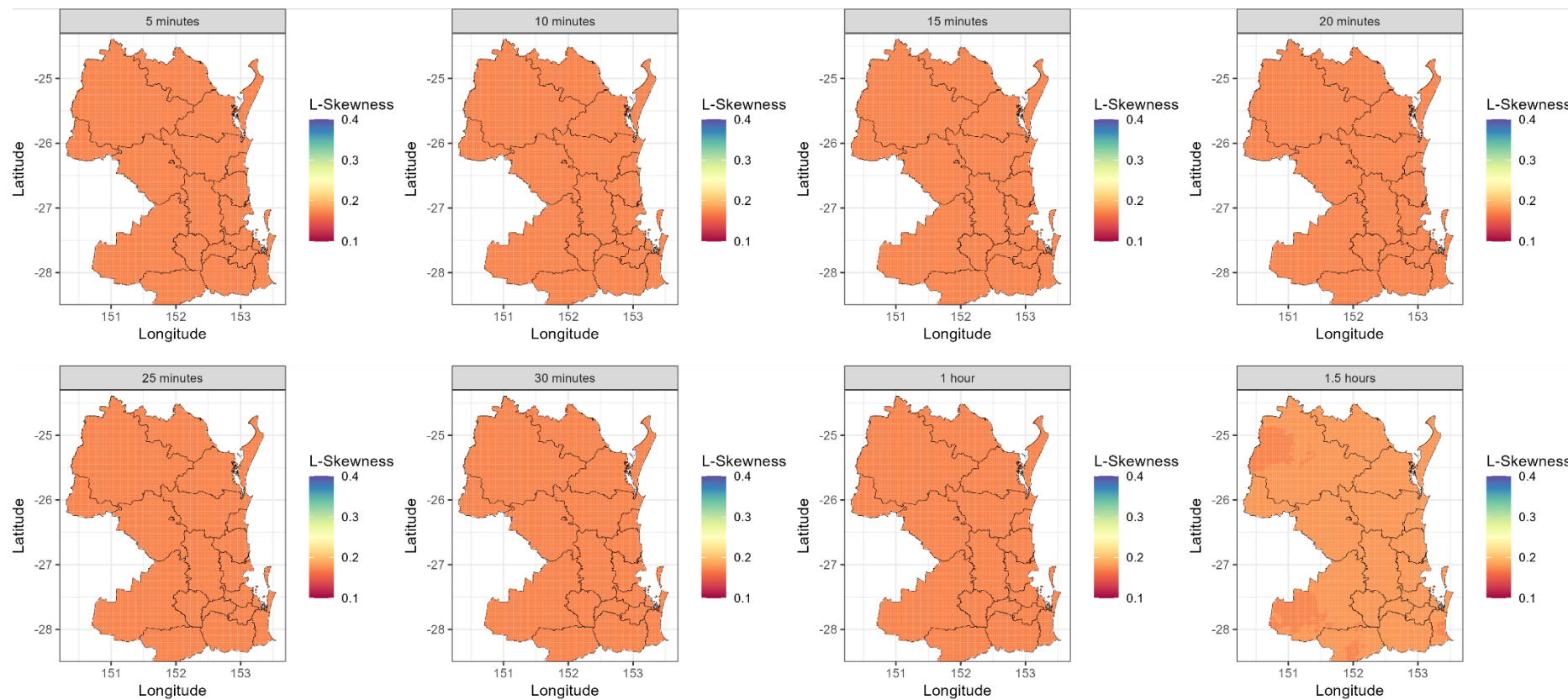


Figure D 4 Gridded L-skewness for durations 5 minutes to 1.5 hours

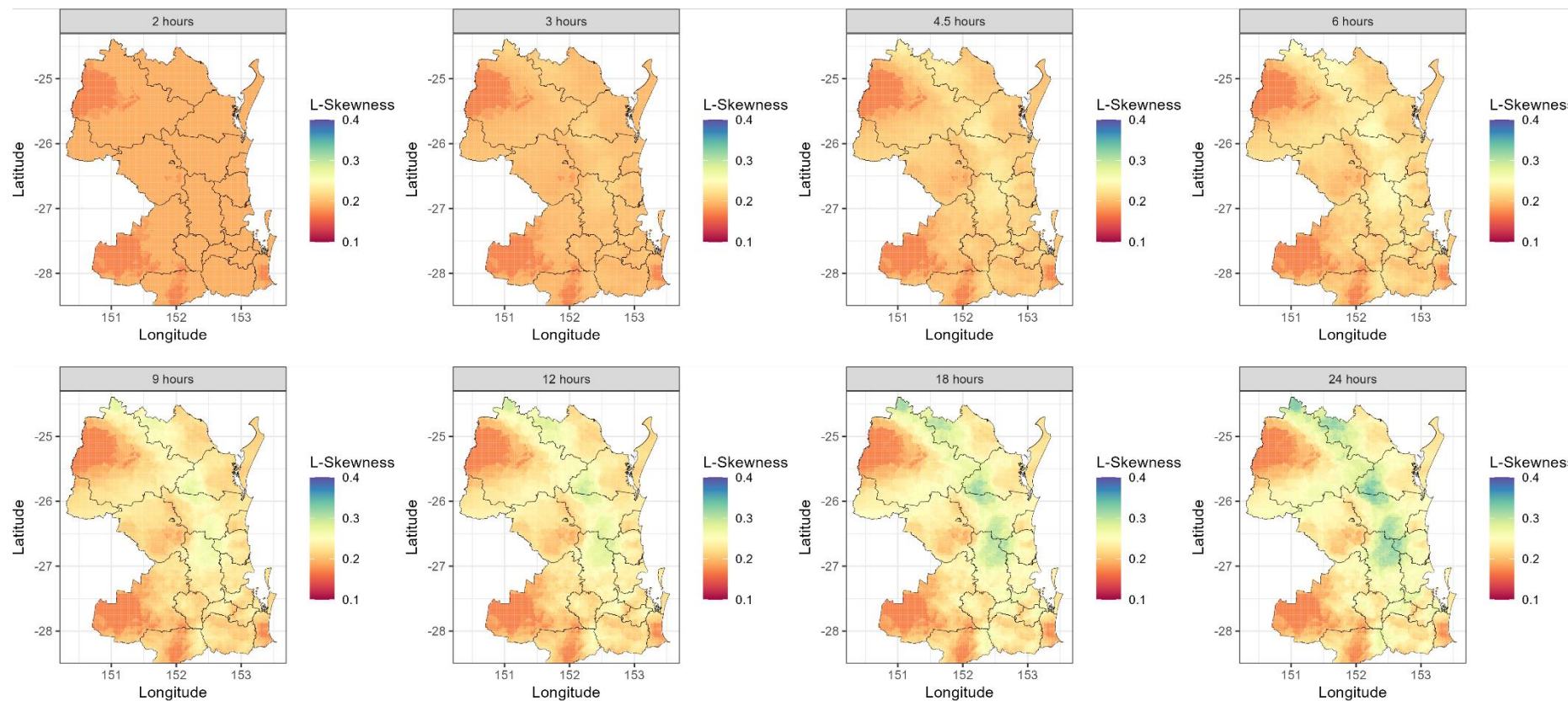


Figure D 5 Gridded L-skewness for durations 2 hours to 24 hours

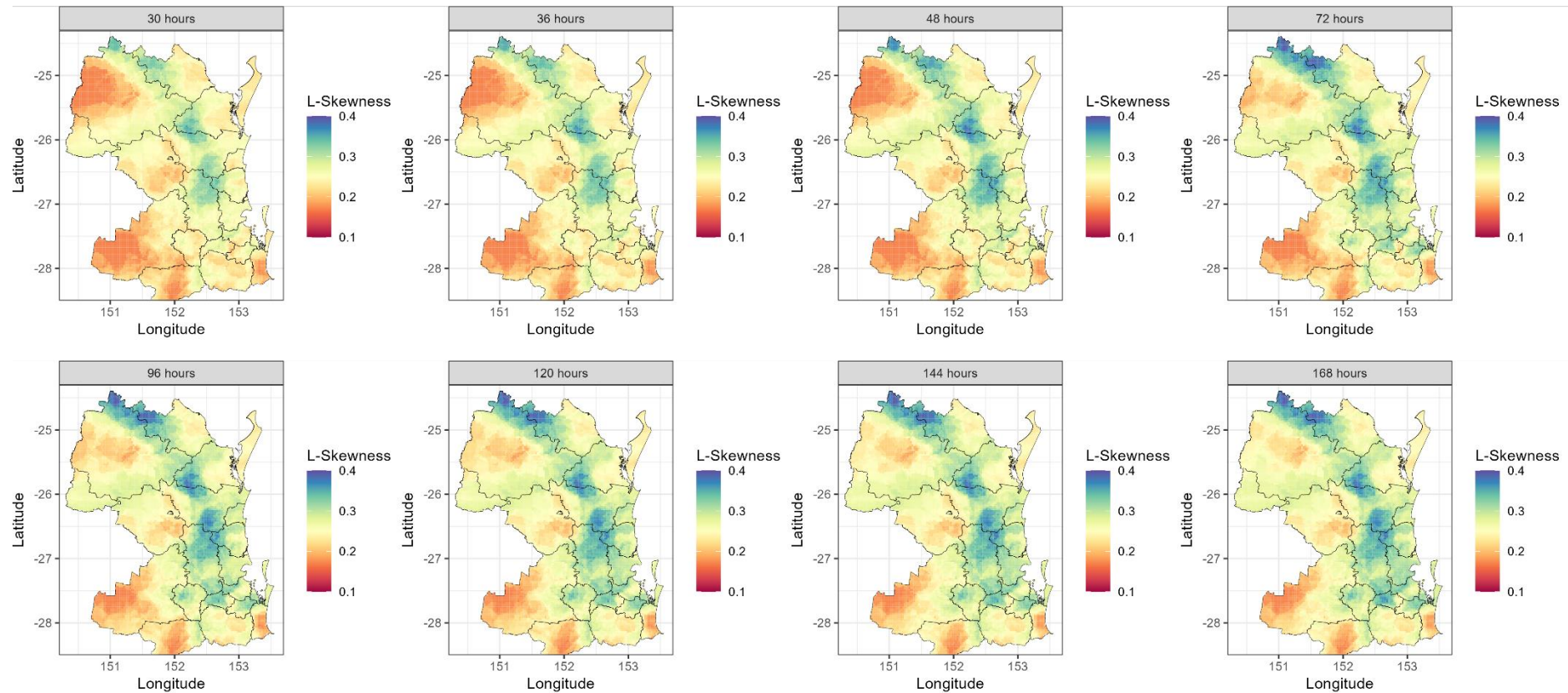


Figure D 6 Gridded L-skewness for durations 30 hours to 168 hours

Appendix F IFD quantiles

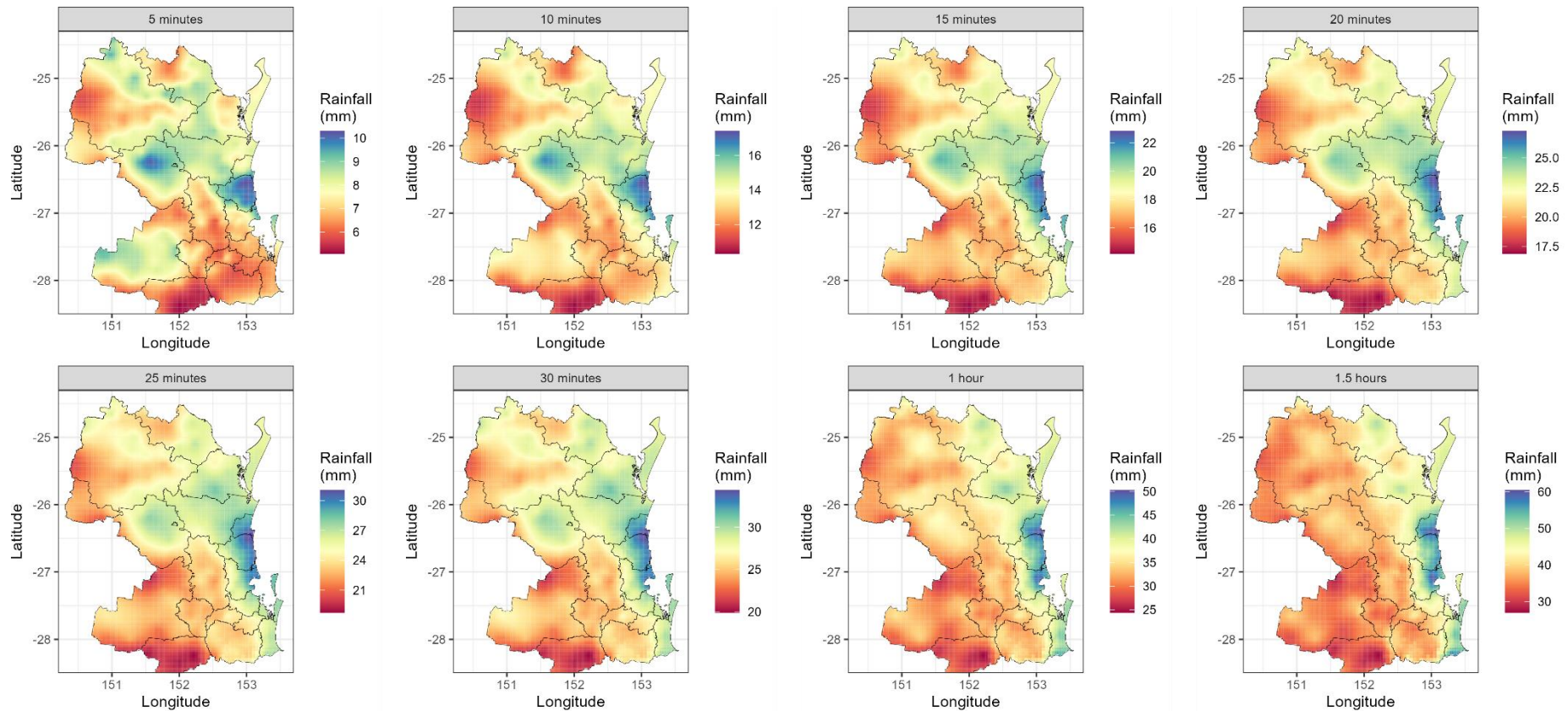


Figure F 1 50% AEP IFDs (5 minutes – 1.5 hours)

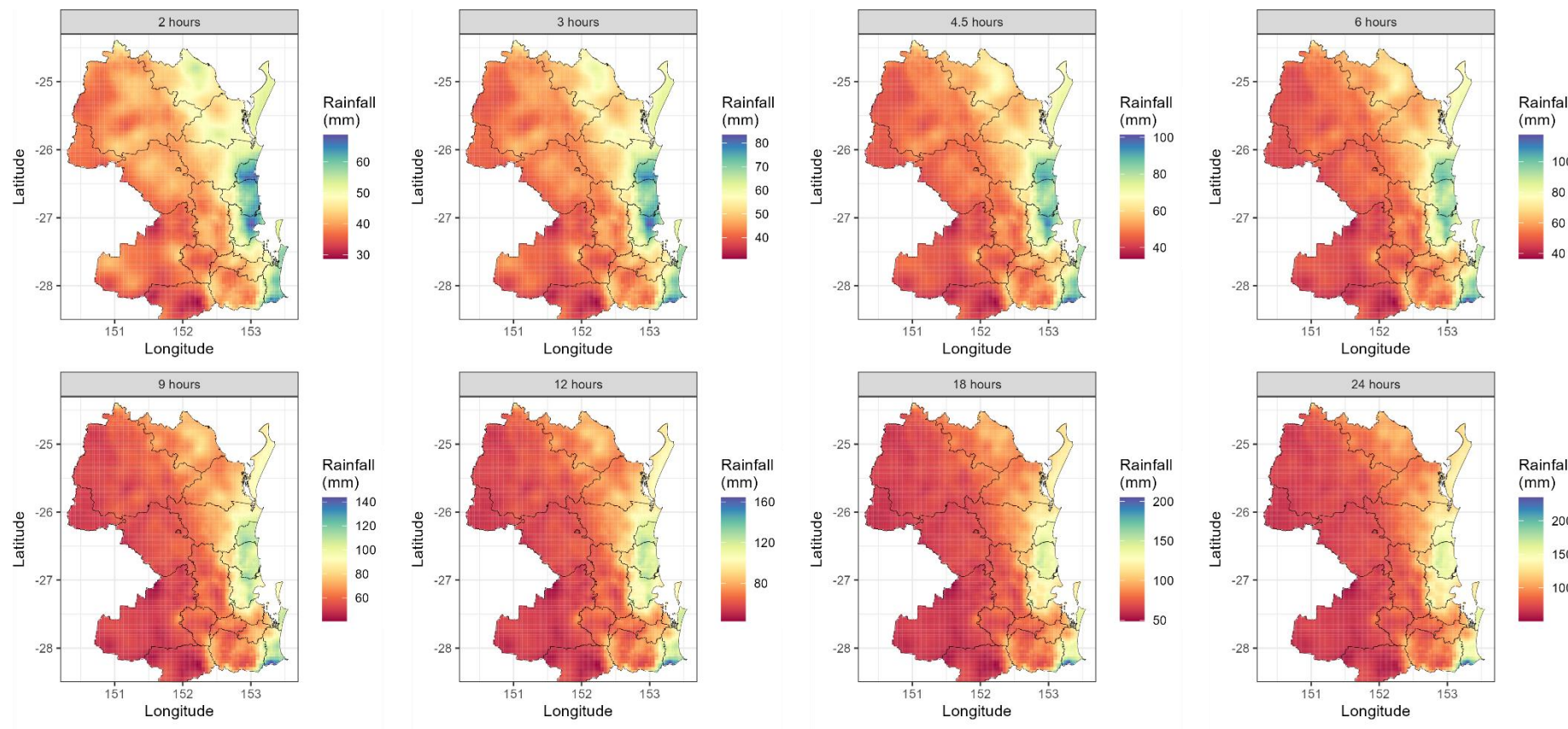


Figure F 2 50% AEP IFDs (2 hours – 24 hours)

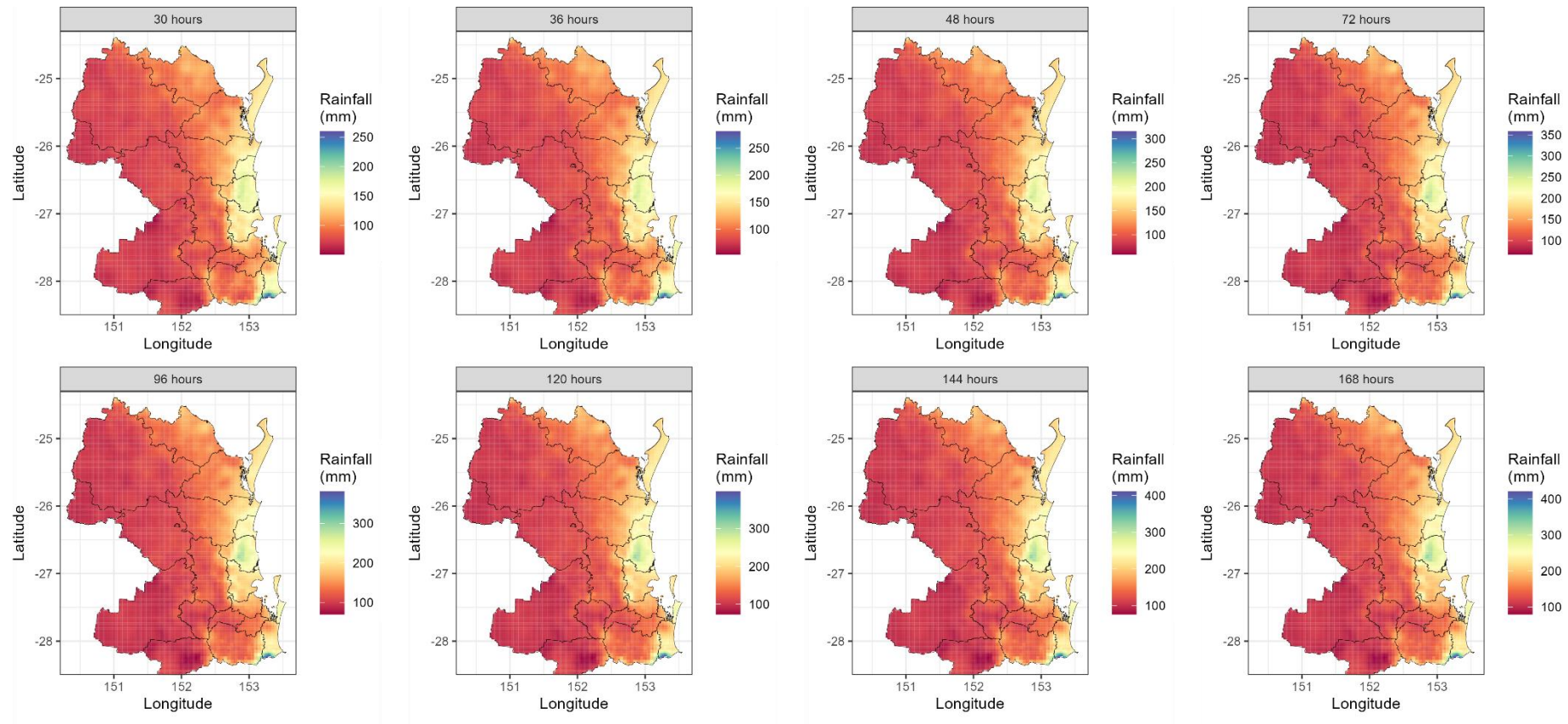


Figure F 3 50% AEP IFDs (30 hours – 168 hours)

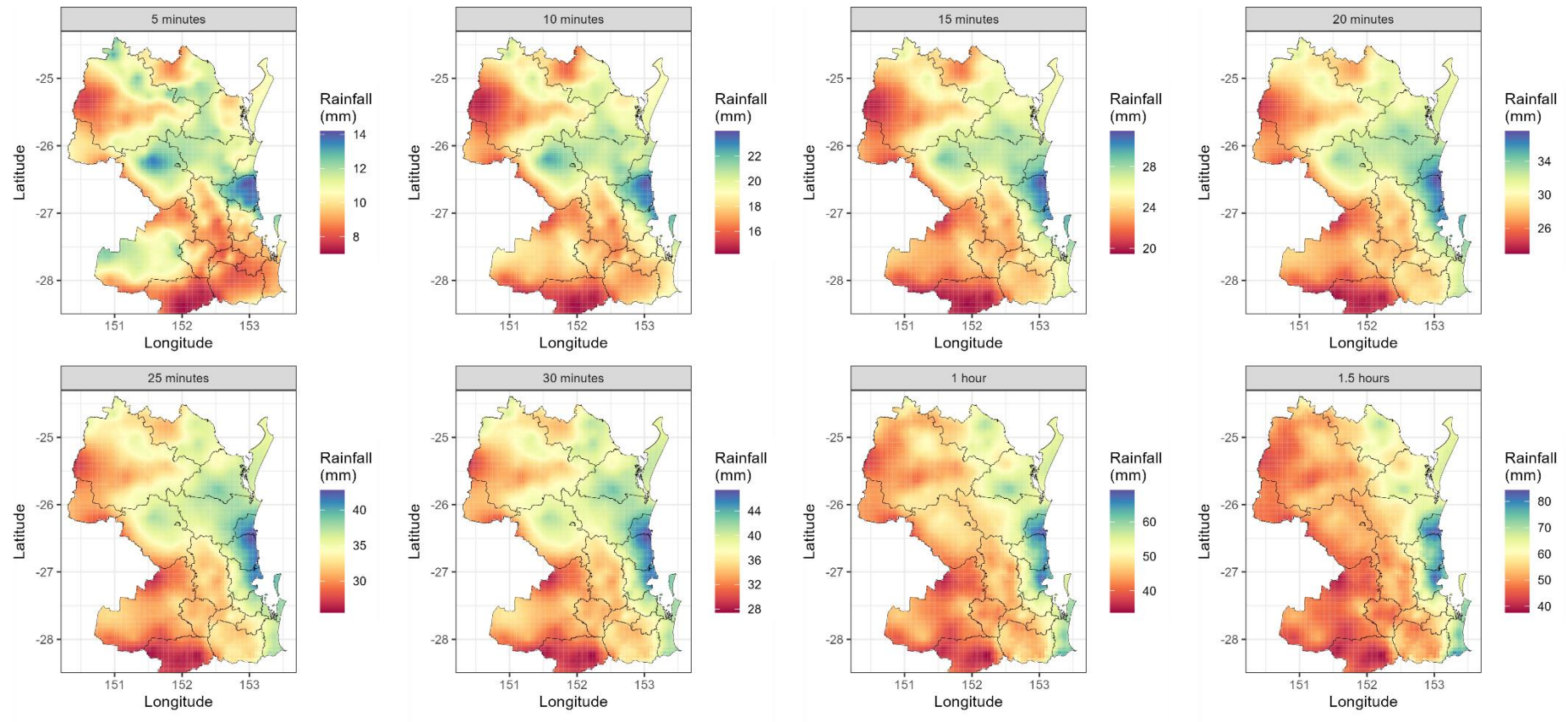


Figure F 4 20% AEP IFDs (5 minutes – 1.5 hours)

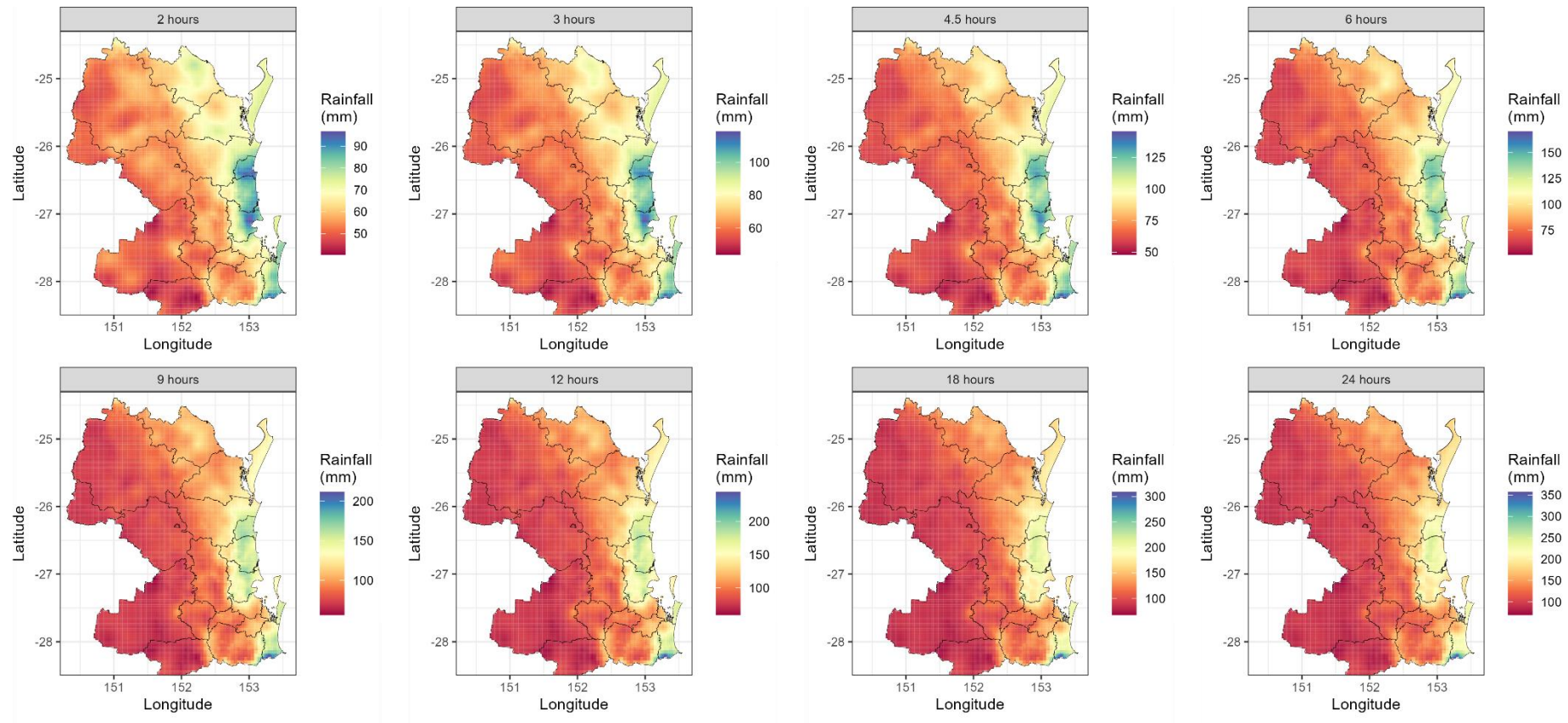


Figure F 5 20% AEP IFDs (2 hours – 24 hours)

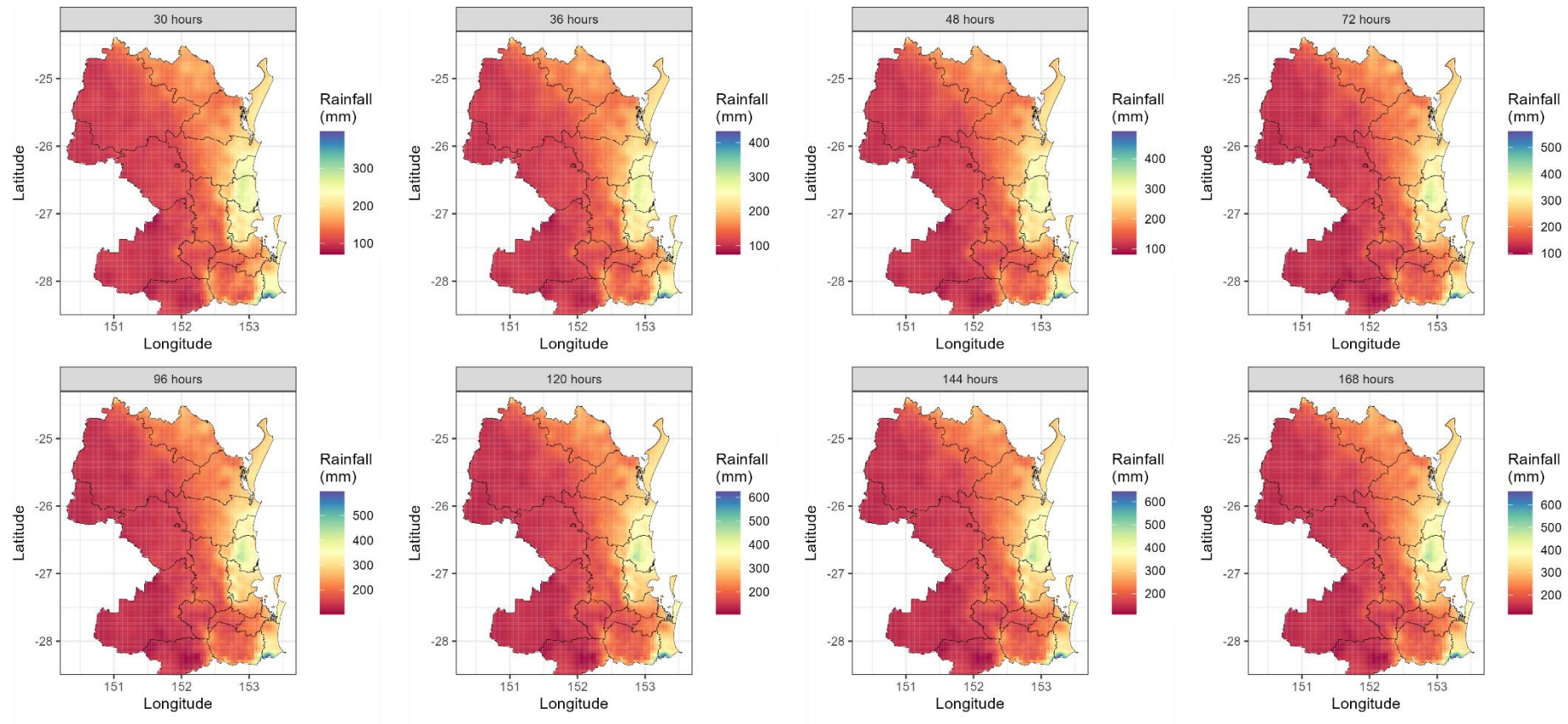


Figure F 6 20% AEP IFDs (30 hours – 168 hours)

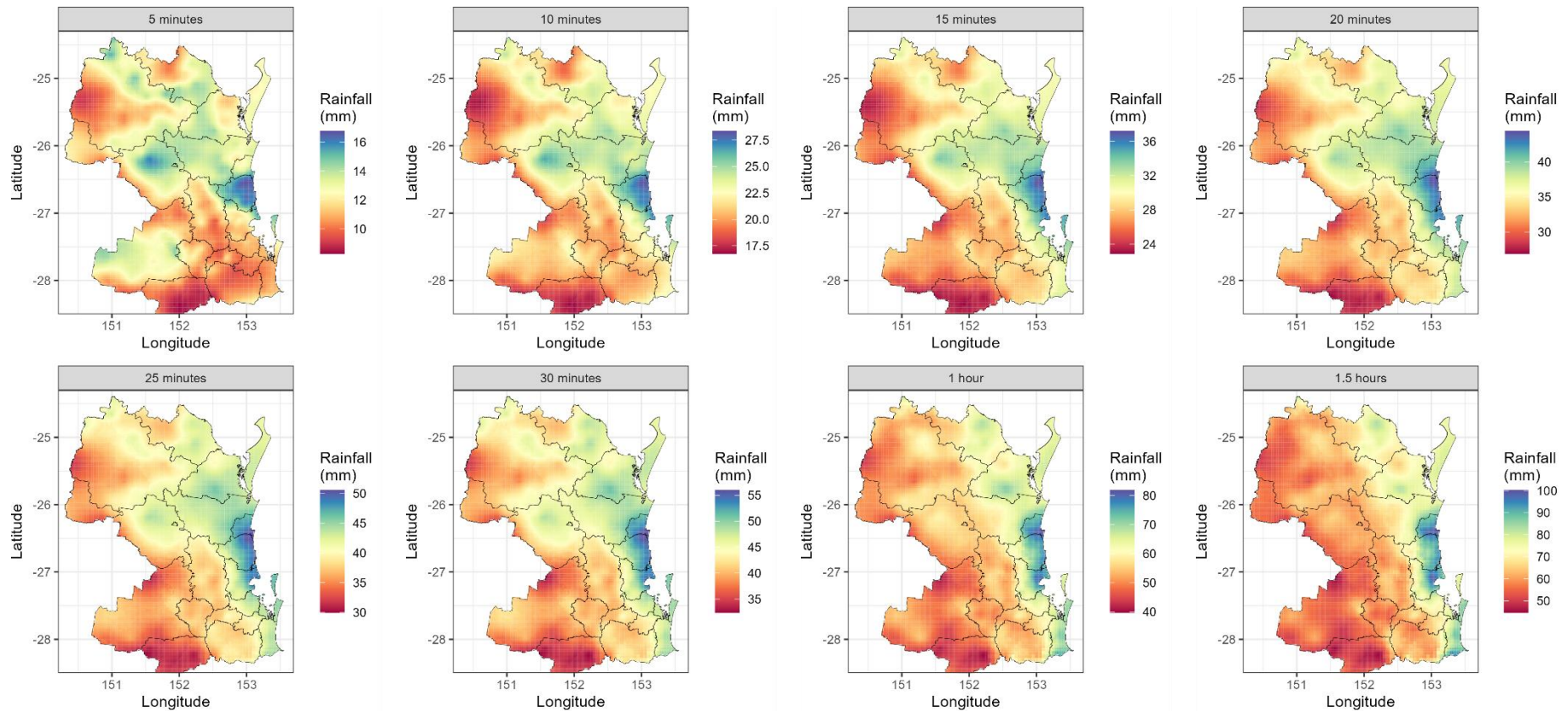


Figure F 7 10% AEP IFDs (5 minutes – 1.5 hours)

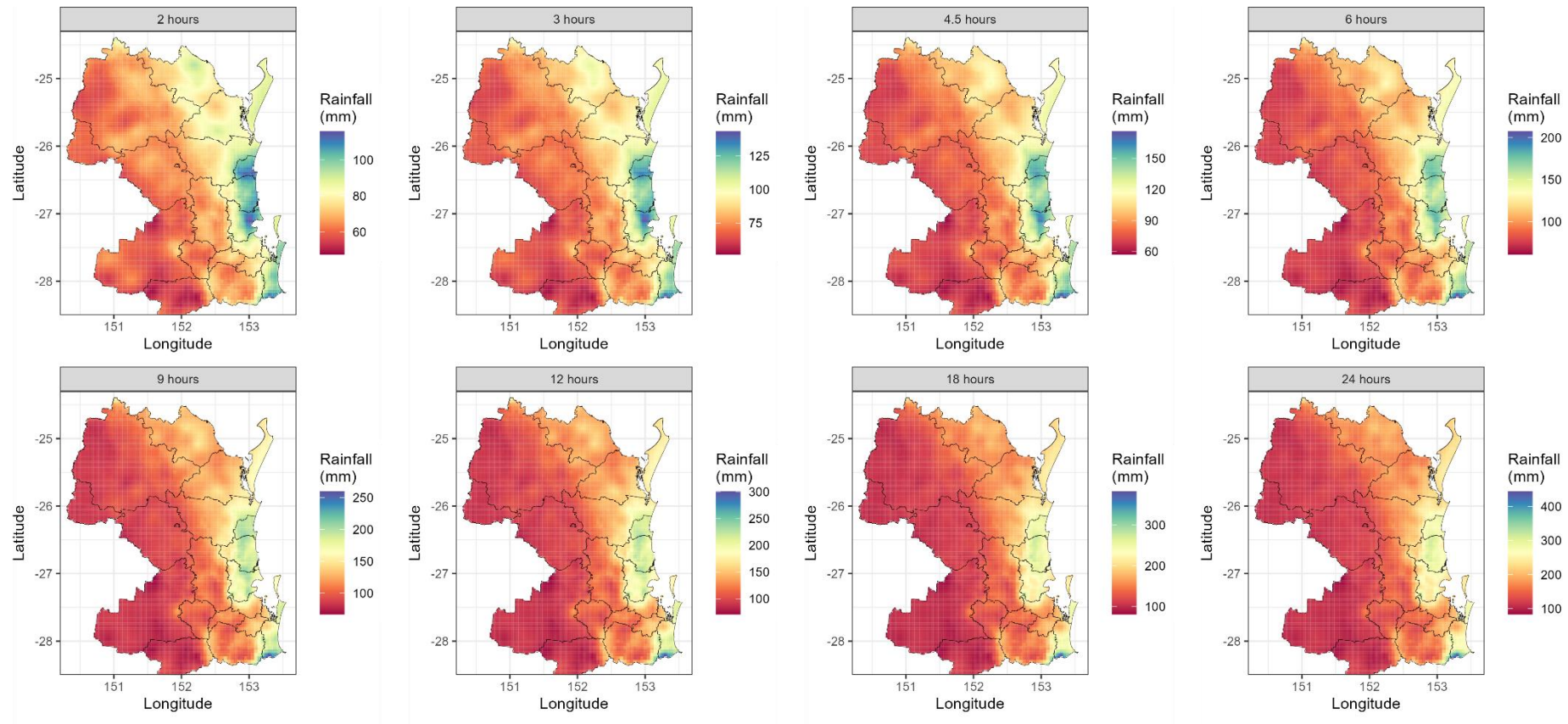


Figure F 8 10% AEP IFDs (2 hours – 24 hours)

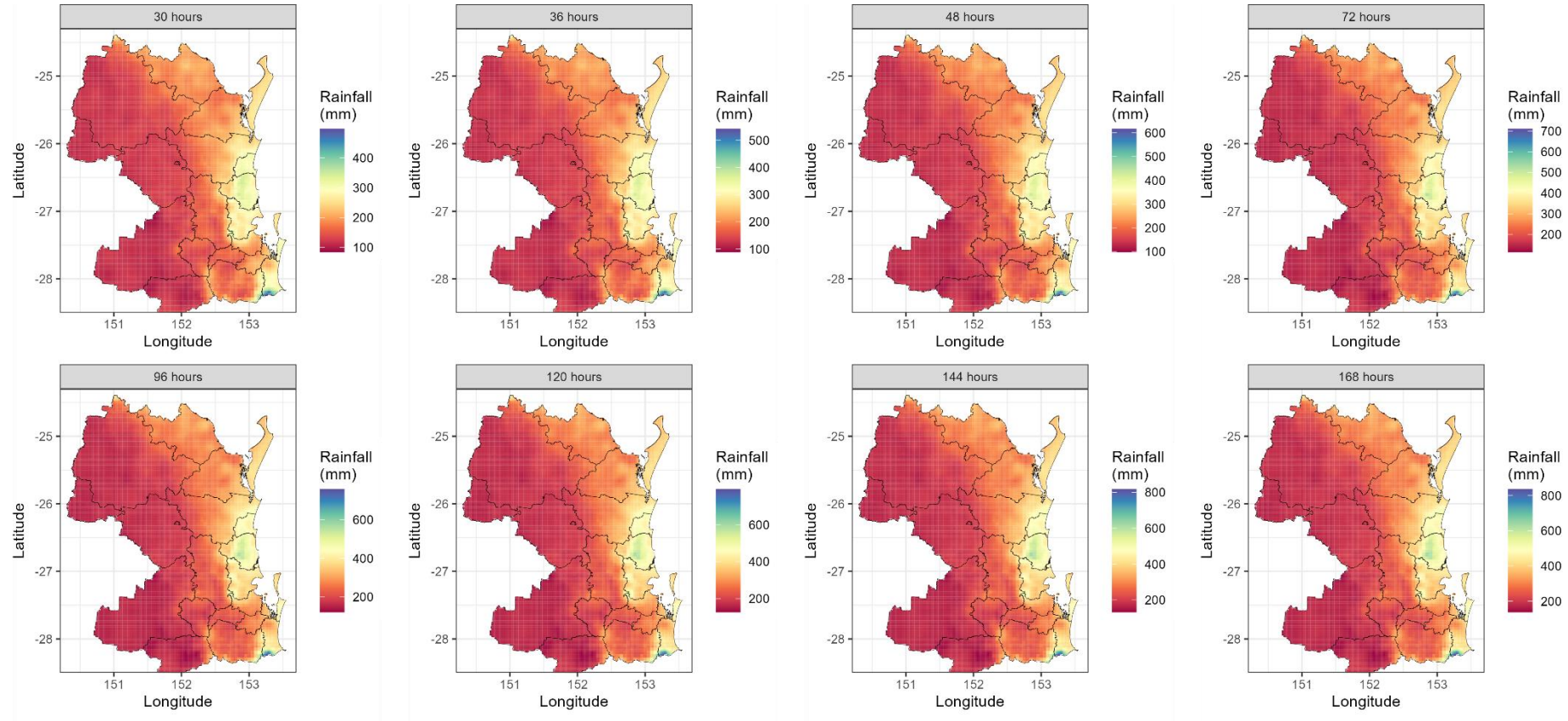


Figure F 9 10% AEP IFDs (30 hours – 168 hours)

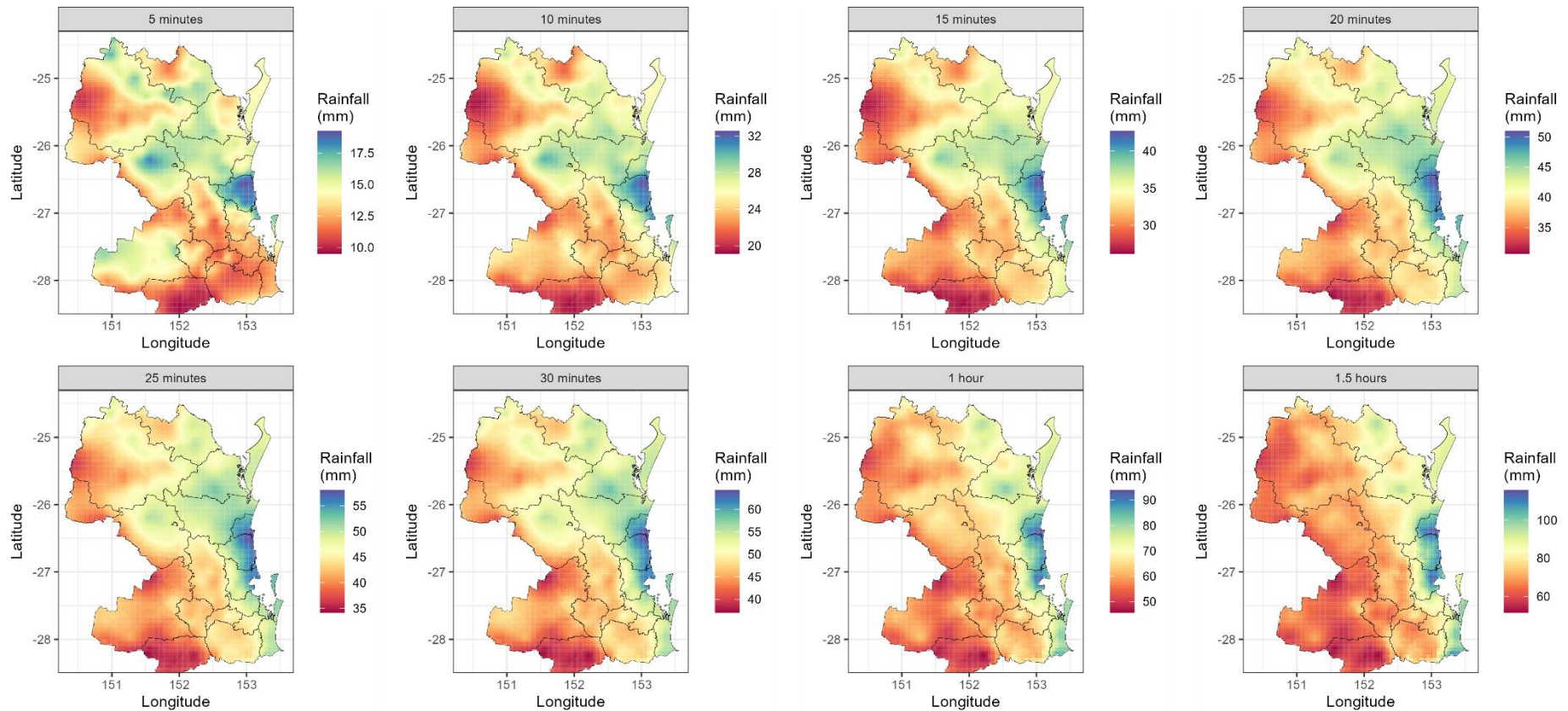


Figure F 10 5% AEP IFDs (5 minutes – 1.5 hours)

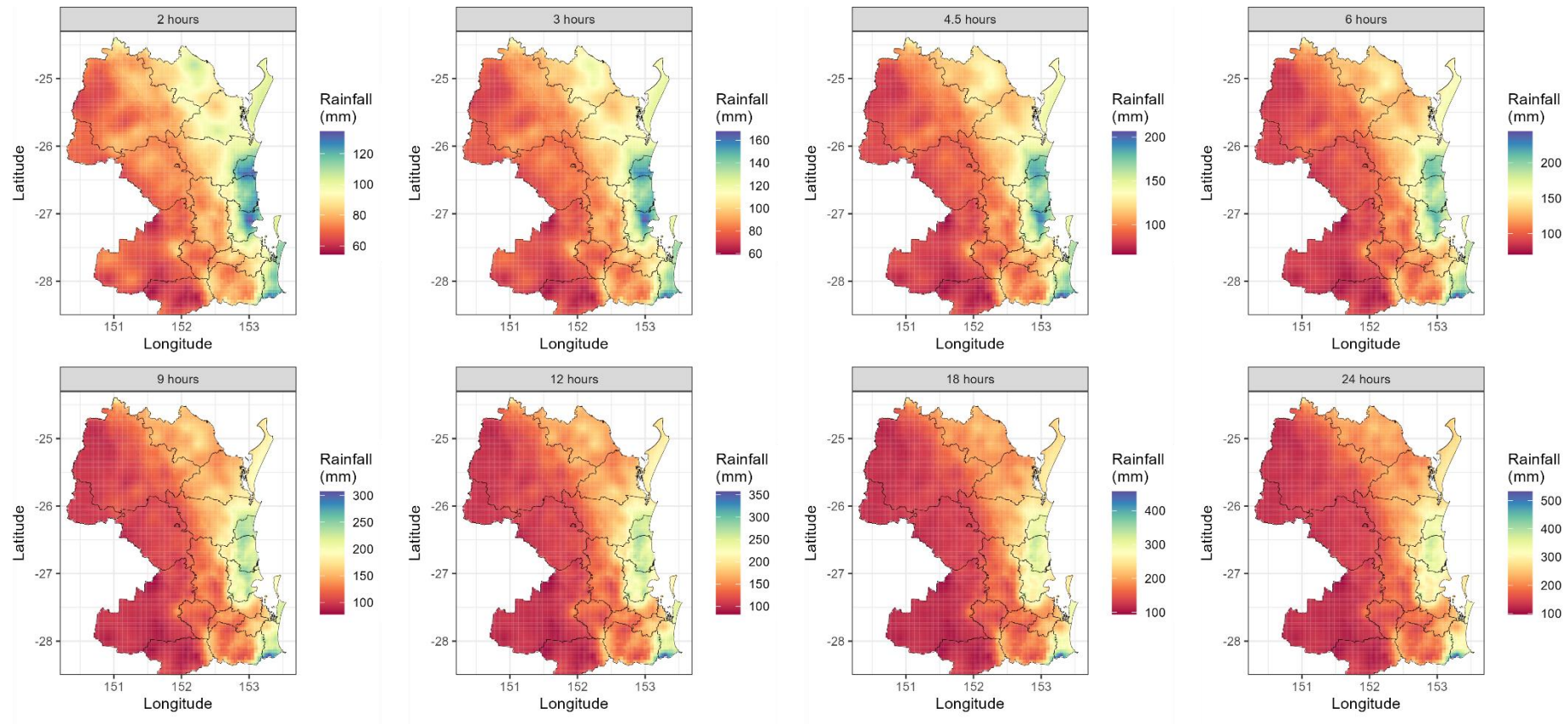


Figure F 11 5% AEP IFDs (2 hours – 24 hours)

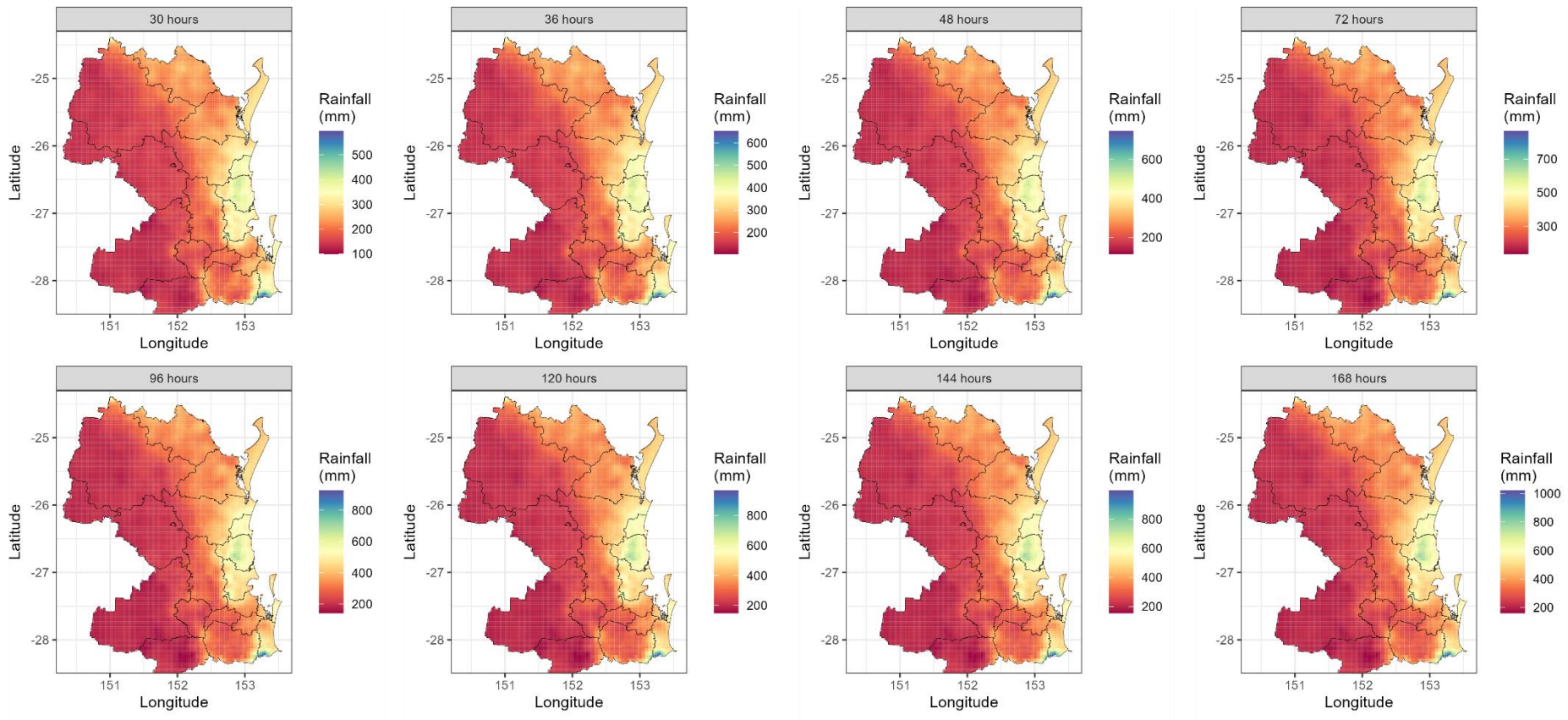


Figure F 12 5% AEP IFDs (30 hours – 168 hours)

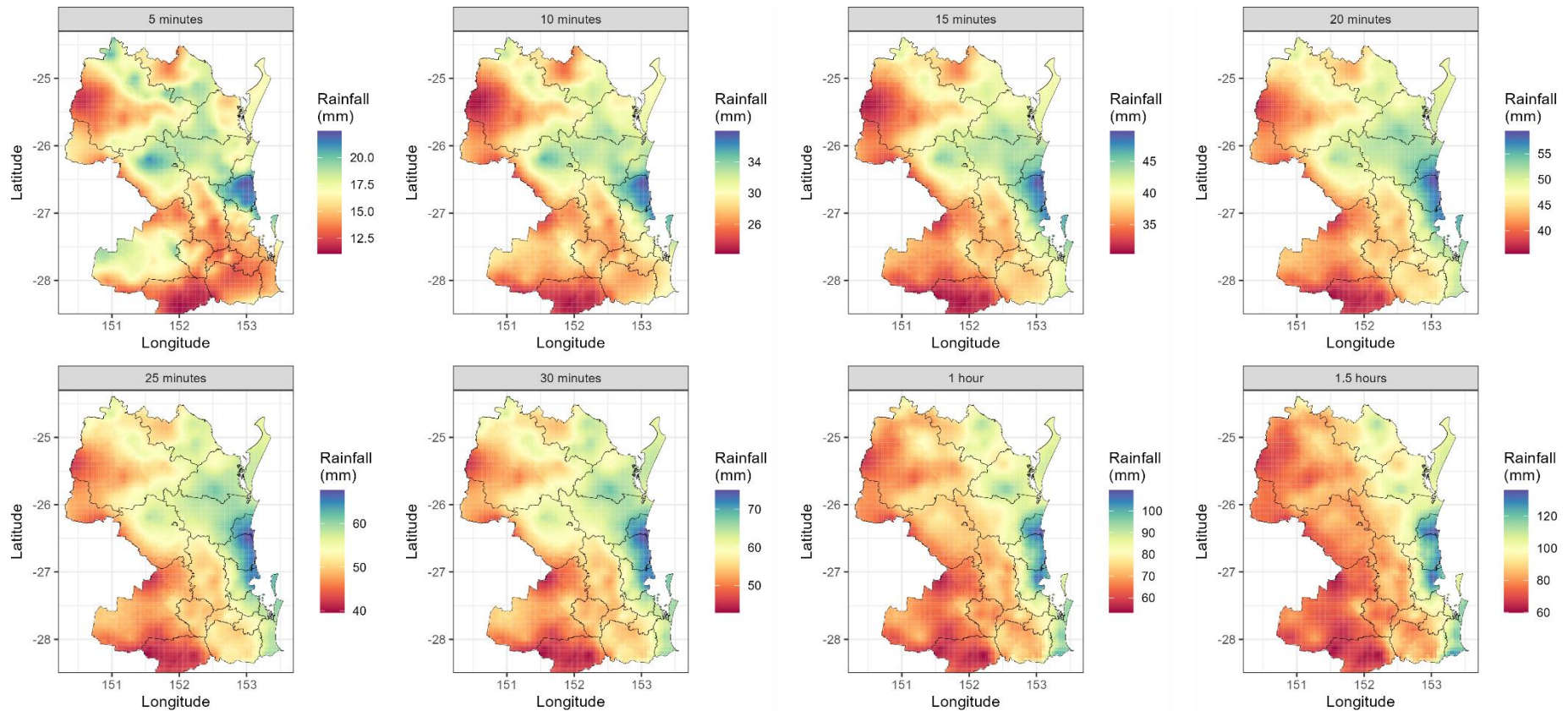


Figure F 13 2% AEP IFDs (5 minutes – 1.5 hours)

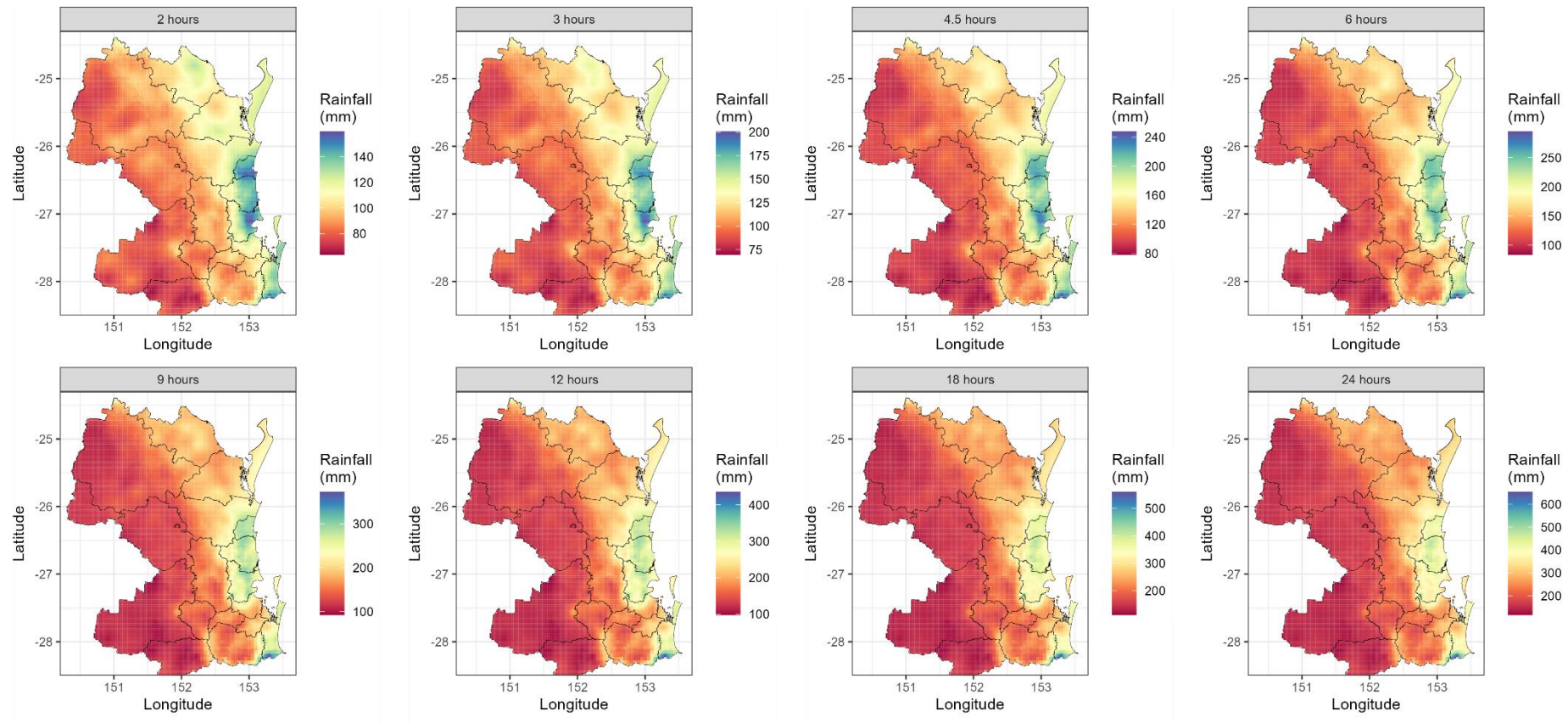


Figure F 14 2% AEP IFDs (2 hours – 24 hours)

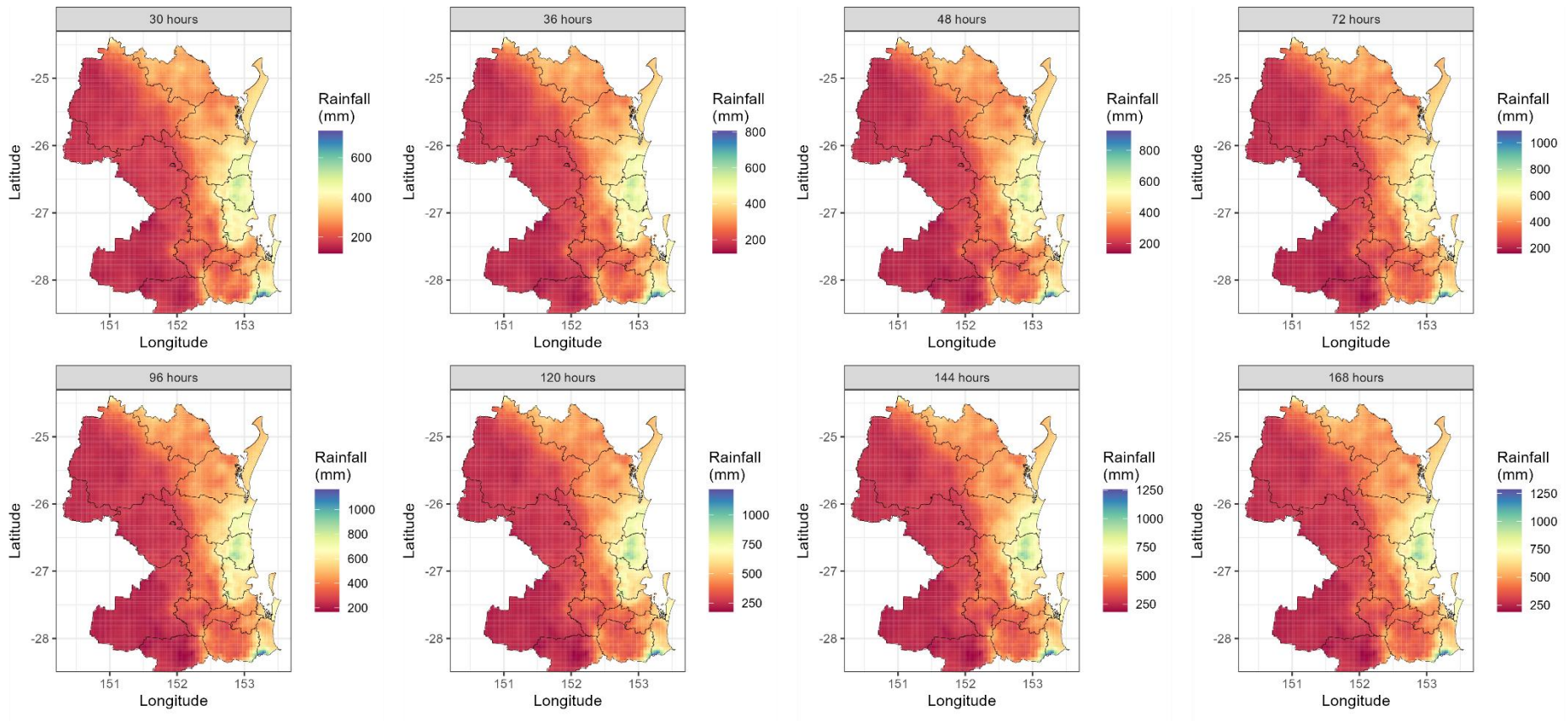


Figure F 15 2% AEP IFDs (30 hours – 168 hours)

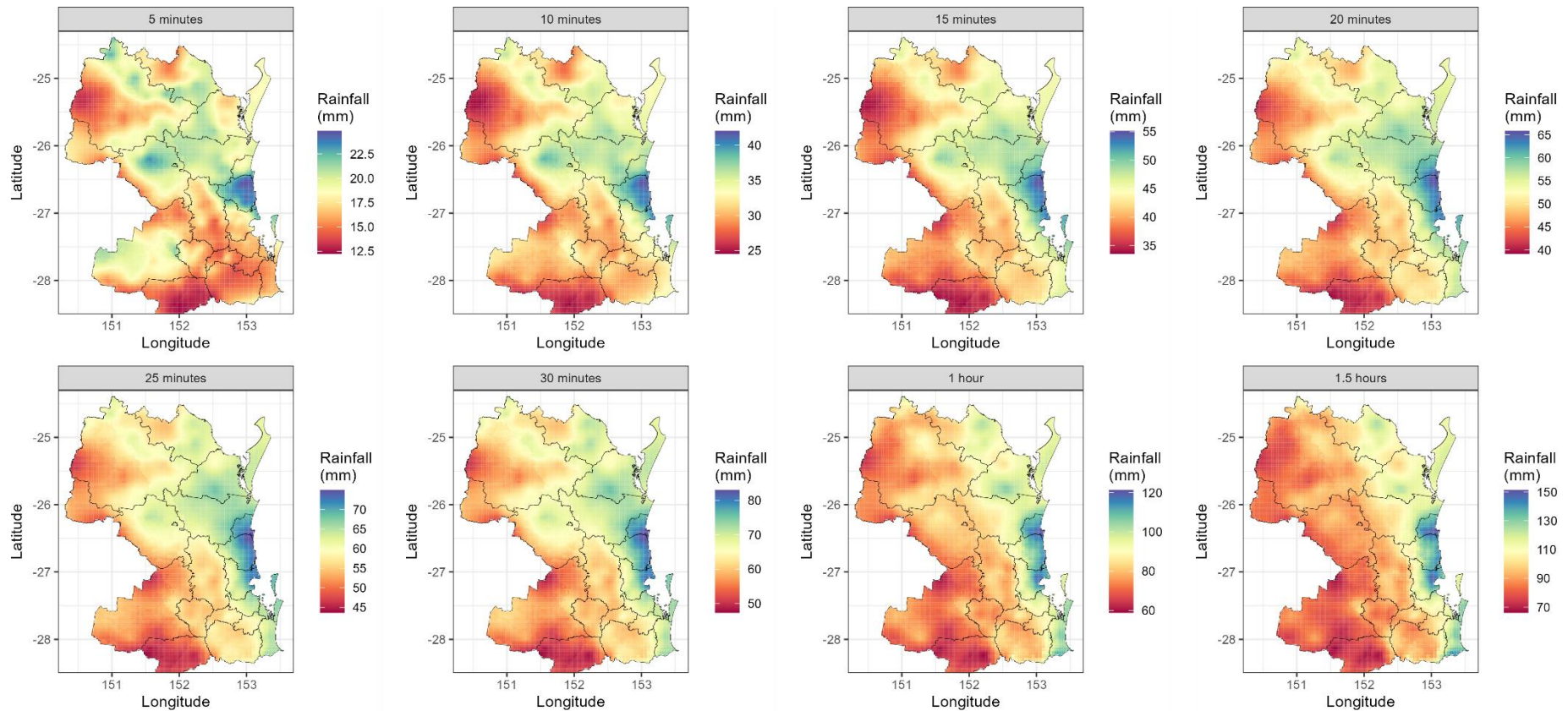


Figure F 16 1% AEP IFDs (5 minutes – 1.5 hours)

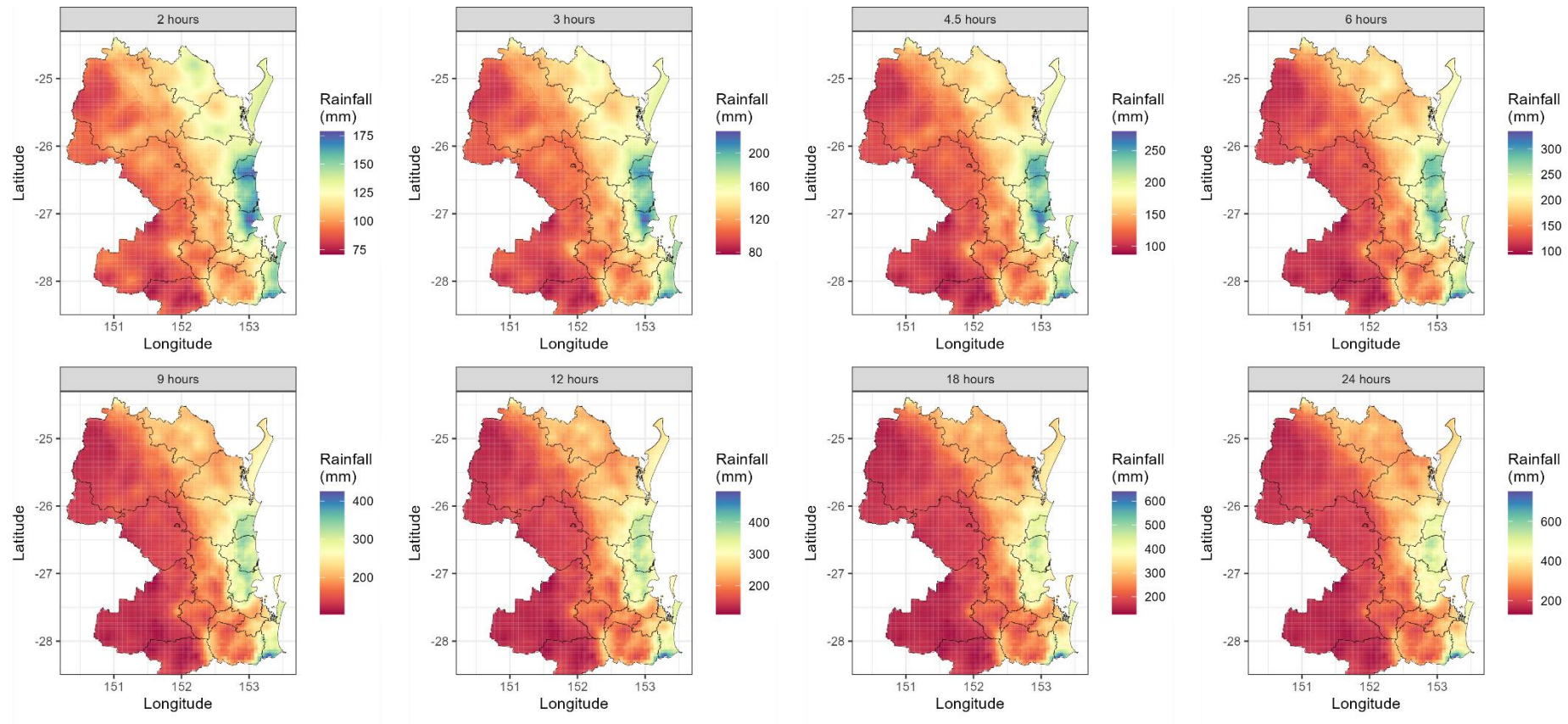


Figure F 17 1% AEP IFDs (2 hours – 24 hours)

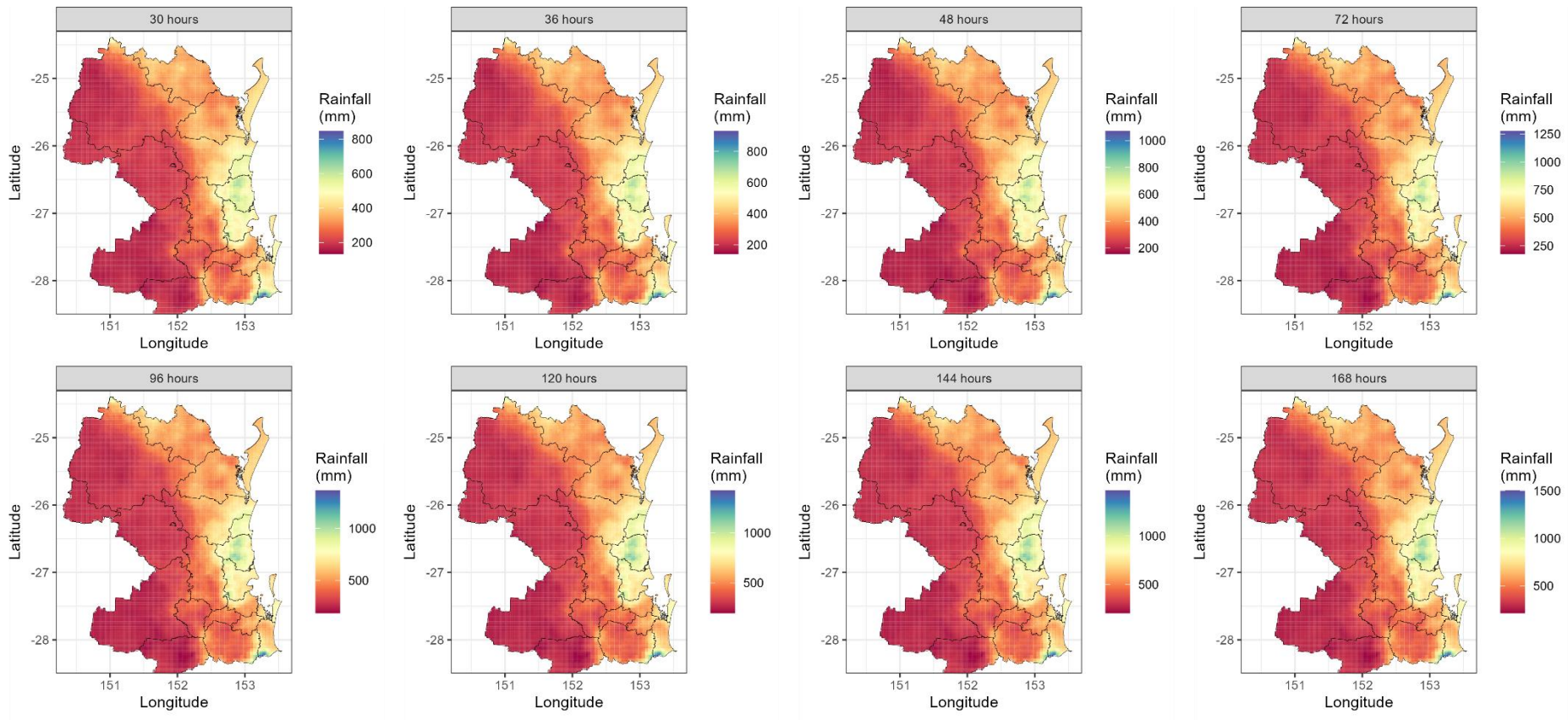


Figure F 18 1% AEP IFDs (30 hours – 168 hours)

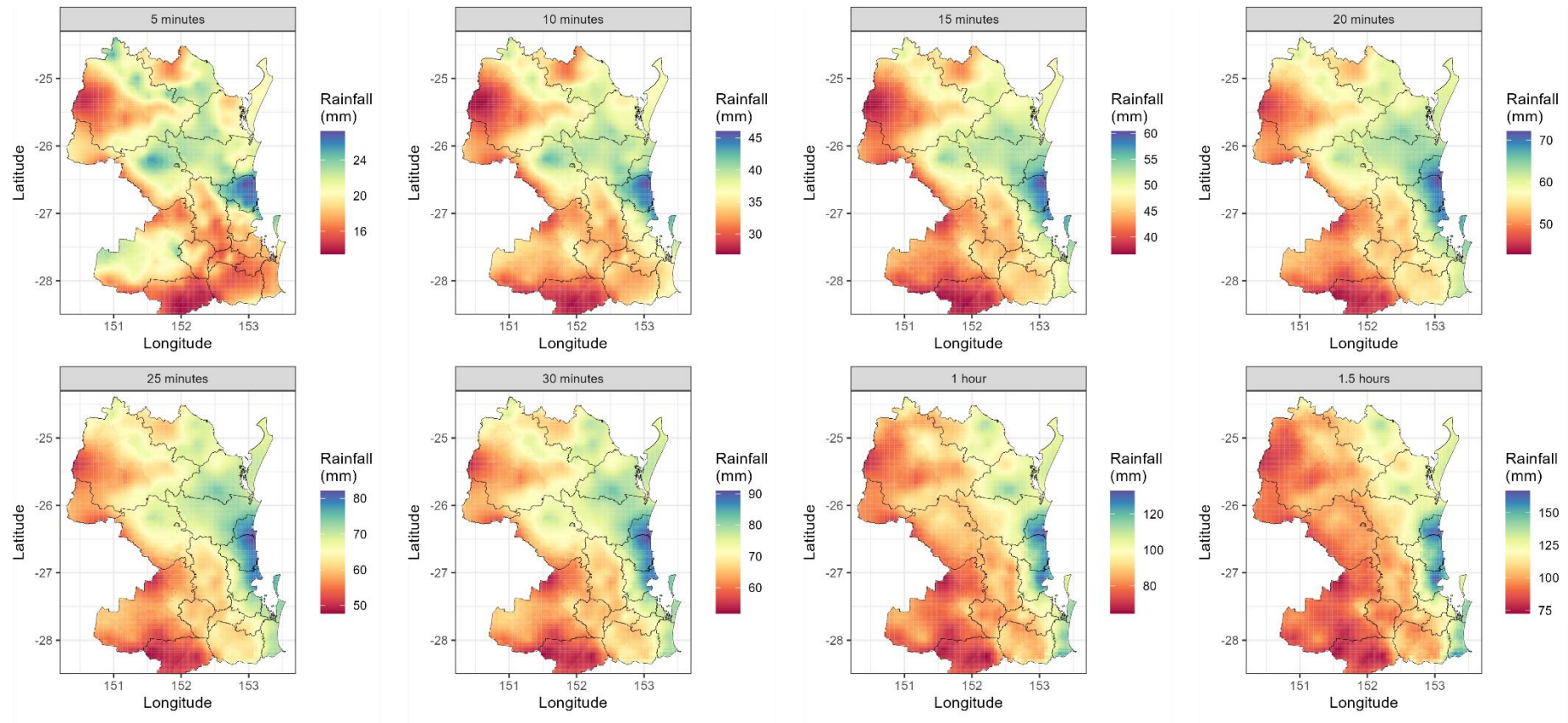


Figure F 19 1 in 200 AEP IFDs (5 minutes – 1.5 hours)

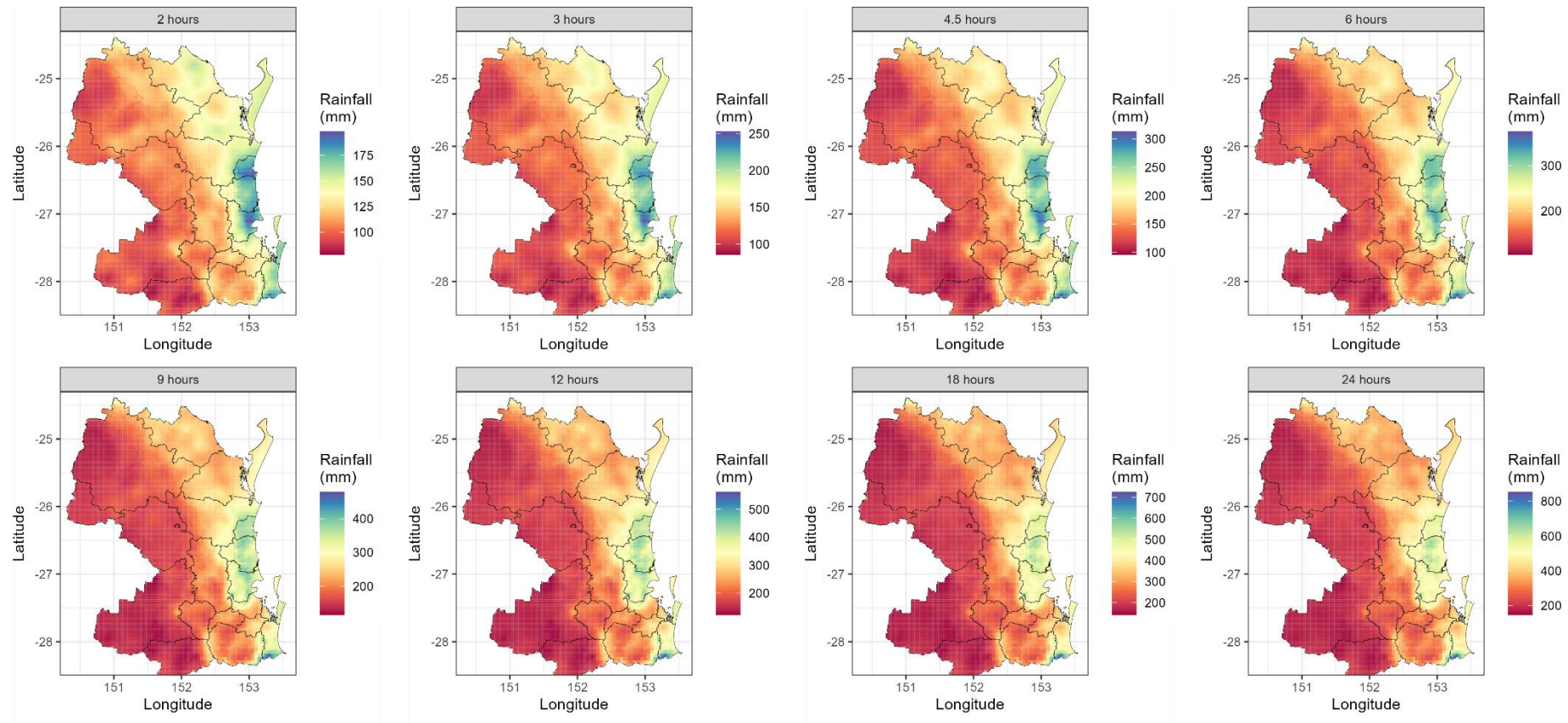


Figure F 20 1 in 200 AEP IFDs (2 hours – 24 hours)

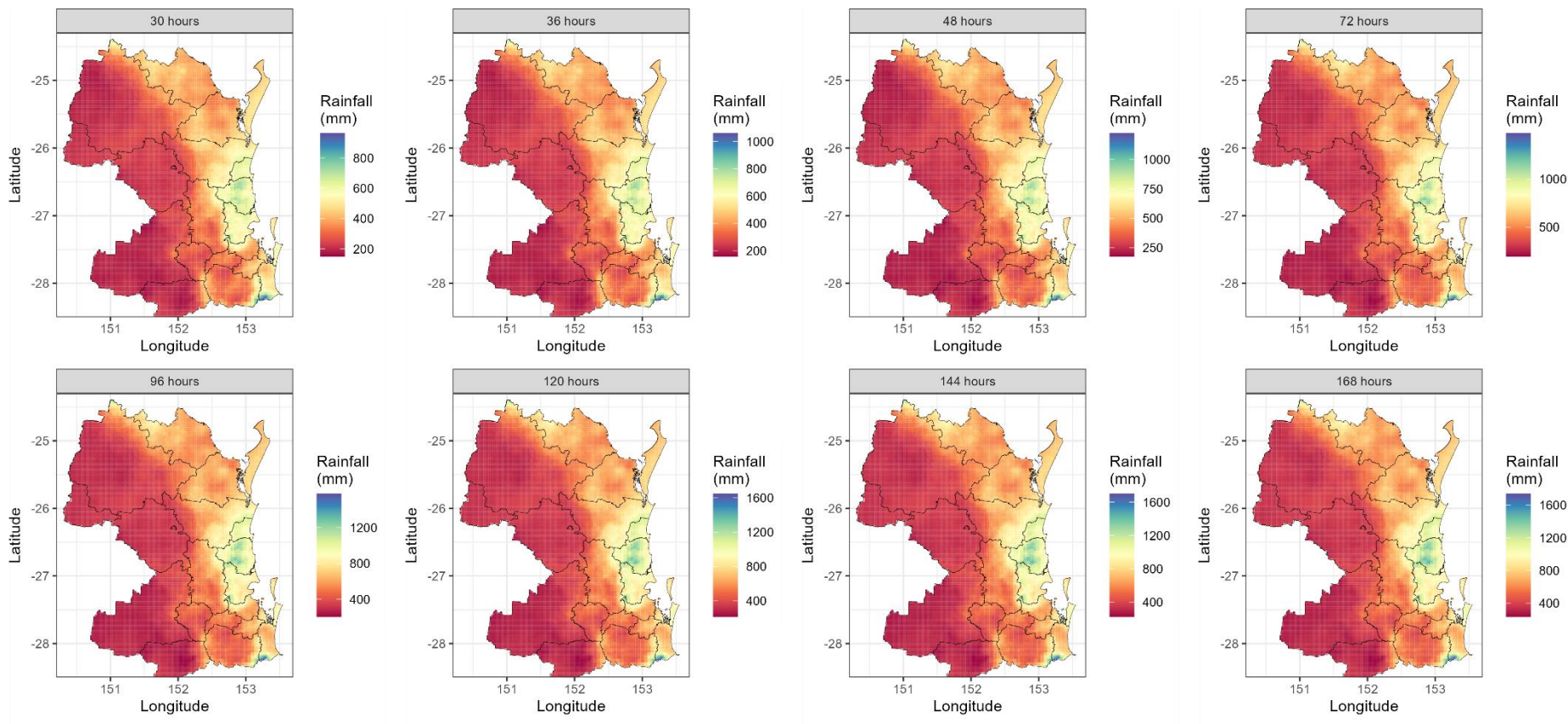


Figure F 21 1 in 200 AEP IFDs (30 hours – 168 hours)

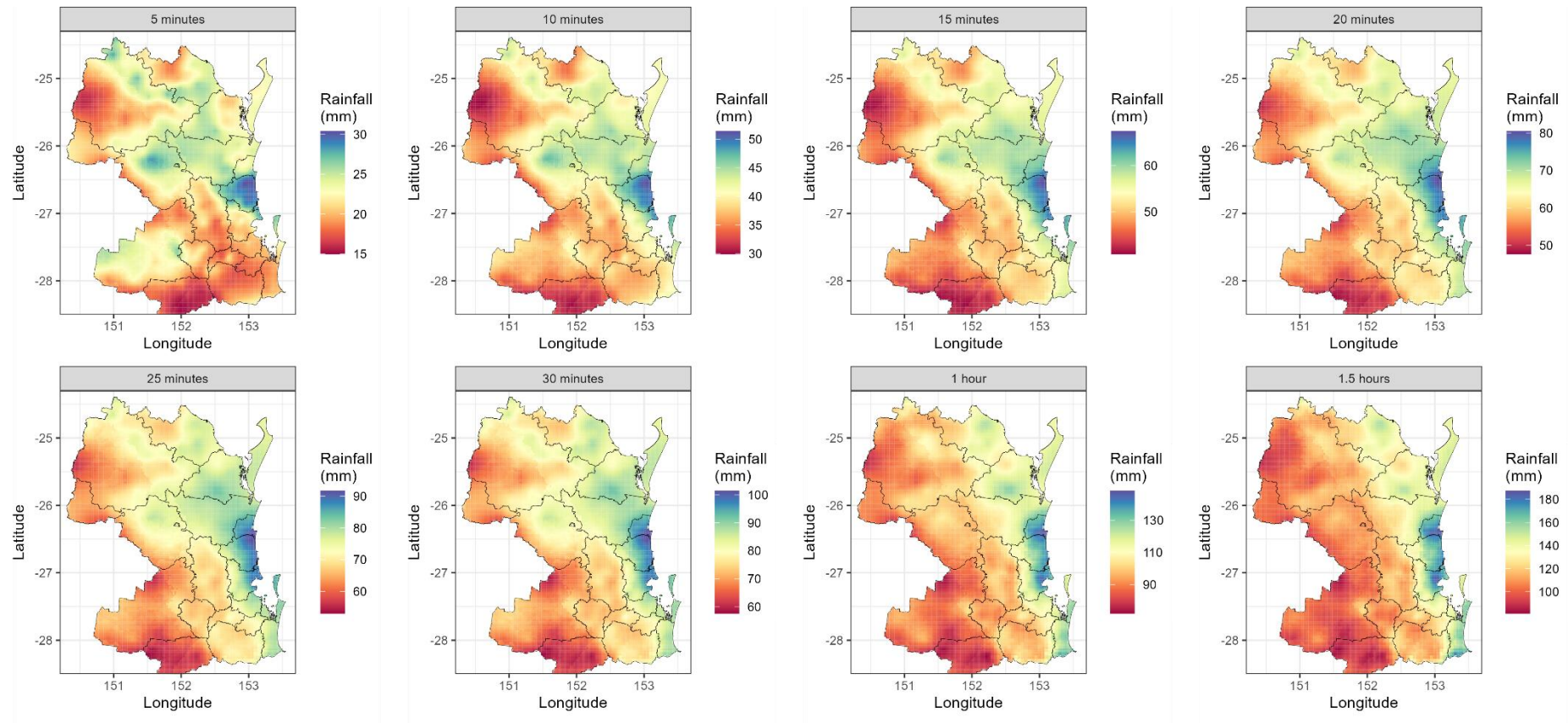


Figure F 22 1 in 500 AEP IFDs (5 minutes – 1.5 hours)

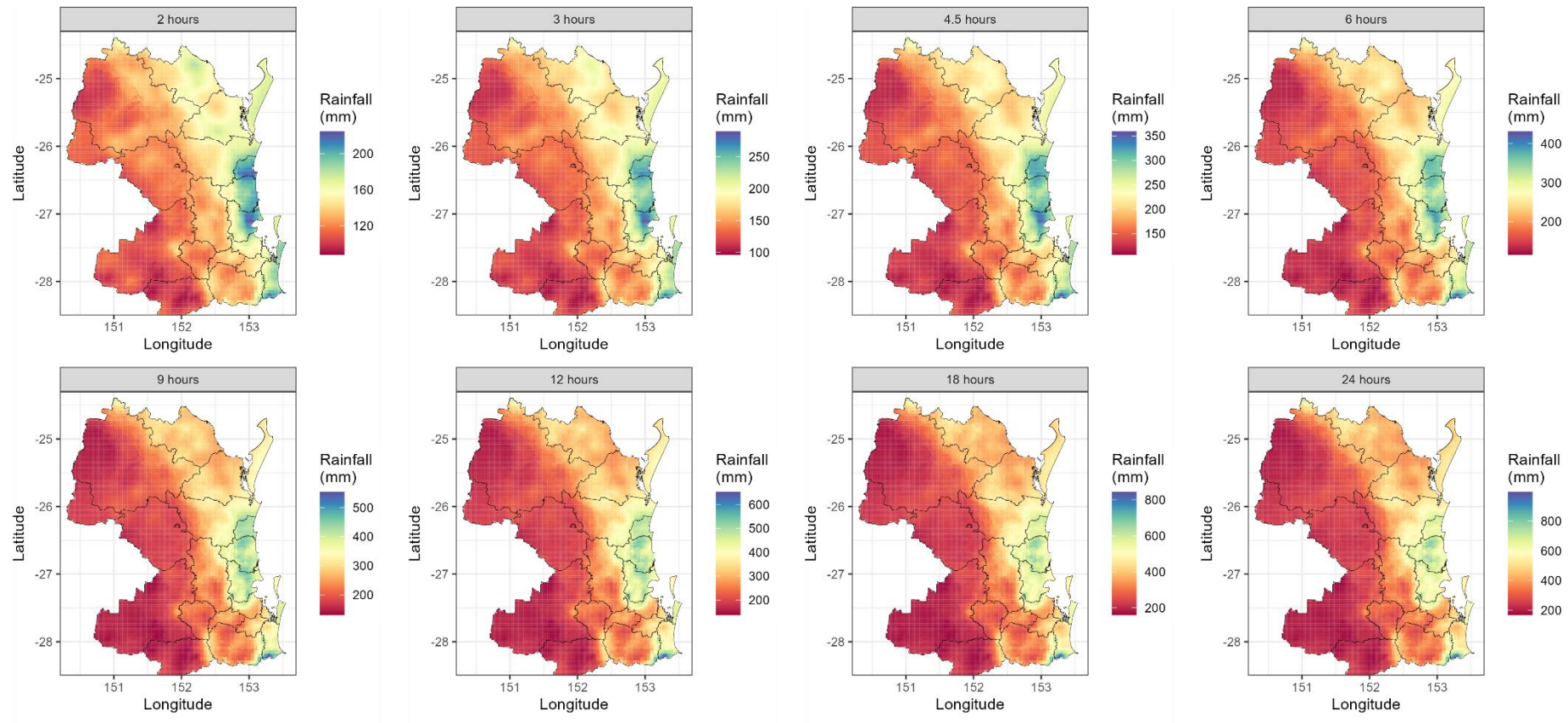


Figure F 23 1 in 500 AEP IFDs (2 hours – 24 hours)

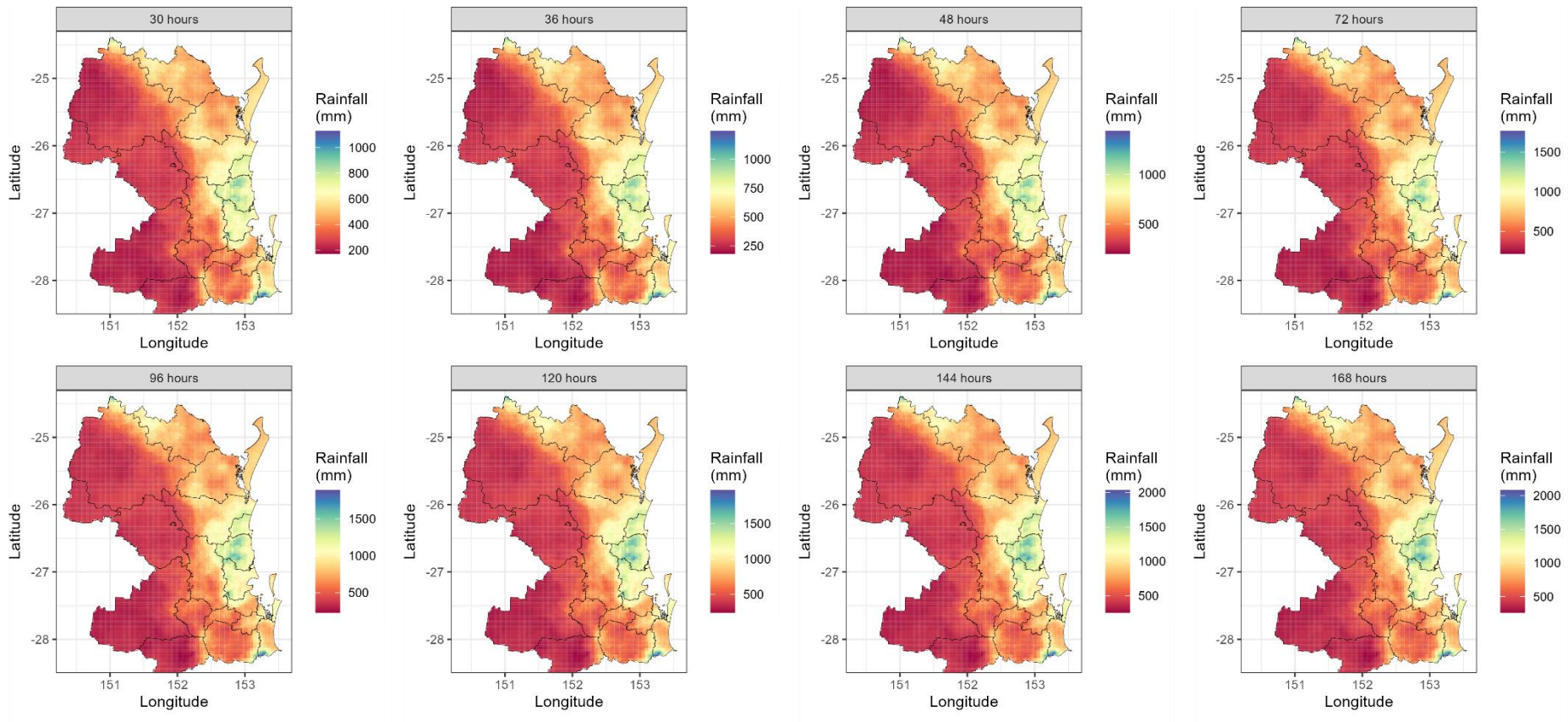


Figure F 24 1 in 500 AEP IFDs (30 hours – 168 hours)

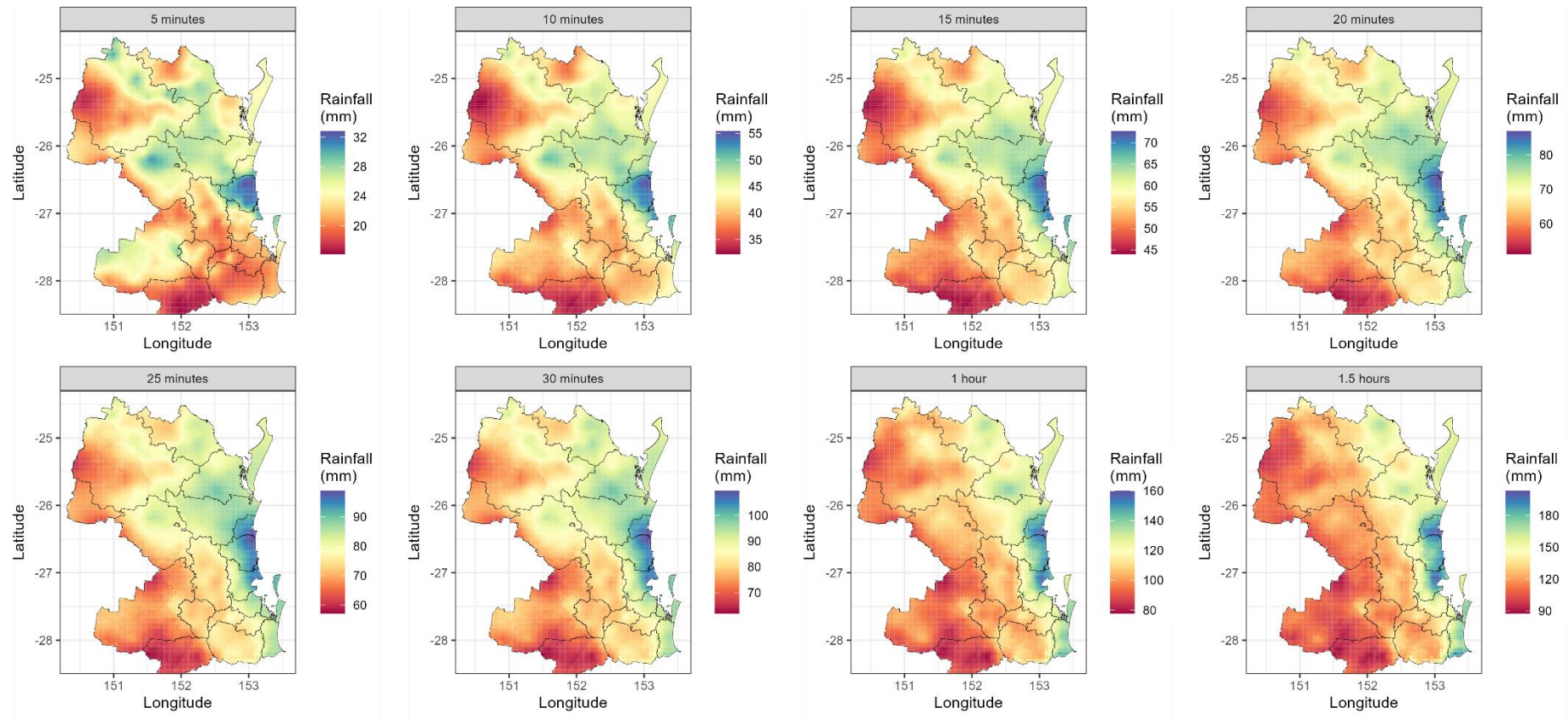


Figure F 25 1 in 1,000 AEP IFDs (5 minutes – 1.5 hours)

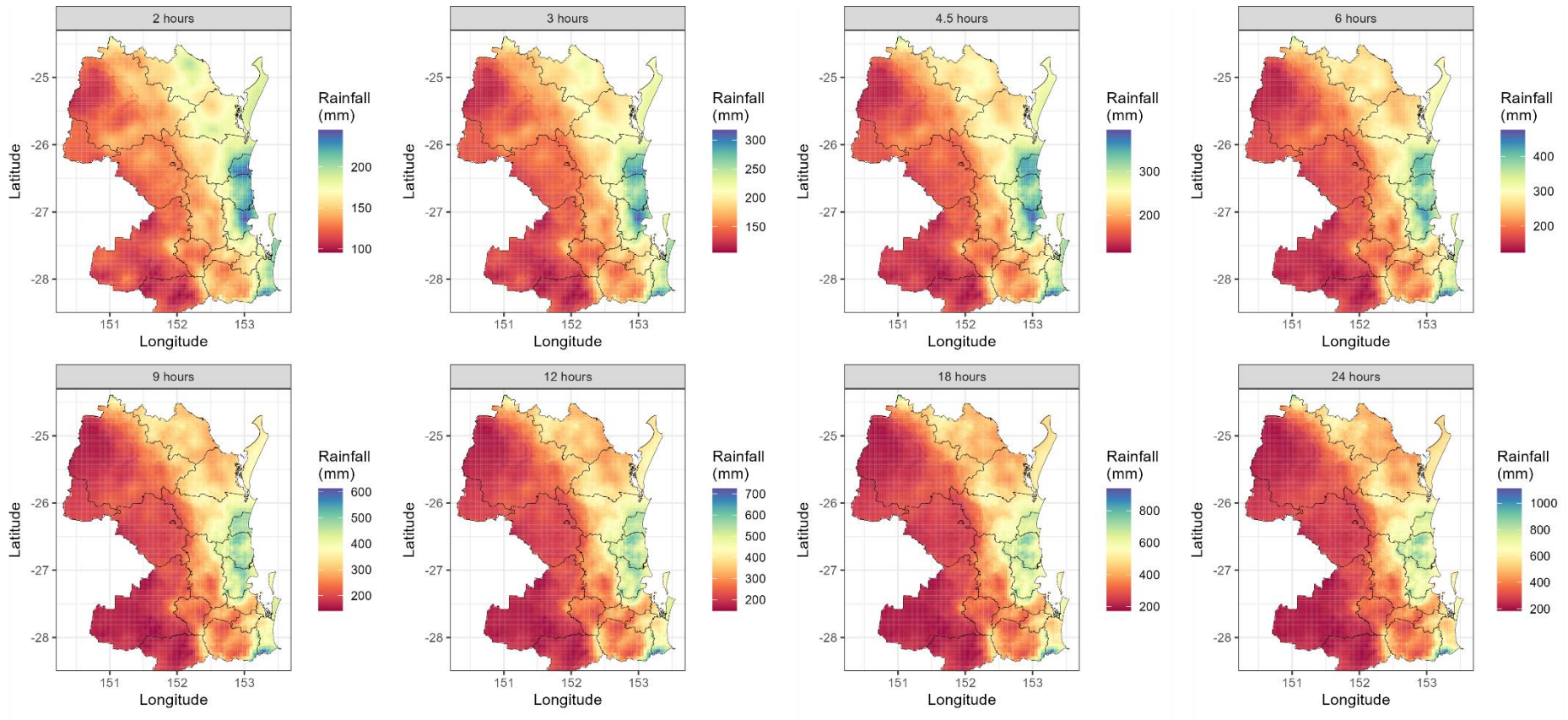


Figure F 26 1 in 1,000 AEP IFDs (2 hours – 24 hours)

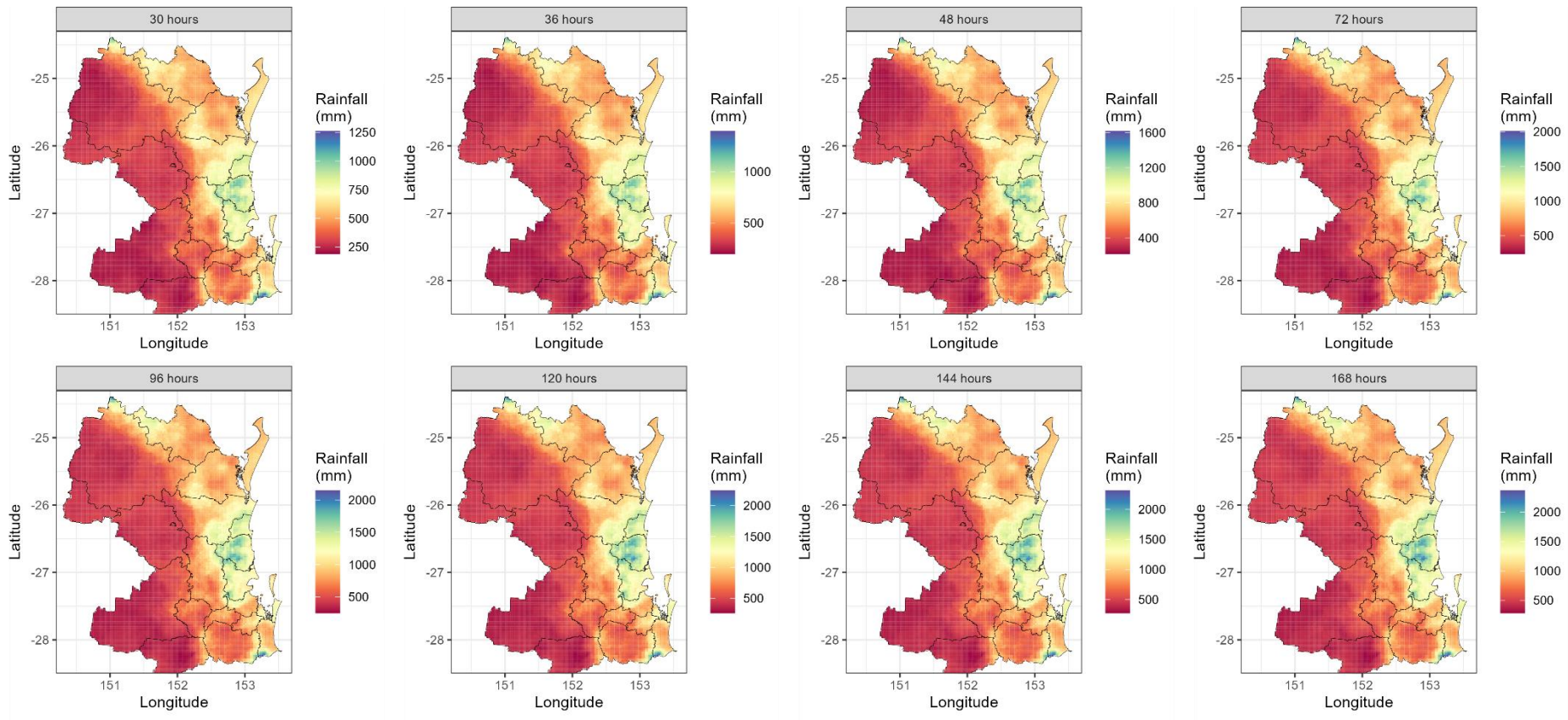


Figure F 27 1 in 1,000 AEP IFDs (30 hours – 168 hours)

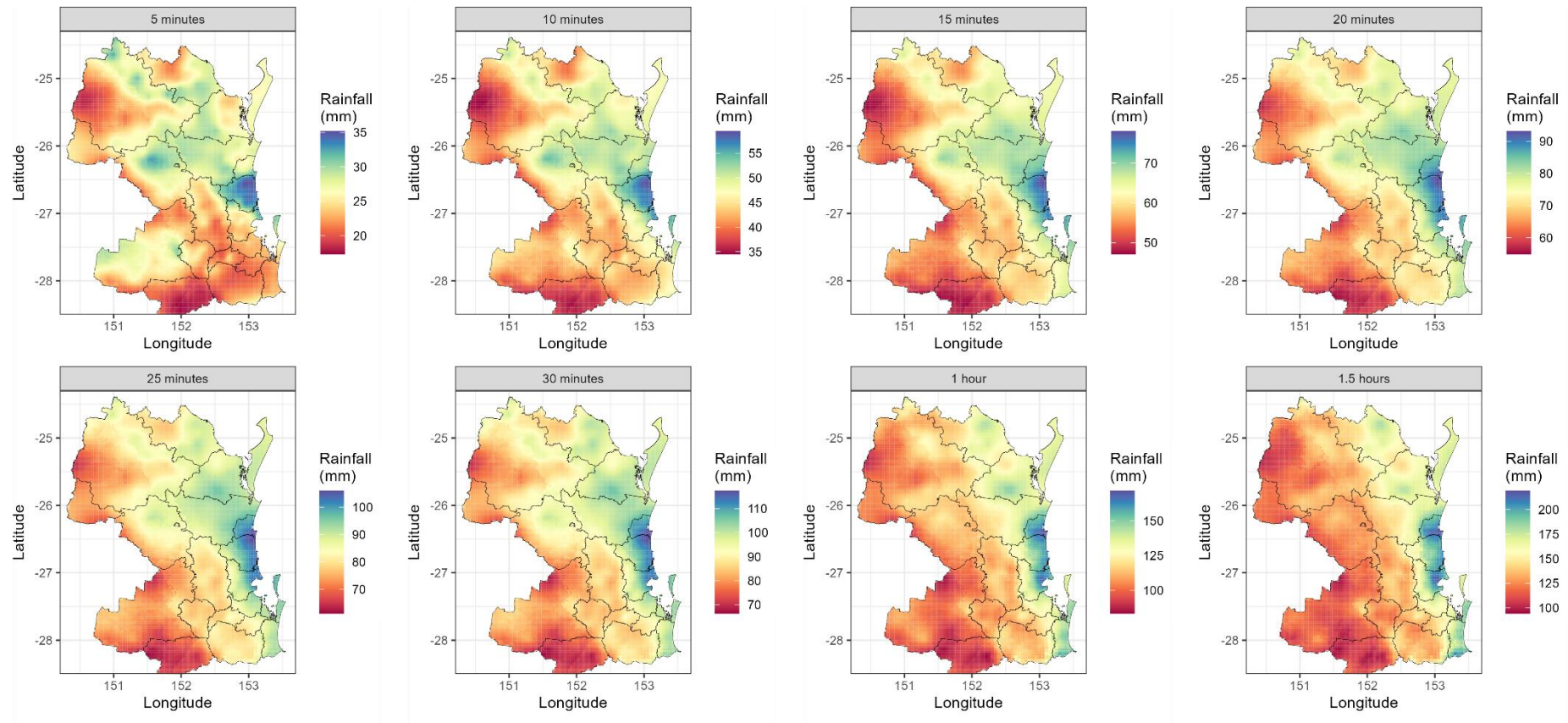


Figure F 28 1 in 2,000 AEP IFDs (5 minutes – 1.5 hours)

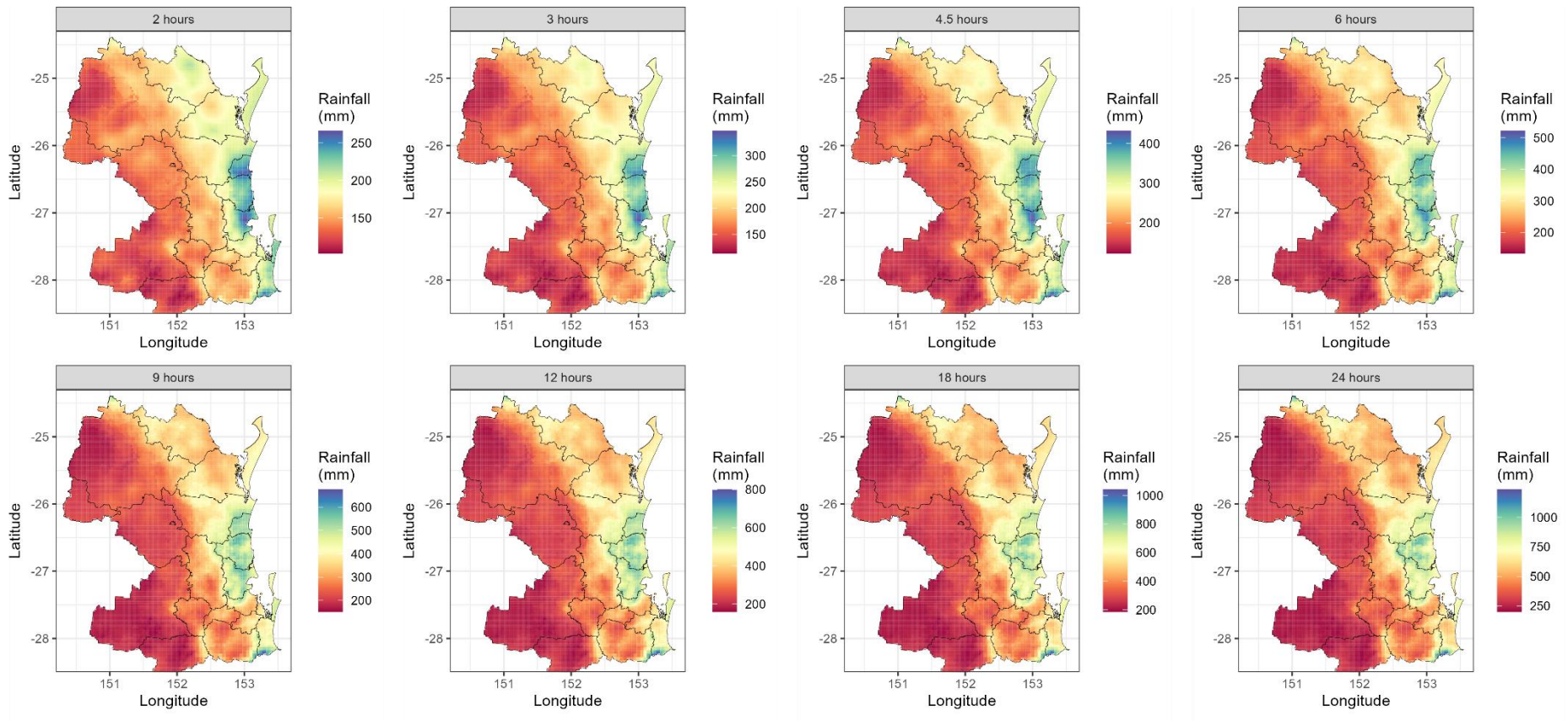


Figure F 29 1 in 2,000 AEP IFDs (2 hours – 24 hours)

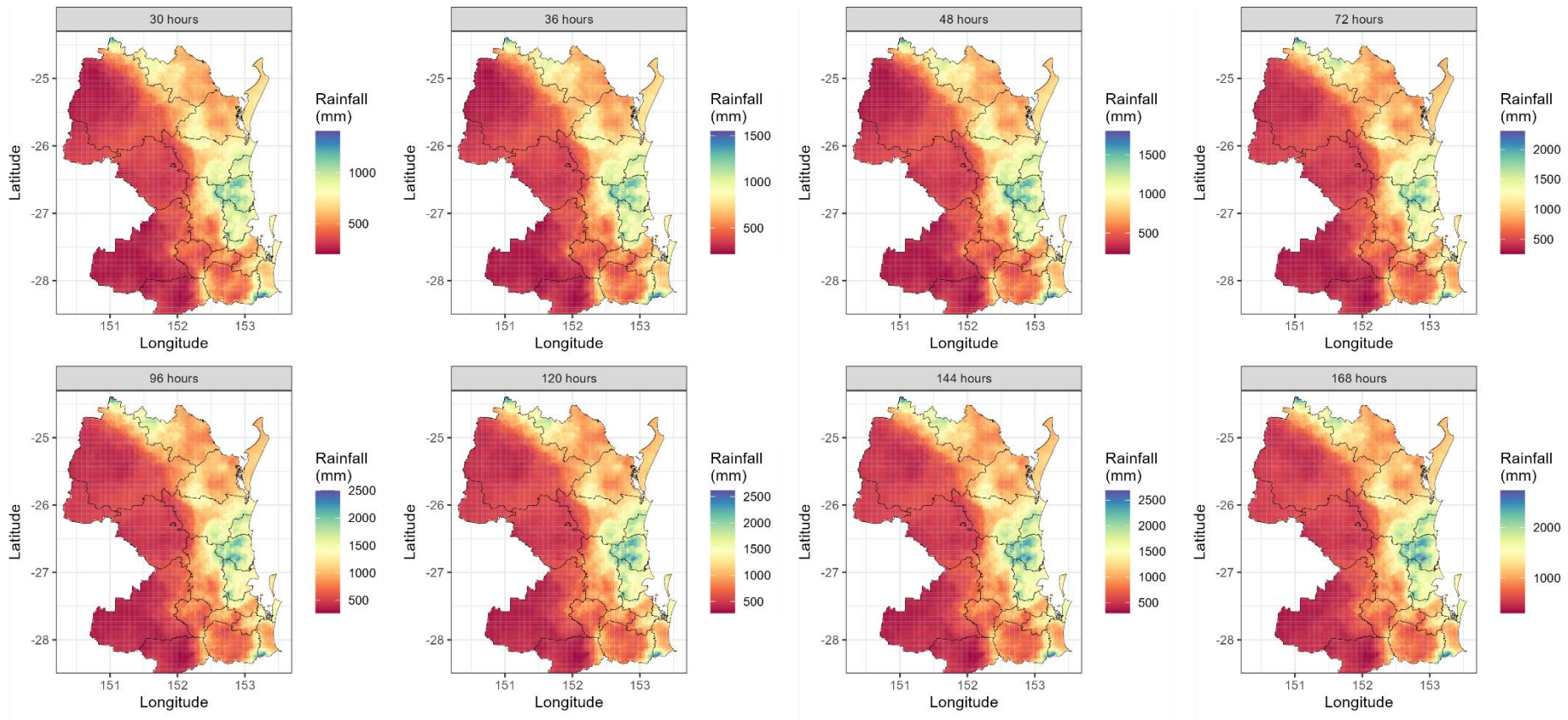


Figure F 30 1 in 2,000 AEP IFDs (30 hours – 168 hours)

Appendix G At-site IFD comparisons

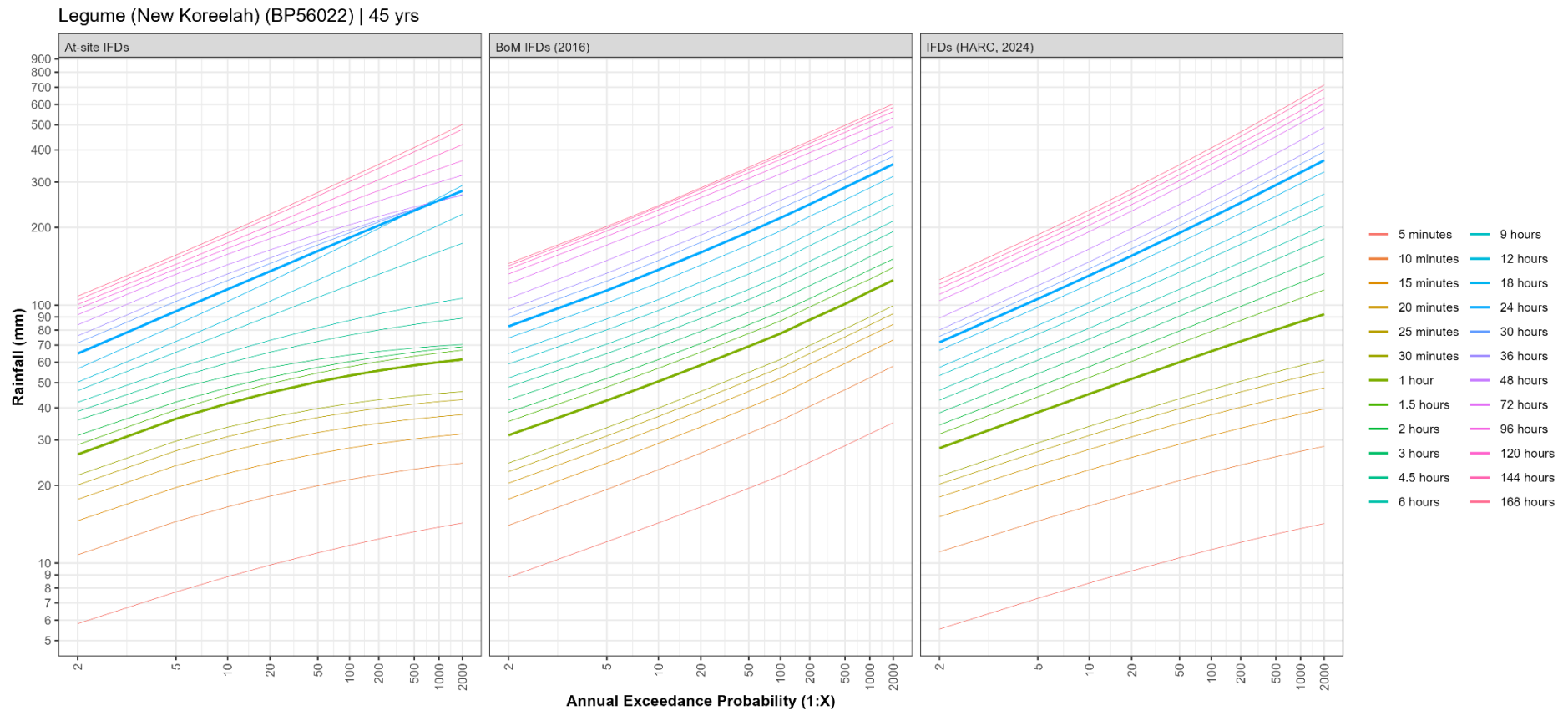


Figure G 1 At-site and Gridded IFDs at BP56022 (Elevation = 385.0 m AHD, Record length = 45 years)

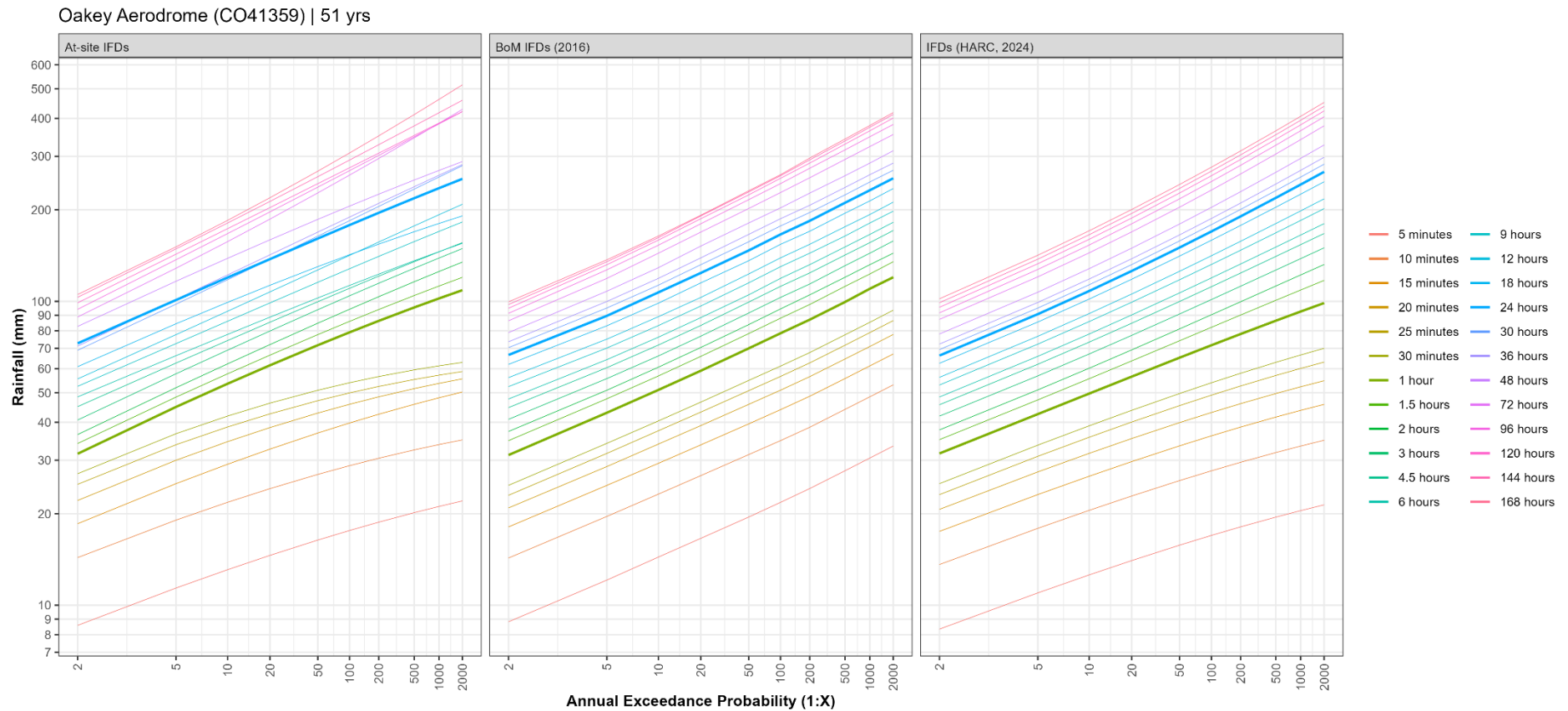


Figure G 2 At-site and Gridded IFDs at CO41359 (Elevation = 405.7 m AHD, Record length = 51 years)

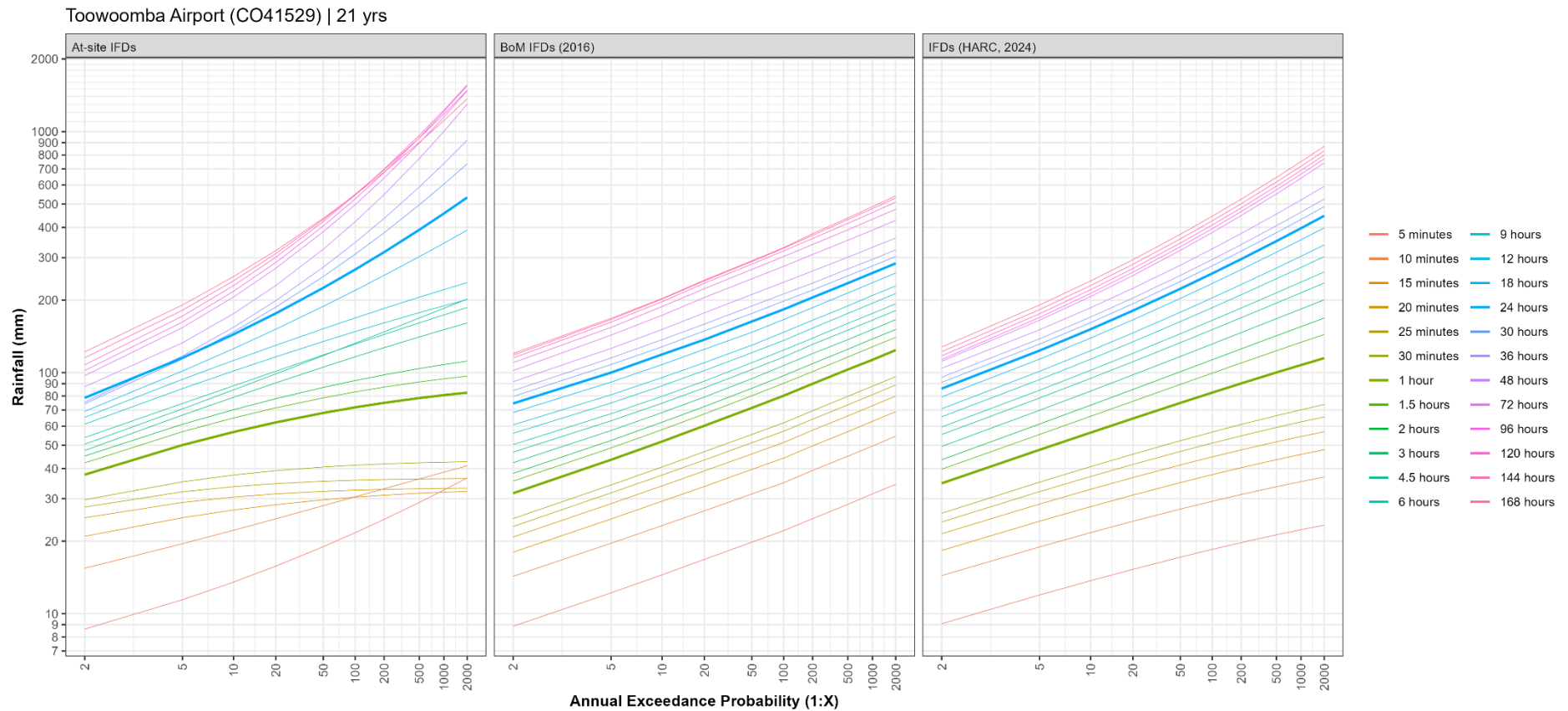


Figure G 3 At-site and Gridded IFDs at CO41529 (Elevation = 640.9 m AHD, Record length = 21years)

Carrs Lookout ALERT (SW541064) | 19 yrs

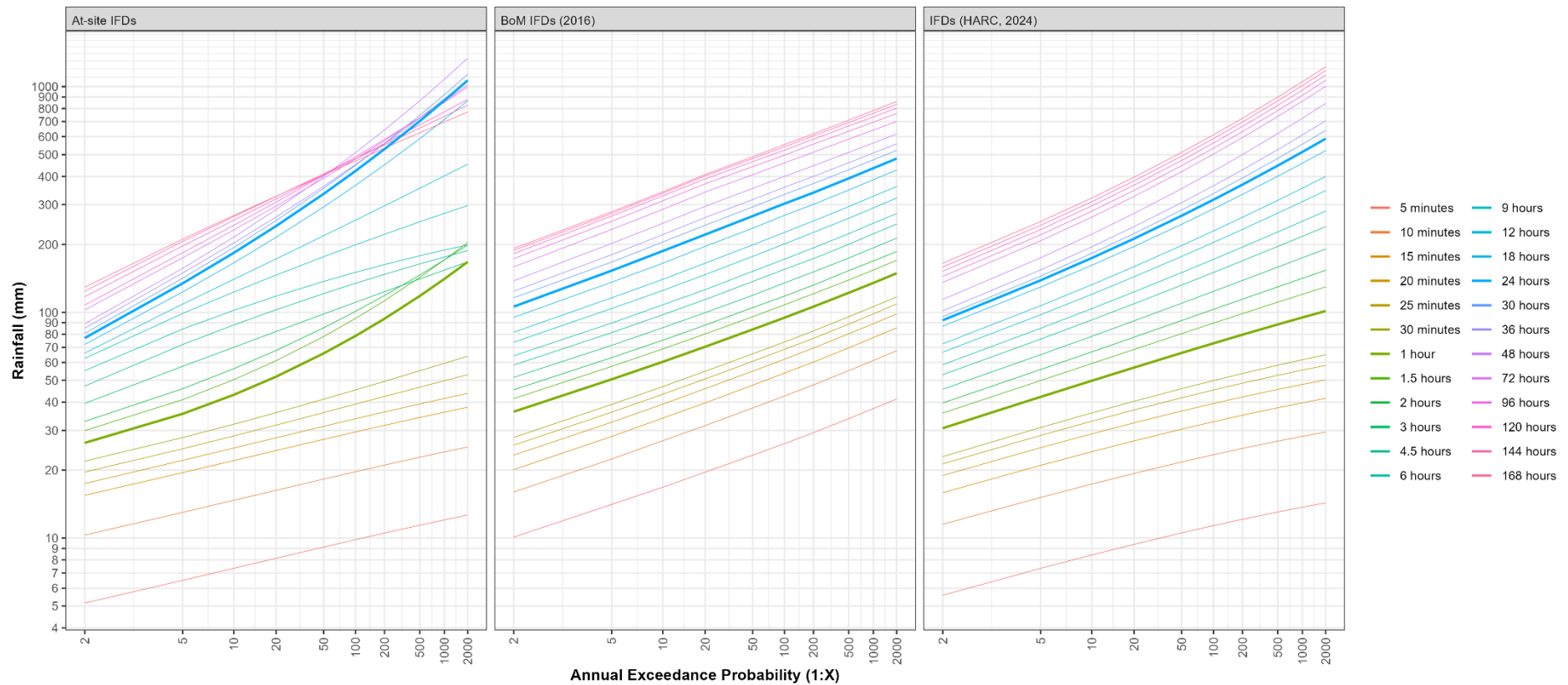


Figure G 4 At-site and Gridded IFDs at SW541064 (Elevation = 1087.0m AHD, Record length = 19 years)

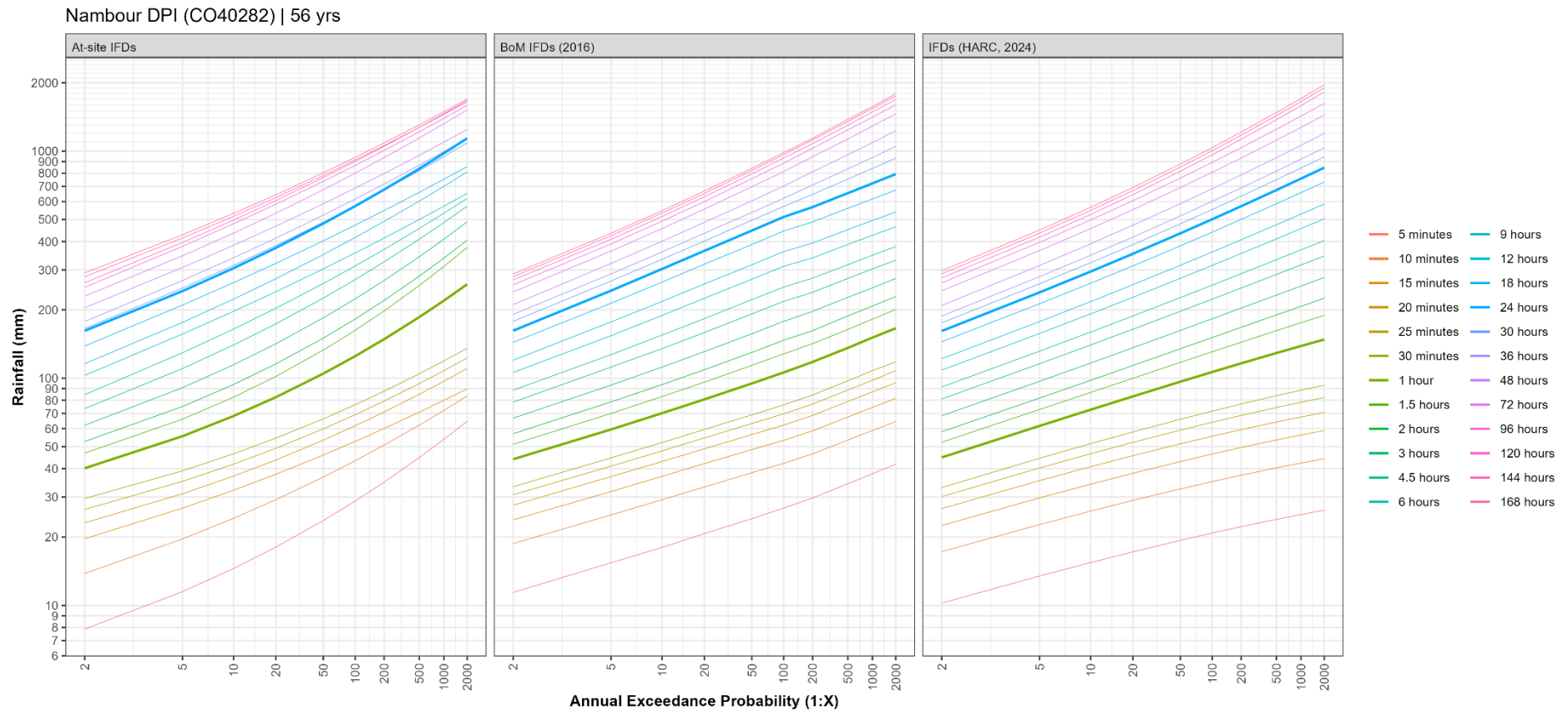


Figure G 5 At-site and Gridded IFDs at CO40282 (Elevation = 32.5 m AHD, Record length = 56 years)

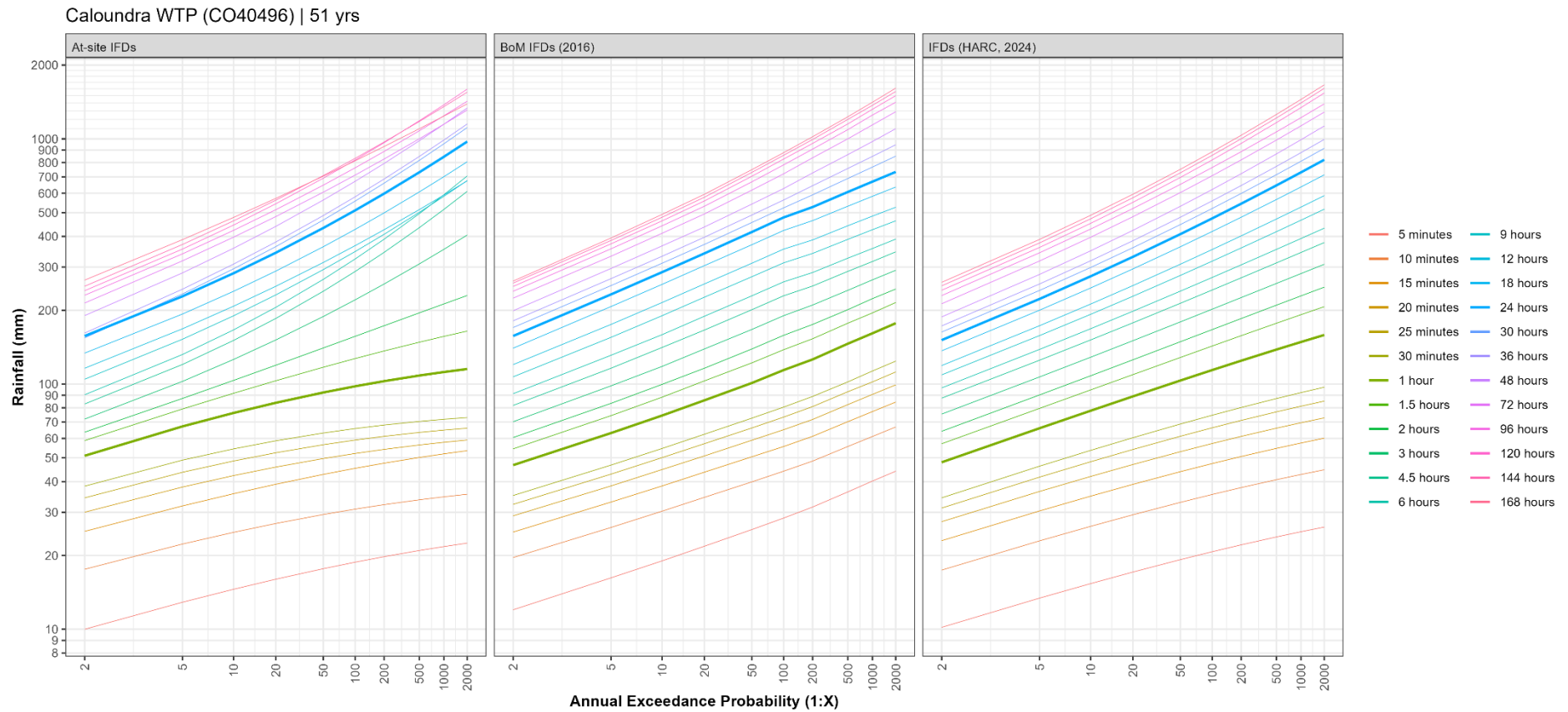


Figure G 6 At-site and Gridded IFDs at CO40496 (Elevation = 57.0 m AHD, Record length = 51 years)

Eerwah Vale ALERT (CO540136) | 30 yrs

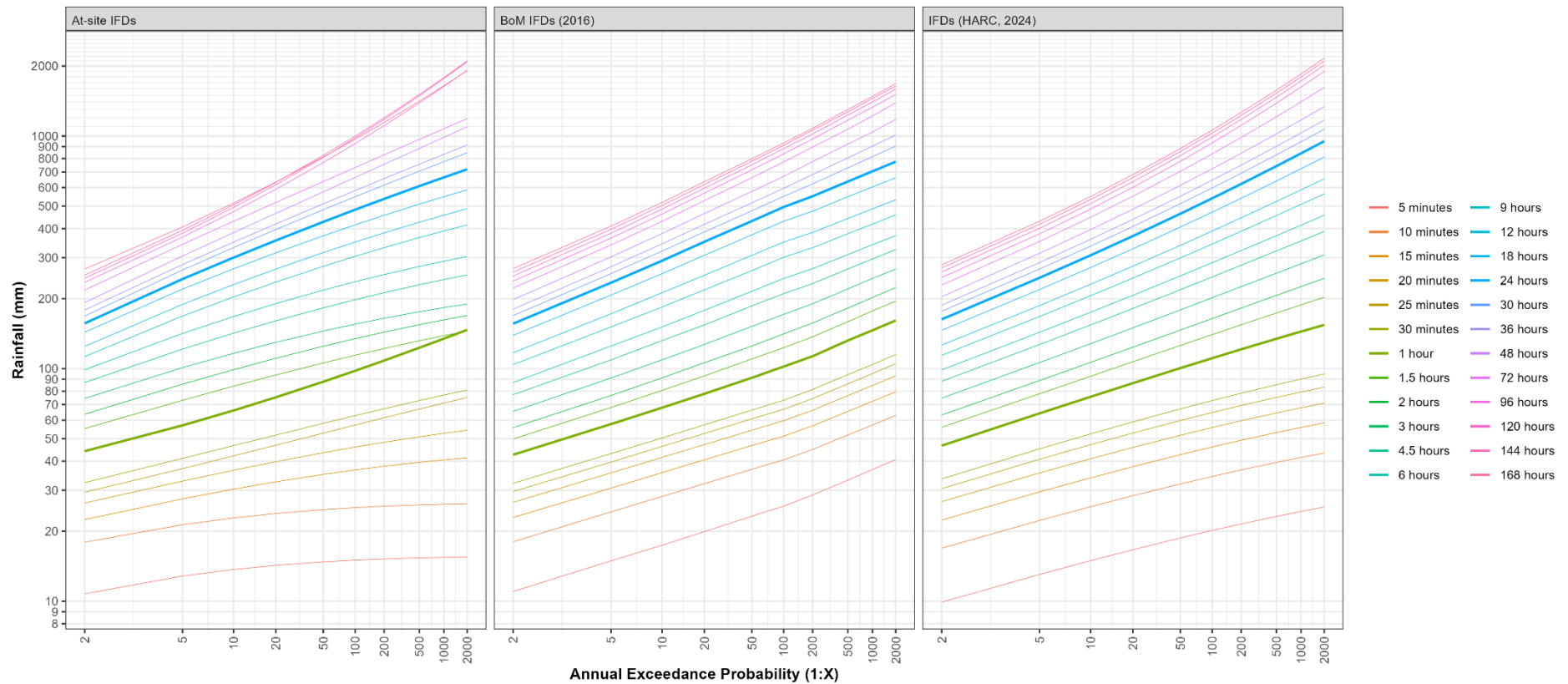


Figure G 7 At-site and Gridded IFDs at CO540136 (Elevation = 127.0 m AHD, Record length = 30 years)

Mapleton ALERT (CO540085) | 28 yrs

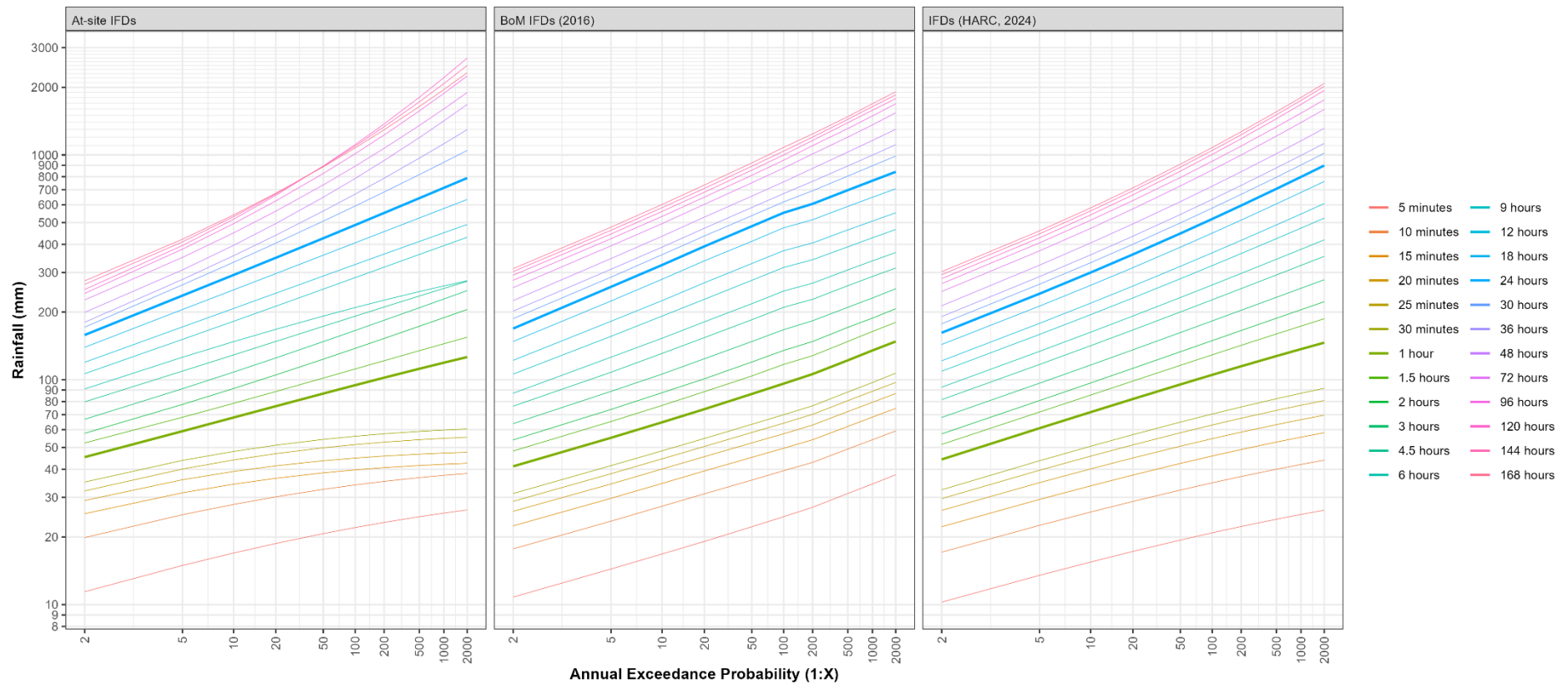


Figure G 8 At-site and Gridded IFDs at CO540085 (Elevation = 395.0 m AHD, Record length = 28 years)

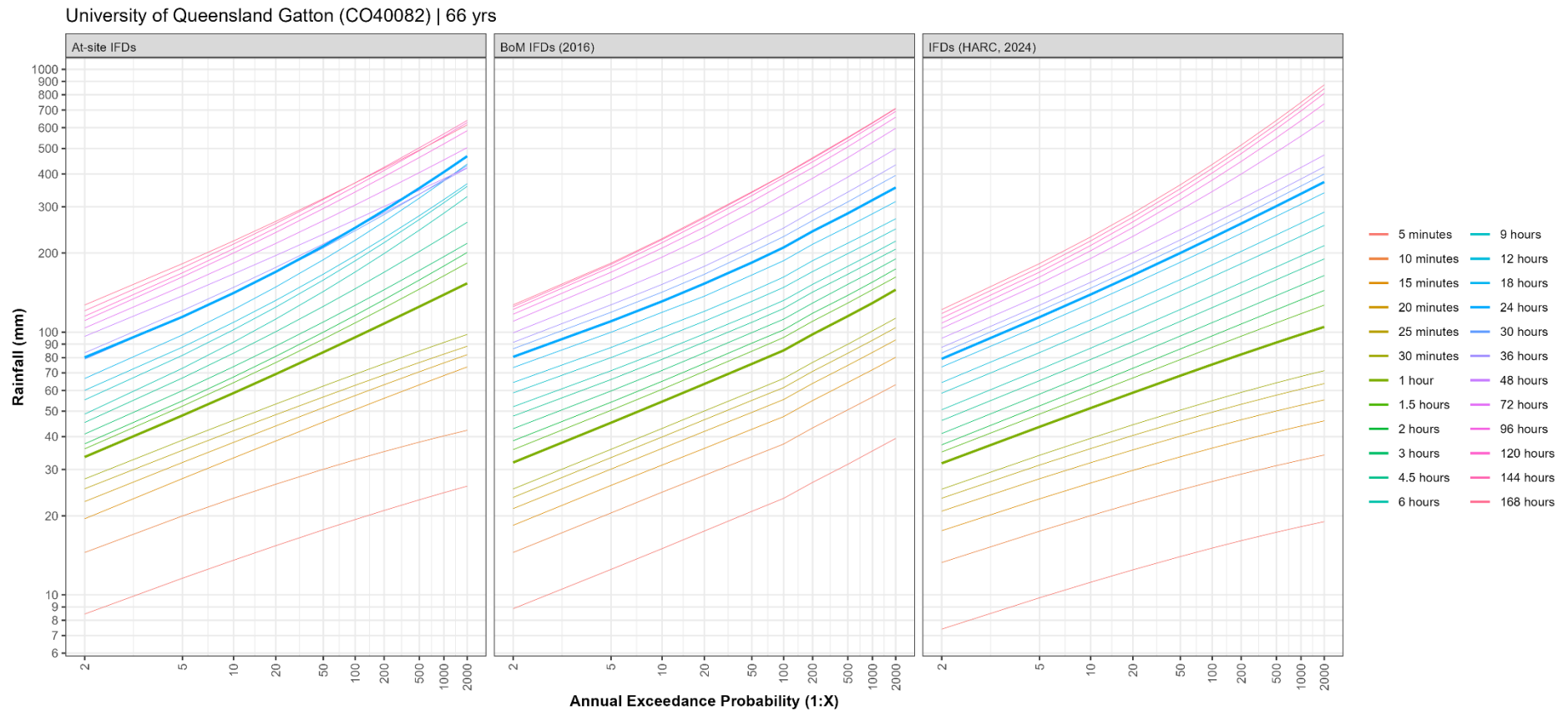


Figure G 9 At-site and Gridded IFDs at CO40082 (Elevation = 89.0 m AHD, Record length = 67 years)

Mt Stanley Station (CO40674) | 38 yrs

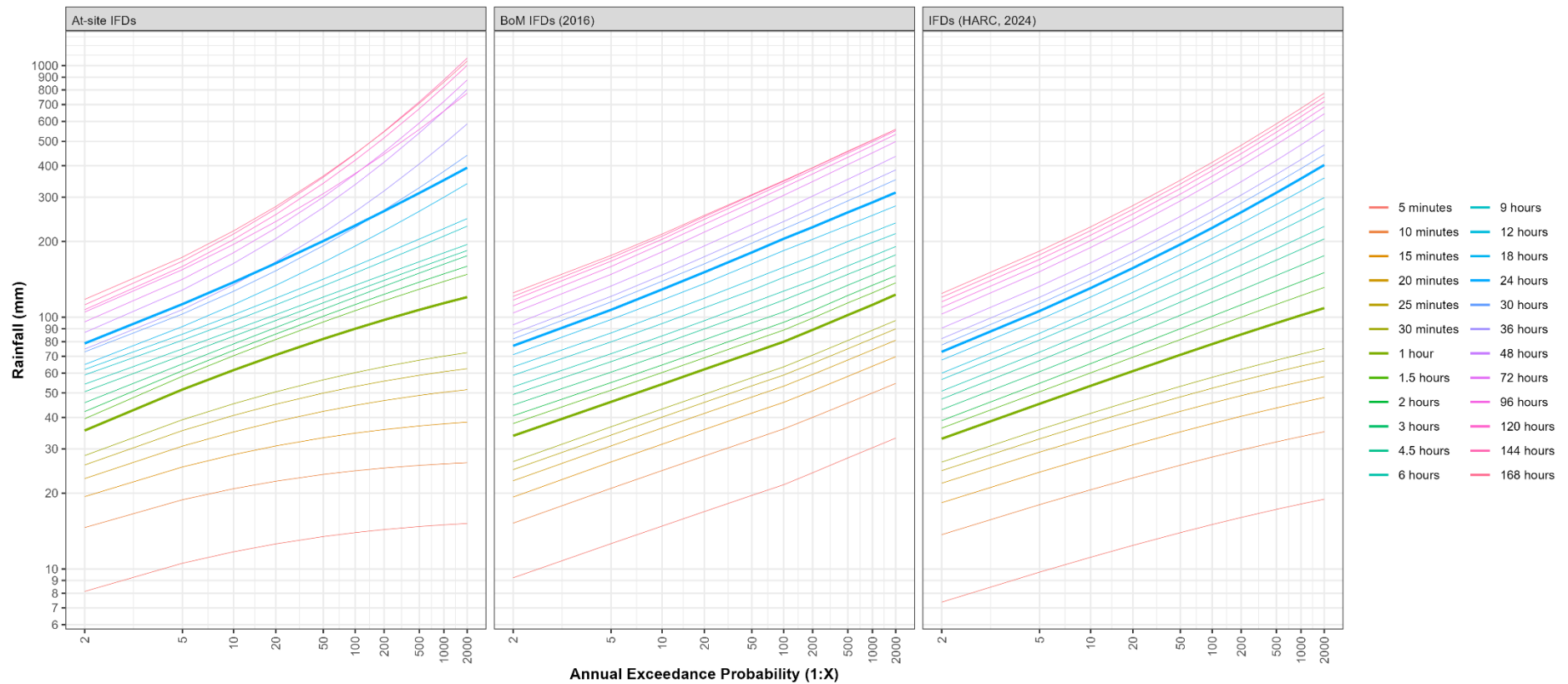


Figure G 10 At-site and Gridded IFDs at CO40674 (Elevation = 219.0 m AHD, Record length = 38 years)

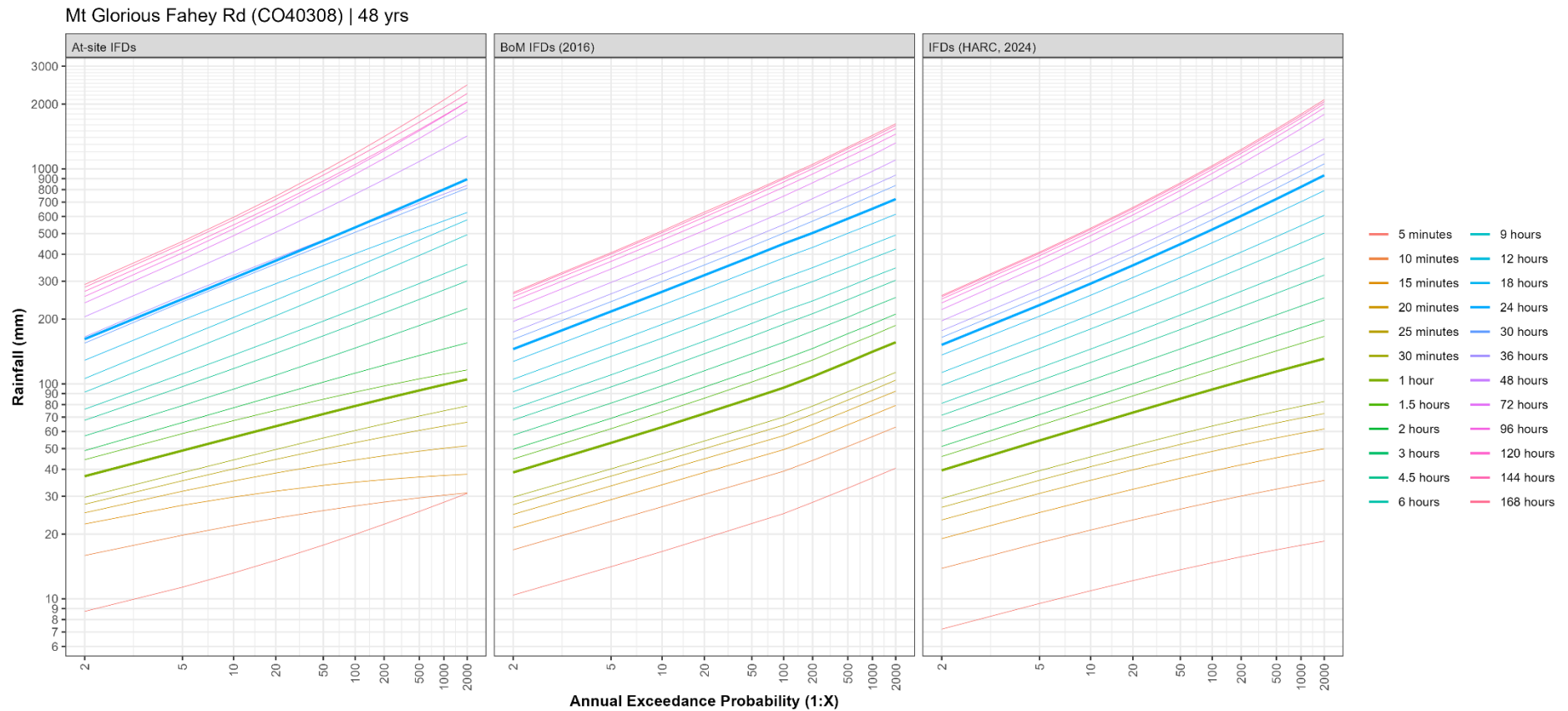


Figure G 11 At-site and Gridded IFDs at CO40308 (Elevation = 618.0 m AHD, Record length = 48 years)

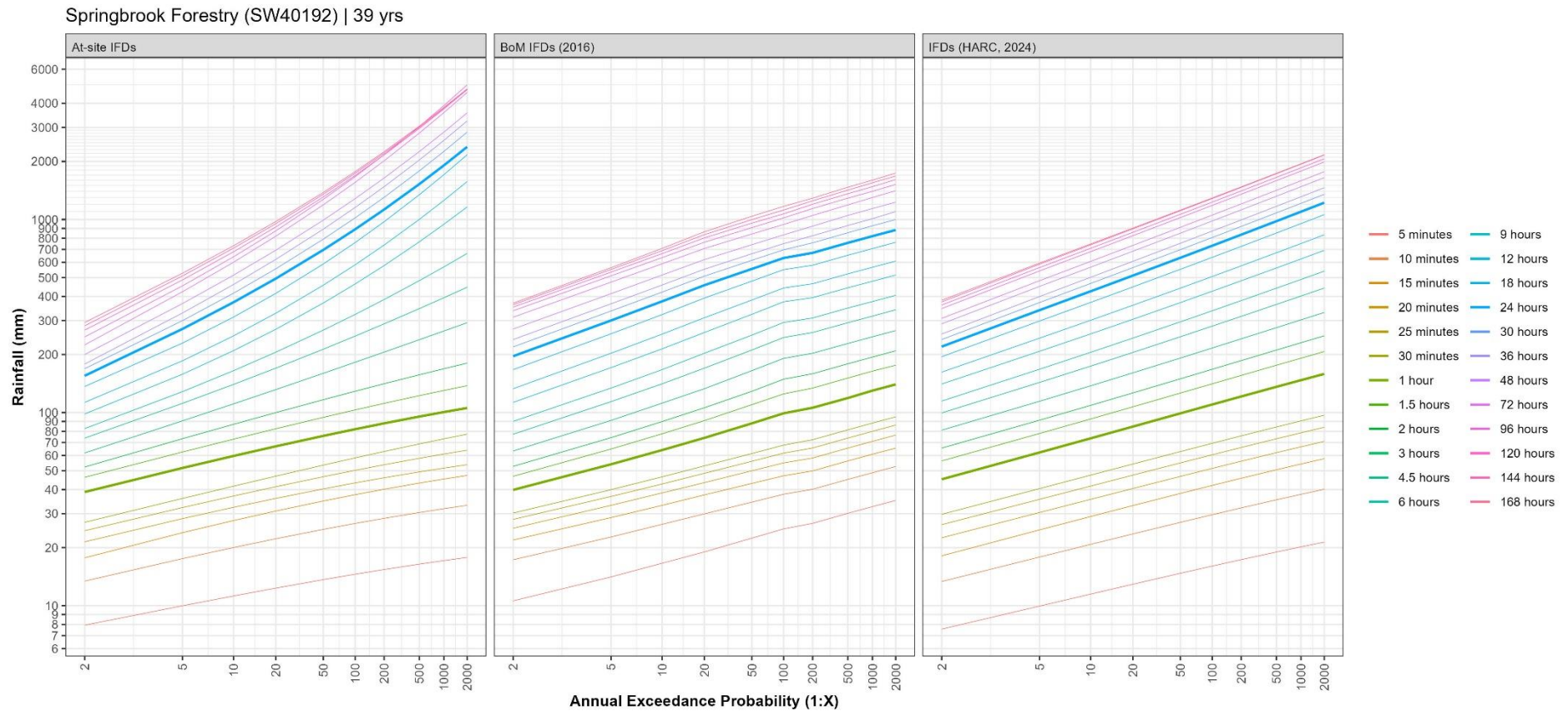


Figure G 12 At-site and Gridded IFDs at SW40192 (Elevation = 806.0 m AHD, Record length = 39 years)

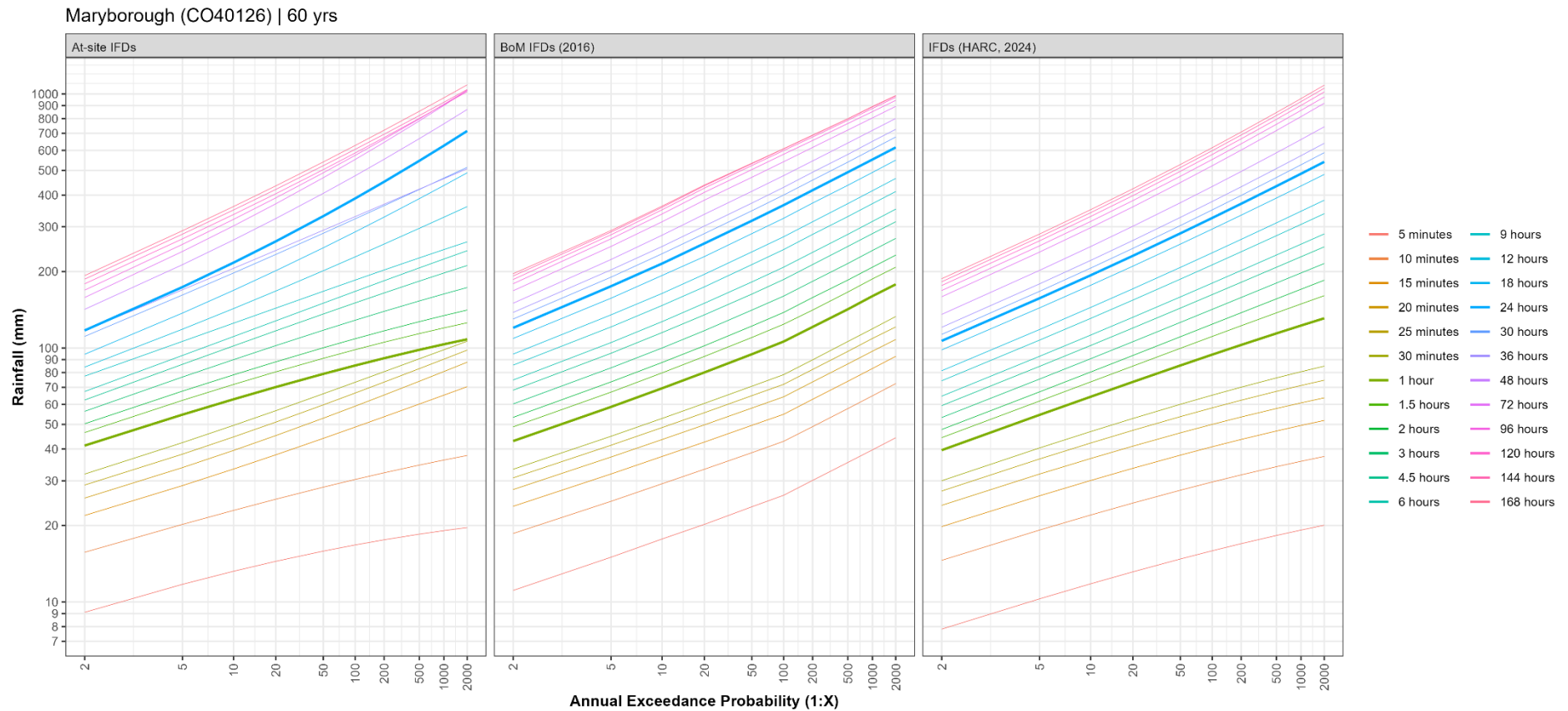


Figure G 13 At-site and Gridded IFDs at CO40126 (Elevation = 9.0 m AHD, Record length = 60 years)

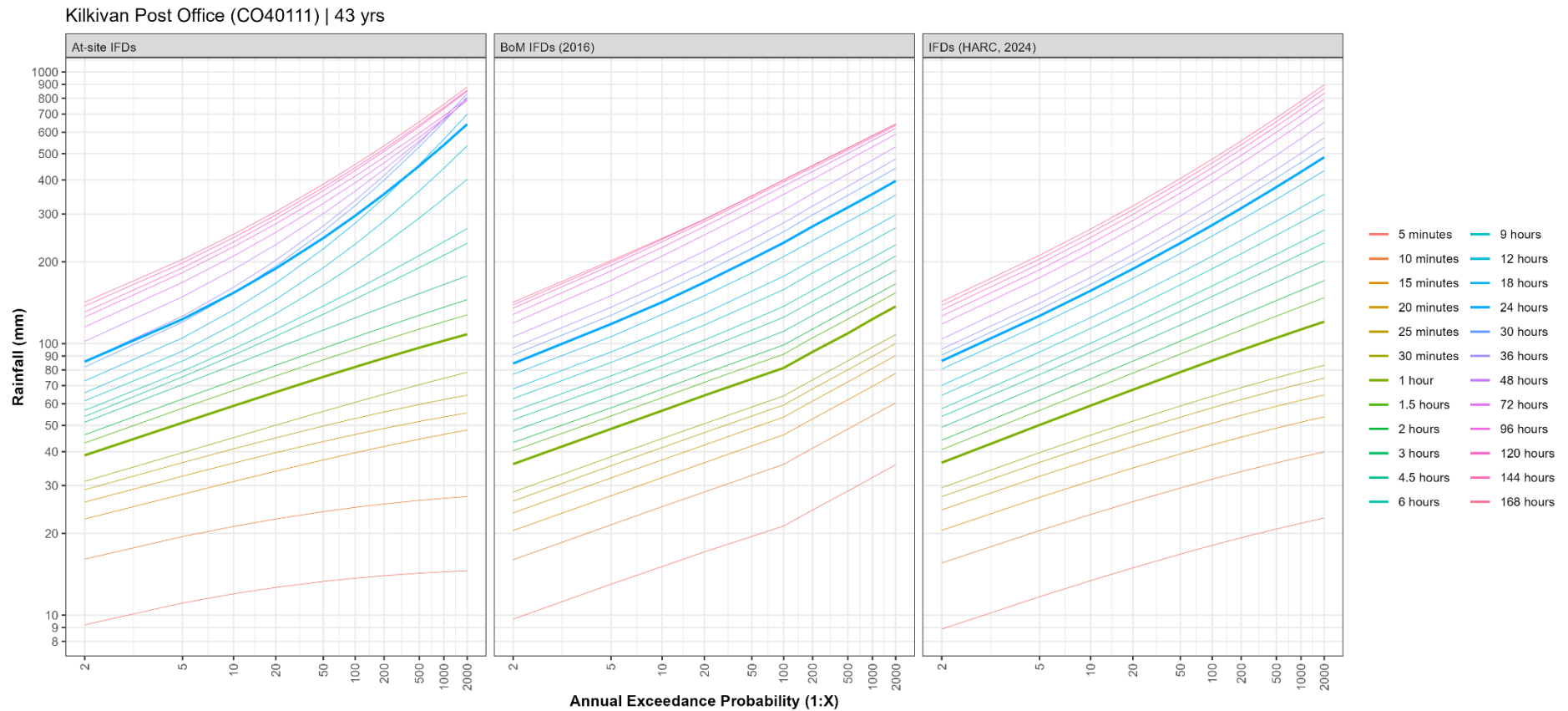


Figure G 14 At-site and Gridded IFDs at CO40111 (Elevation = 159.0 m AHD, Record length = 43 years)

Fairlies Knob Standalone Pluvio (QG1371P002) | 38 yrs

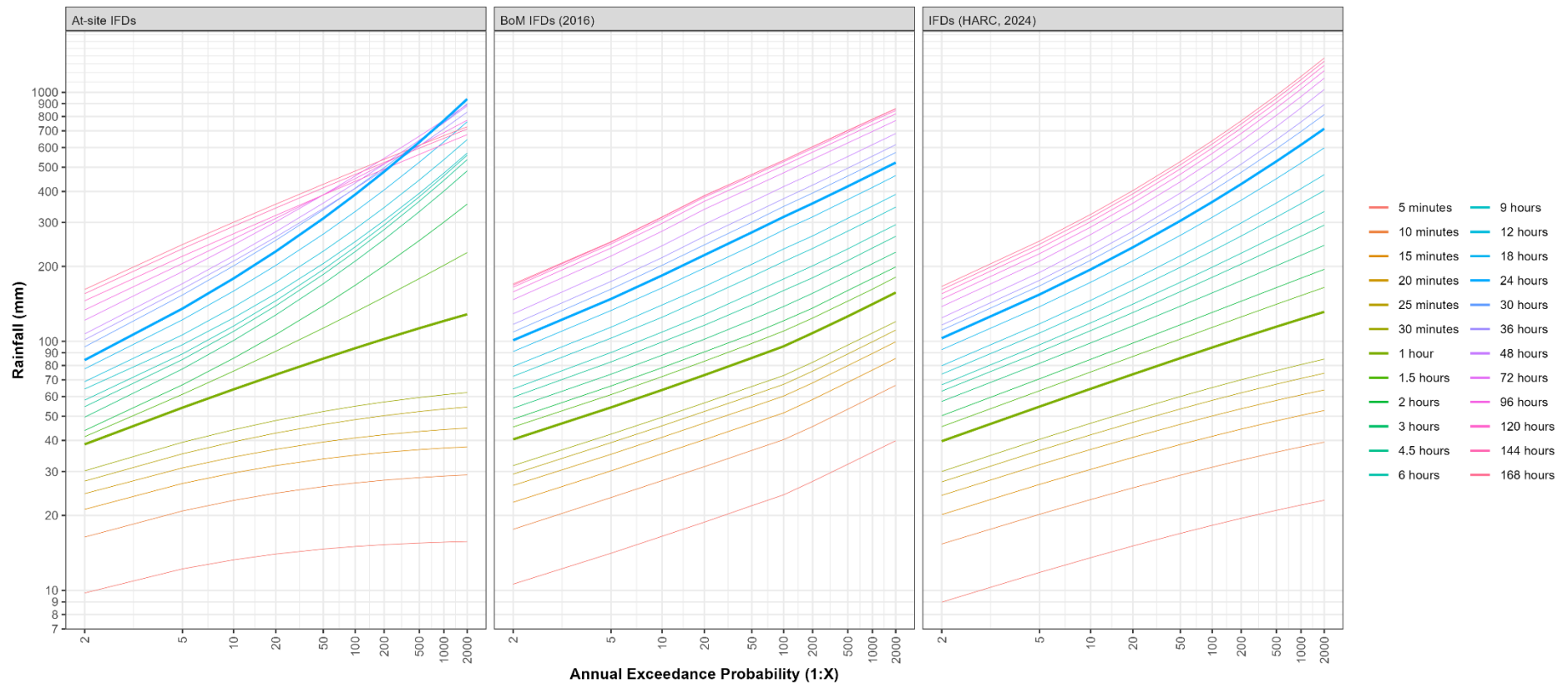


Figure G 15 At-site and Gridded IFDs at QG1371P002 (Elevation = 316.0 m AHD, Record length = 38 years)

Jimna Composite (CO40102) | 41 yrs

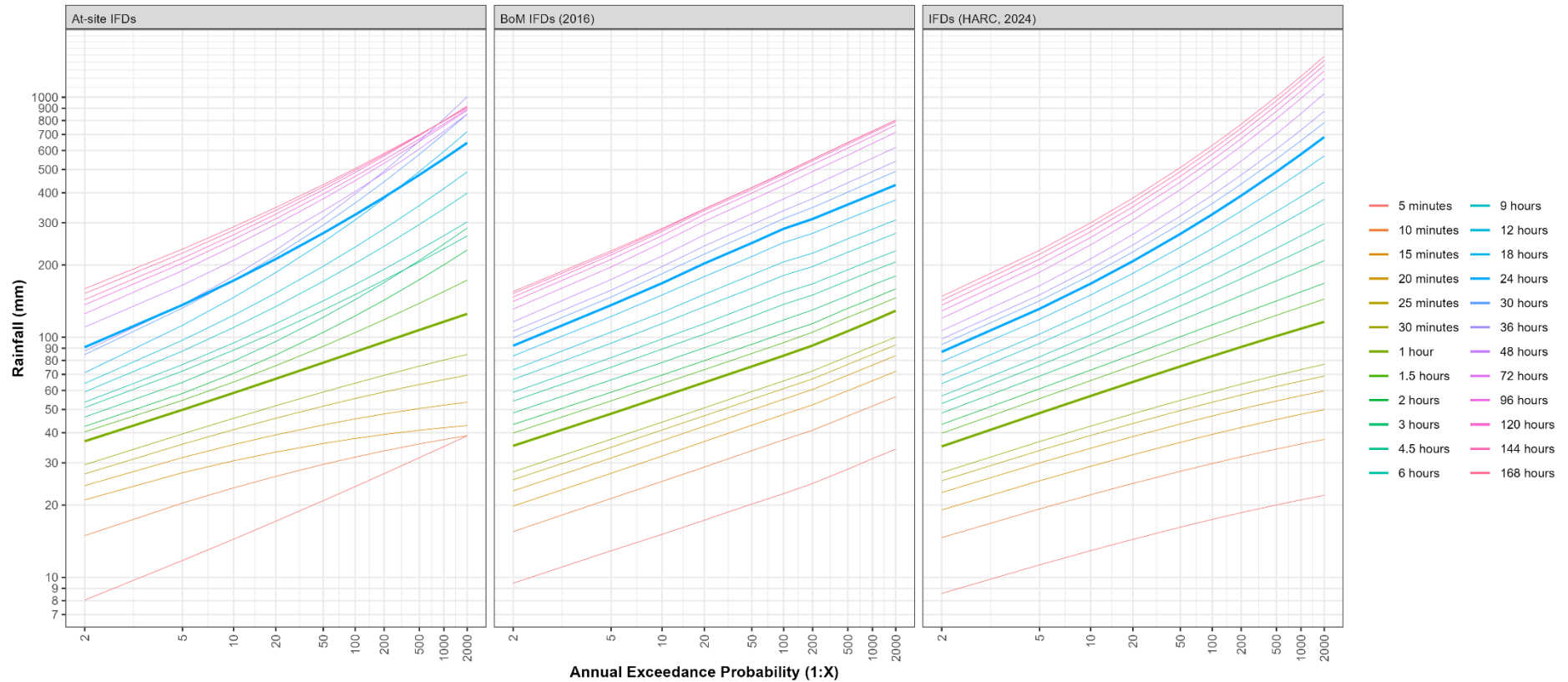


Figure G 16 At-site and Gridded IFDs at CO40102 (Elevation = 513.0 m AHD, Record length = 41 years)

Degilbo Creek at Coringa (QG136011A) | 34 yrs

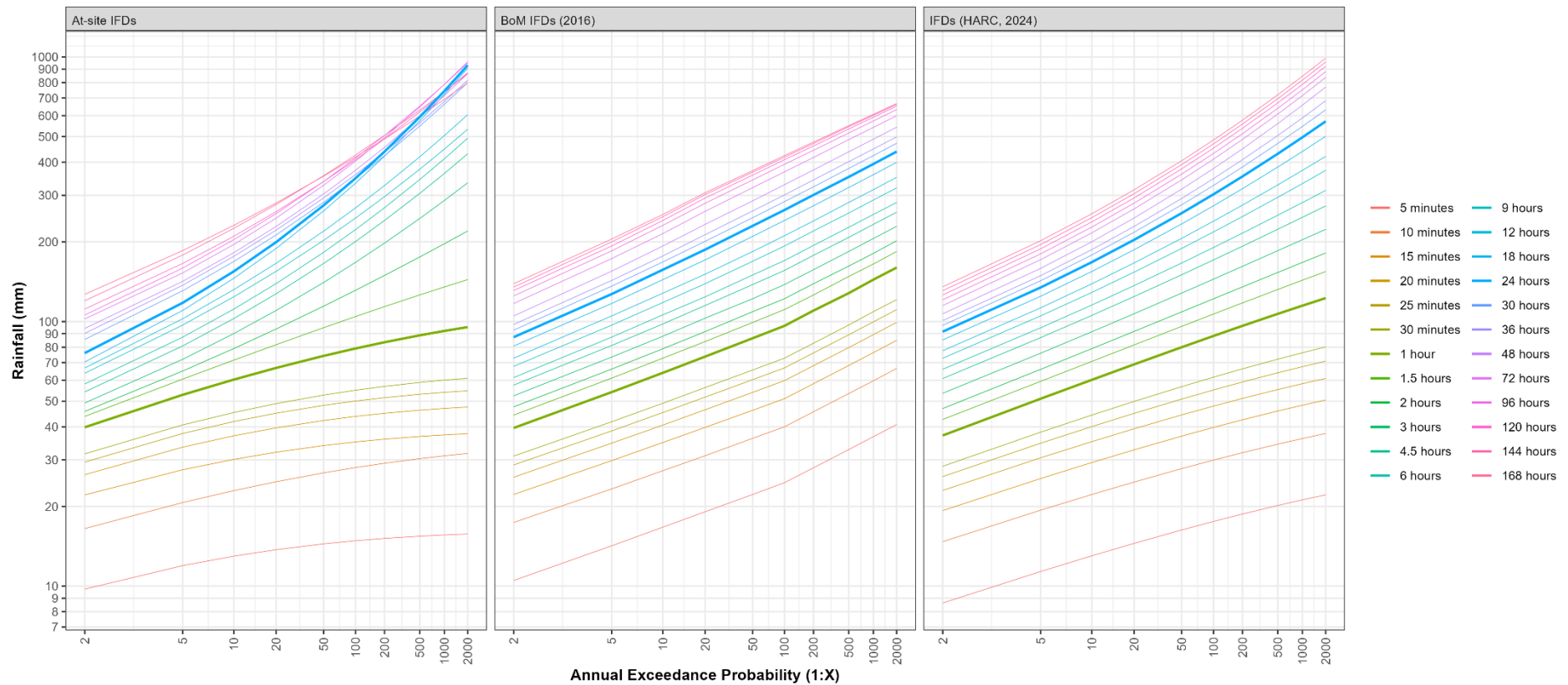


Figure G 17 At-site and Gridded IFDs at QG136011A (Elevation = 52.6 m AHD, Record length = 34 years)

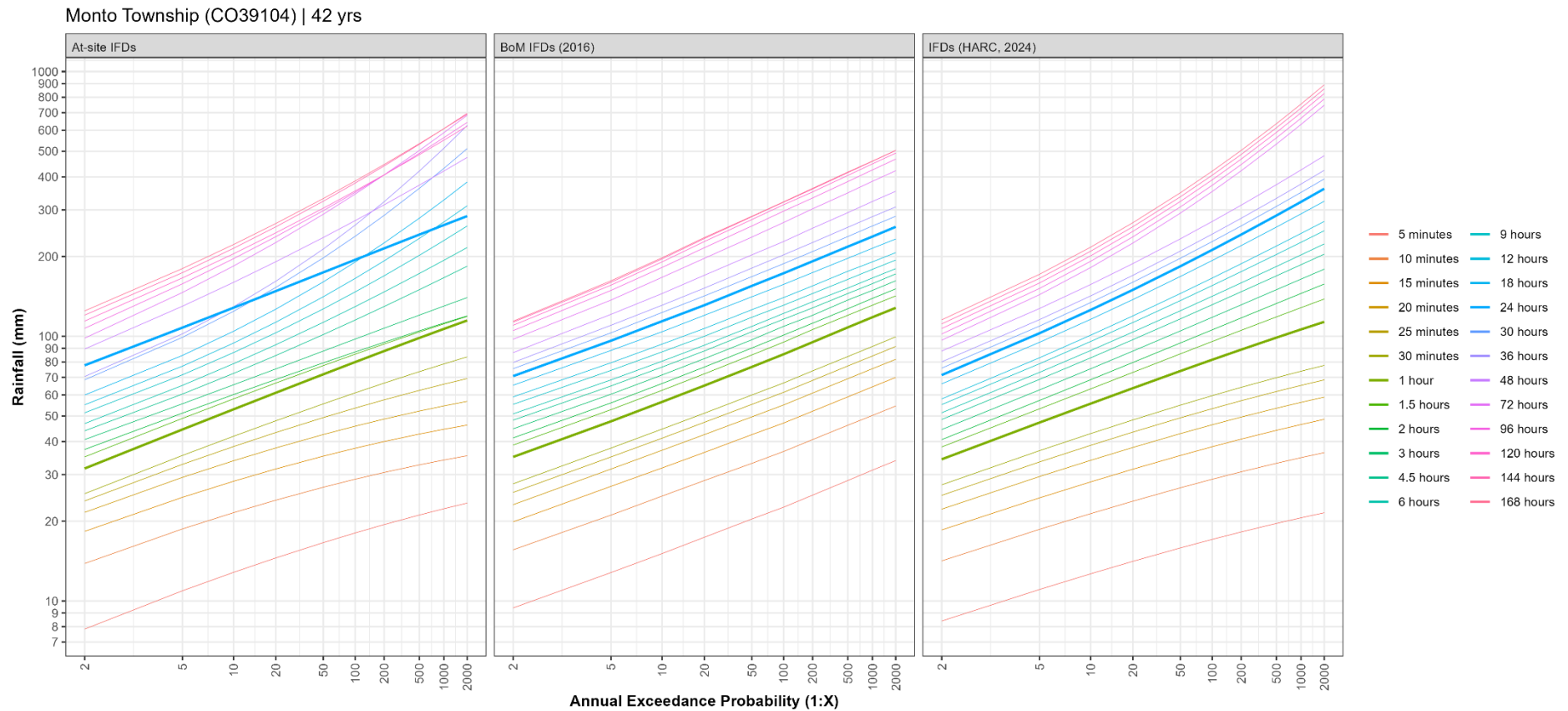


Figure G 18 At-site and Gridded IFDs at CO39104 (Elevation = 239.0m AHD, Record length = 42 years)

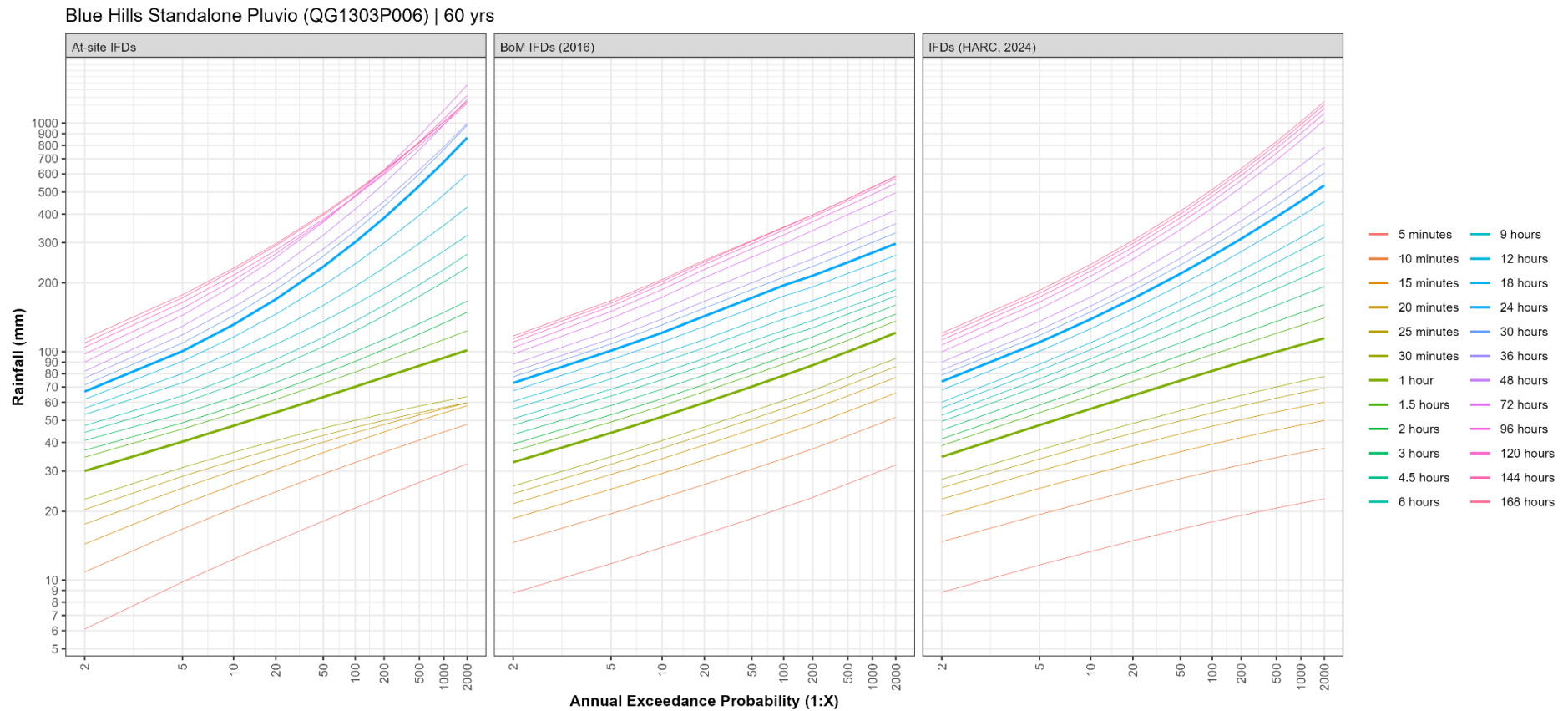


Figure G 19 At-site and Gridded IFDs at QG1303P006 (Elevation = 547.0 m AHD, Record length = 60 years)

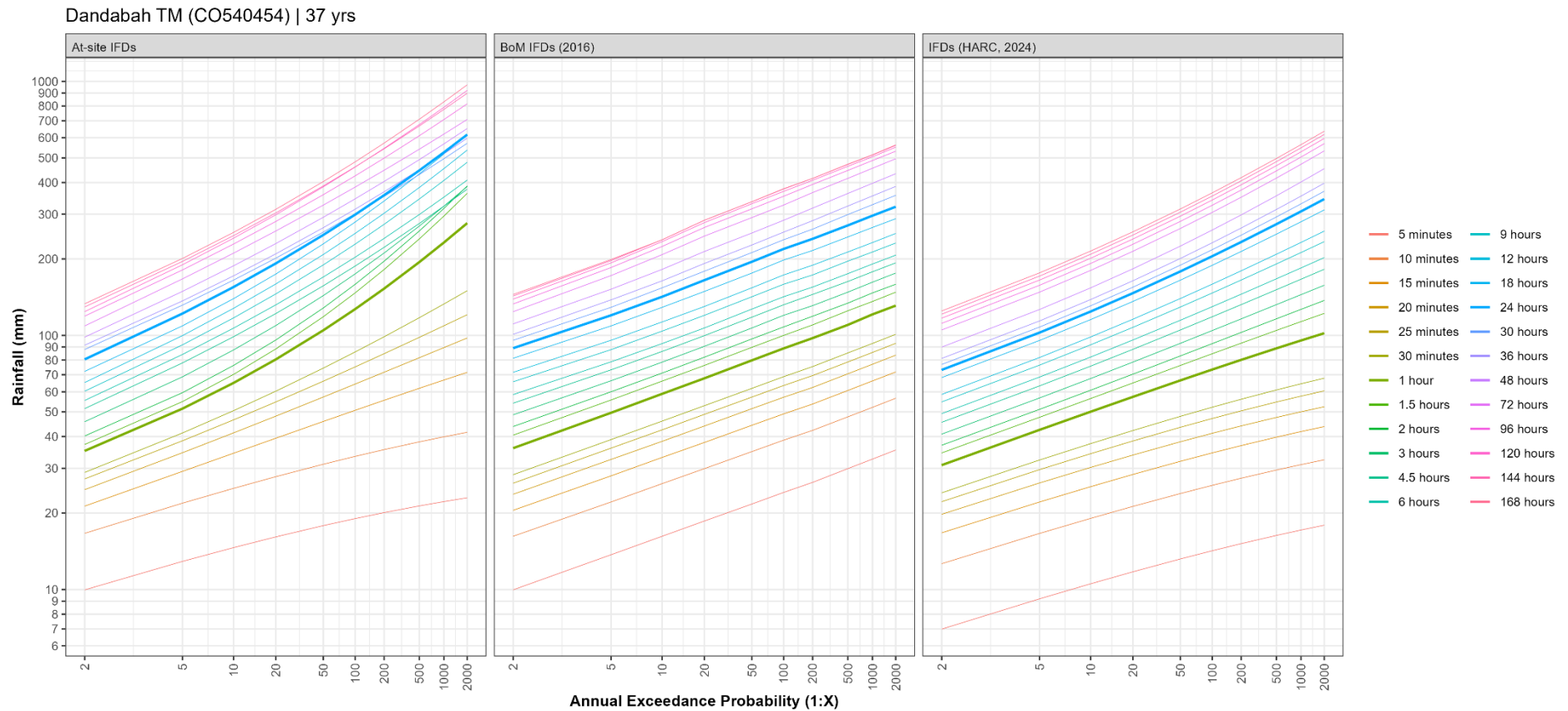


Figure G 20 At-site and Gridded IFDs at CO540454 (Elevation = 974.0 m AHD, Record length = 37 years)

Appendix H Spatial variation of the percentage difference between at-site and gridded IFDs

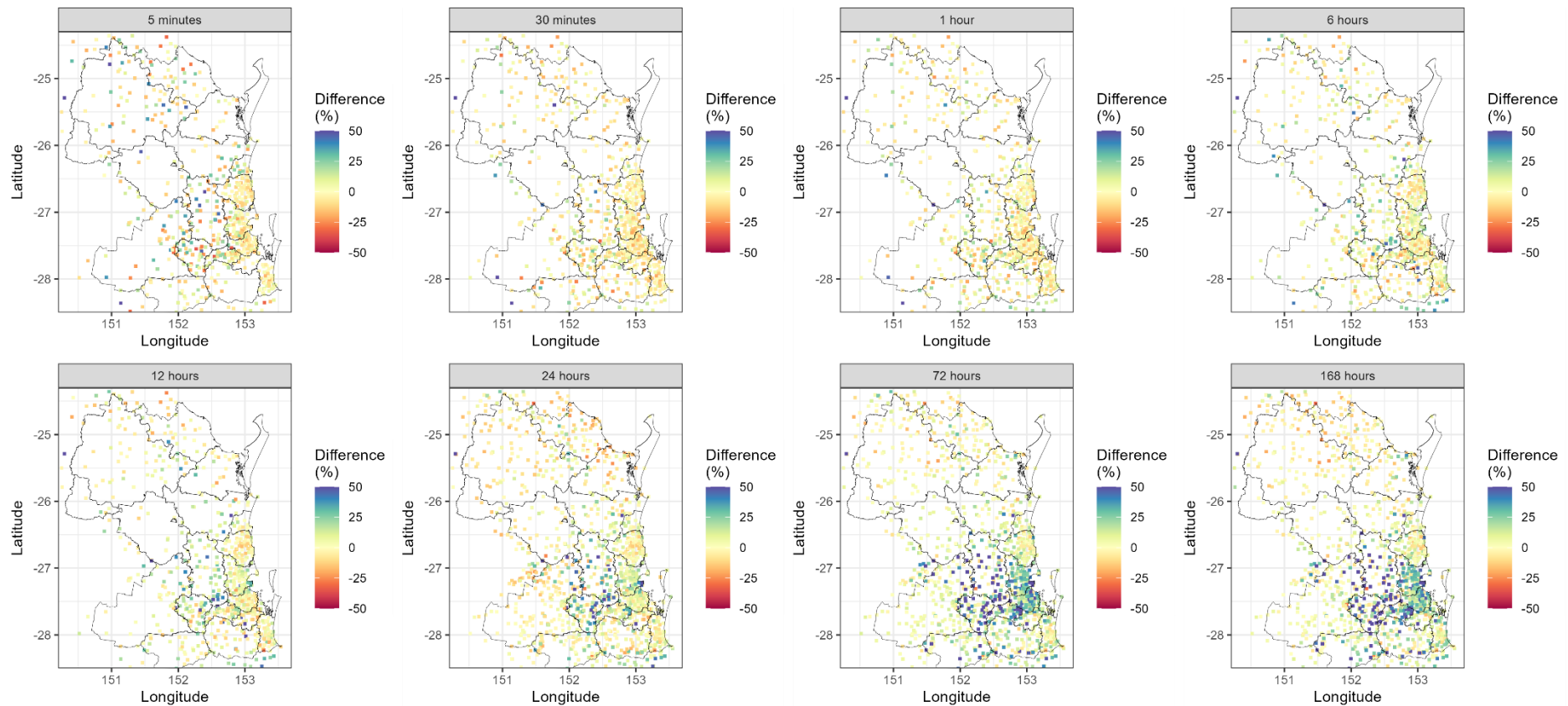


Figure H 1 Percentage changes in at-site and gridded IFDs for 50% AEP

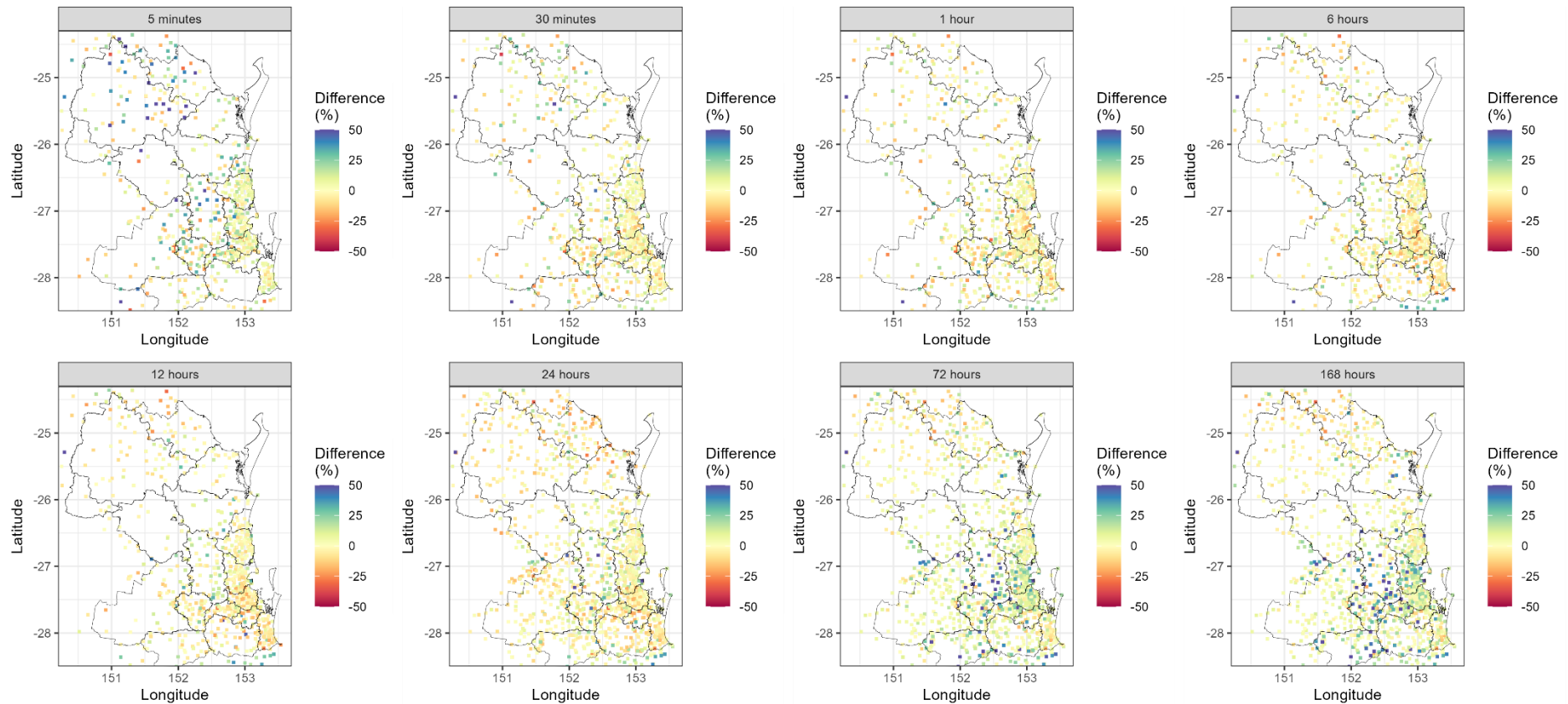


Figure H 2 Percentage changes in at-site and gridded IFDs for 20% AEP

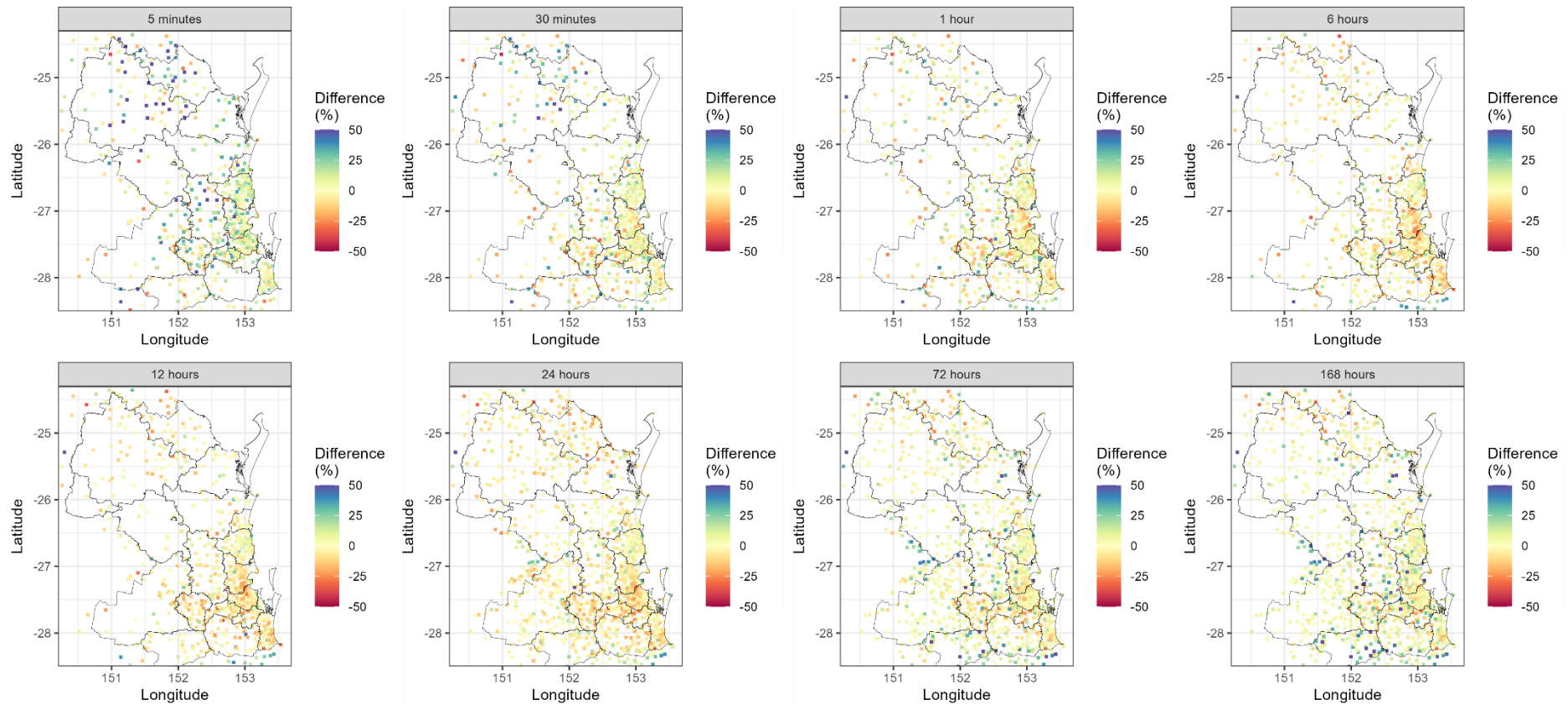


Figure H 3 Percentage changes in at-site and gridded IFDs for 10% AEP

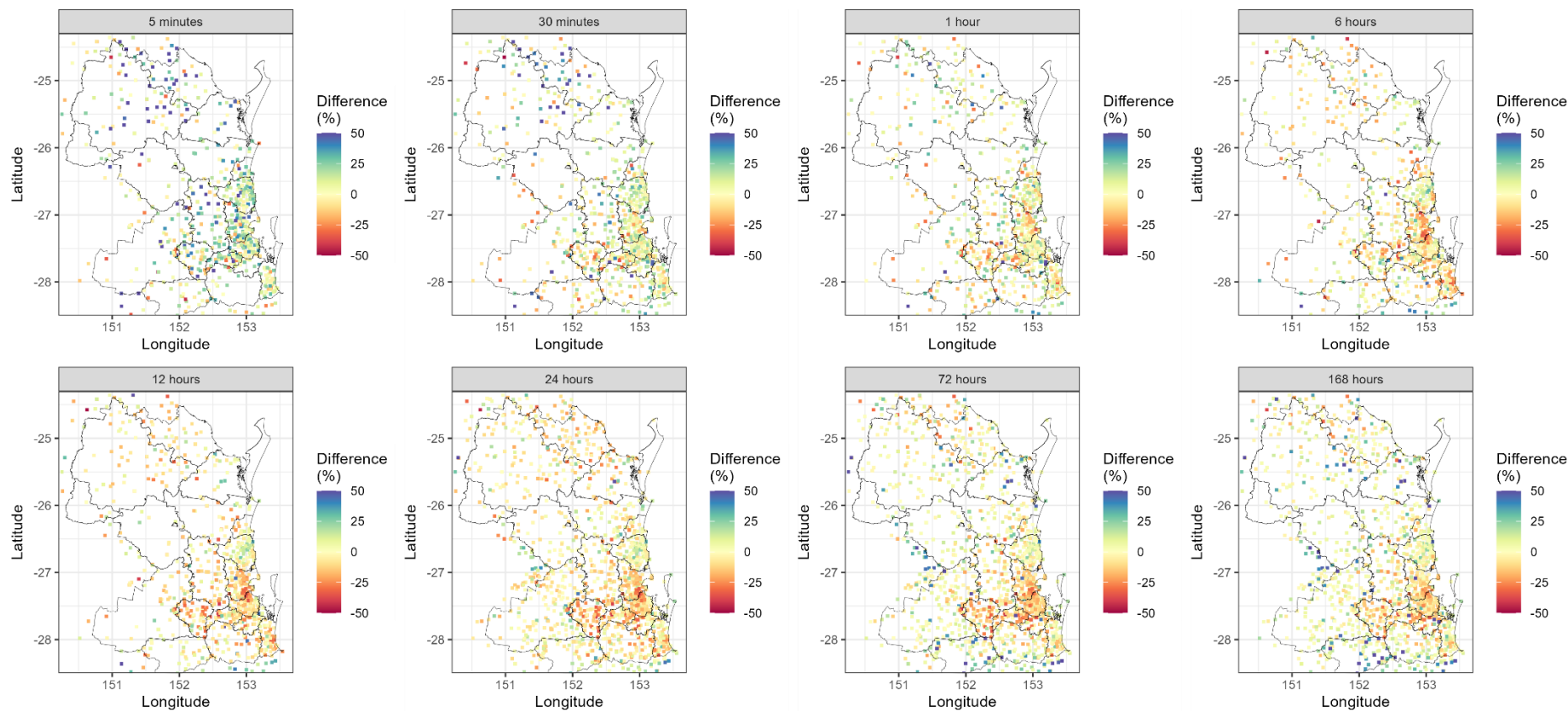


Figure H 4 Percentage changes in at-site and gridded IFDs for 5% AEP

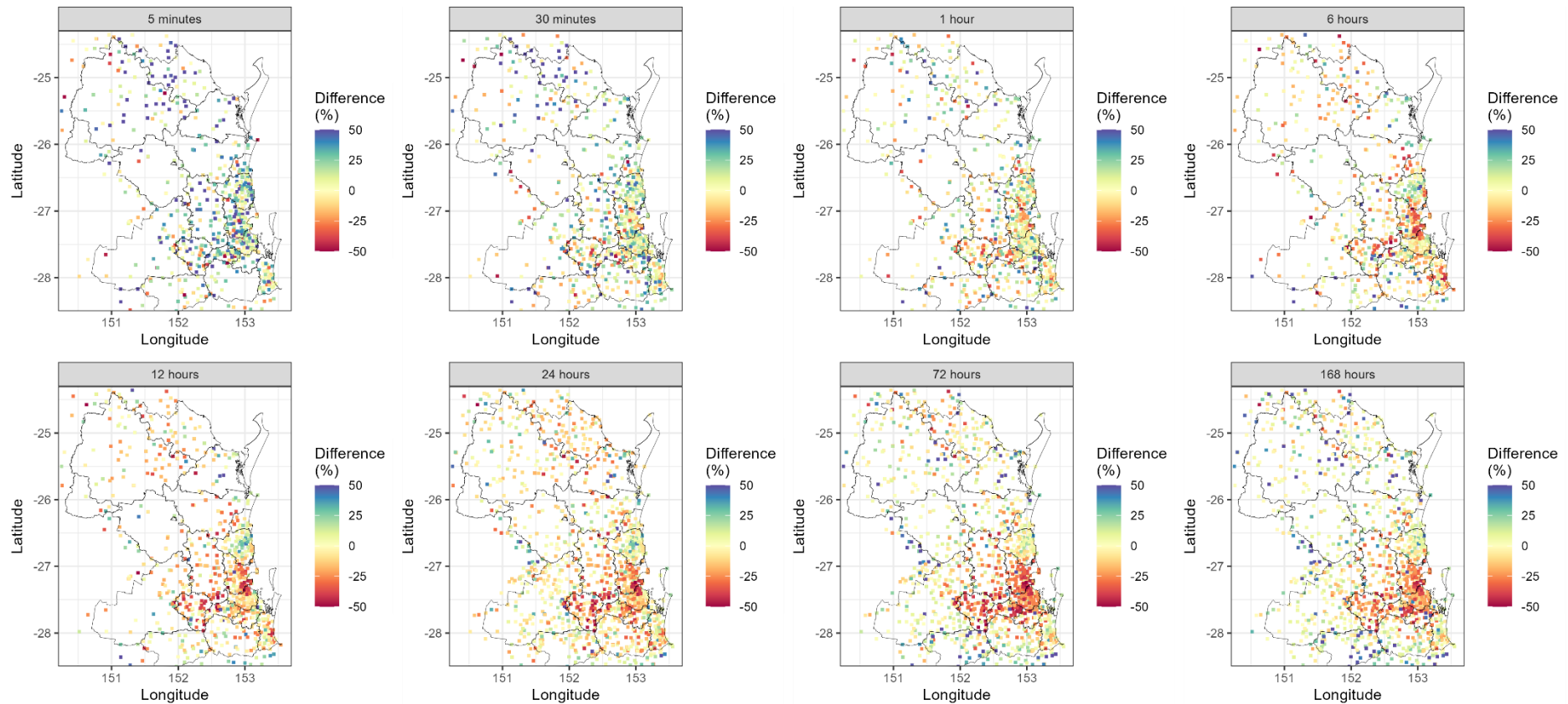


Figure H 5 Percentage changes in at-site and gridded IFDs for 2% AEP

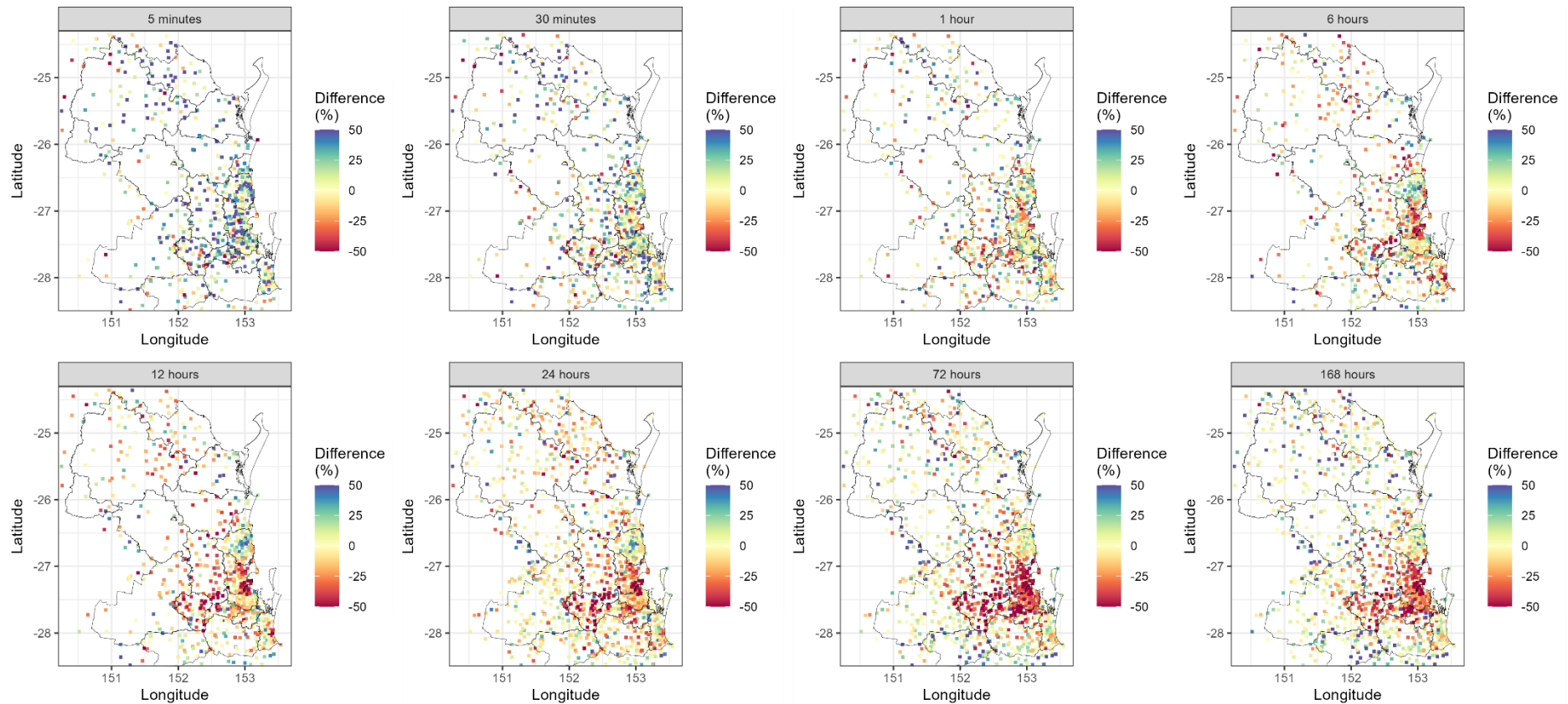


Figure H 6 Percentage changes in at-site and gridded IFDs for 1% AEP

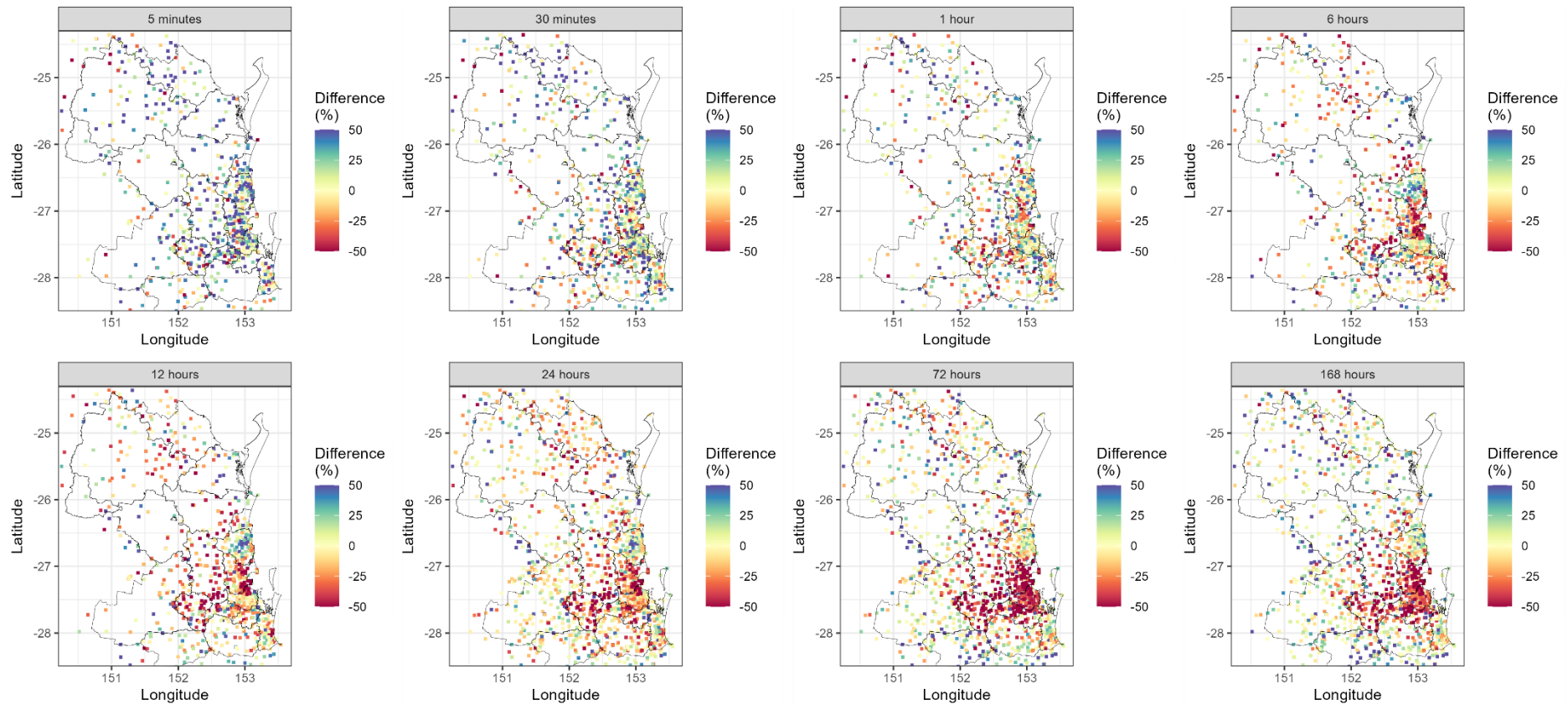


Figure H 7 Percentage changes in at-site and gridded IFDs for 1 in 200 AEP

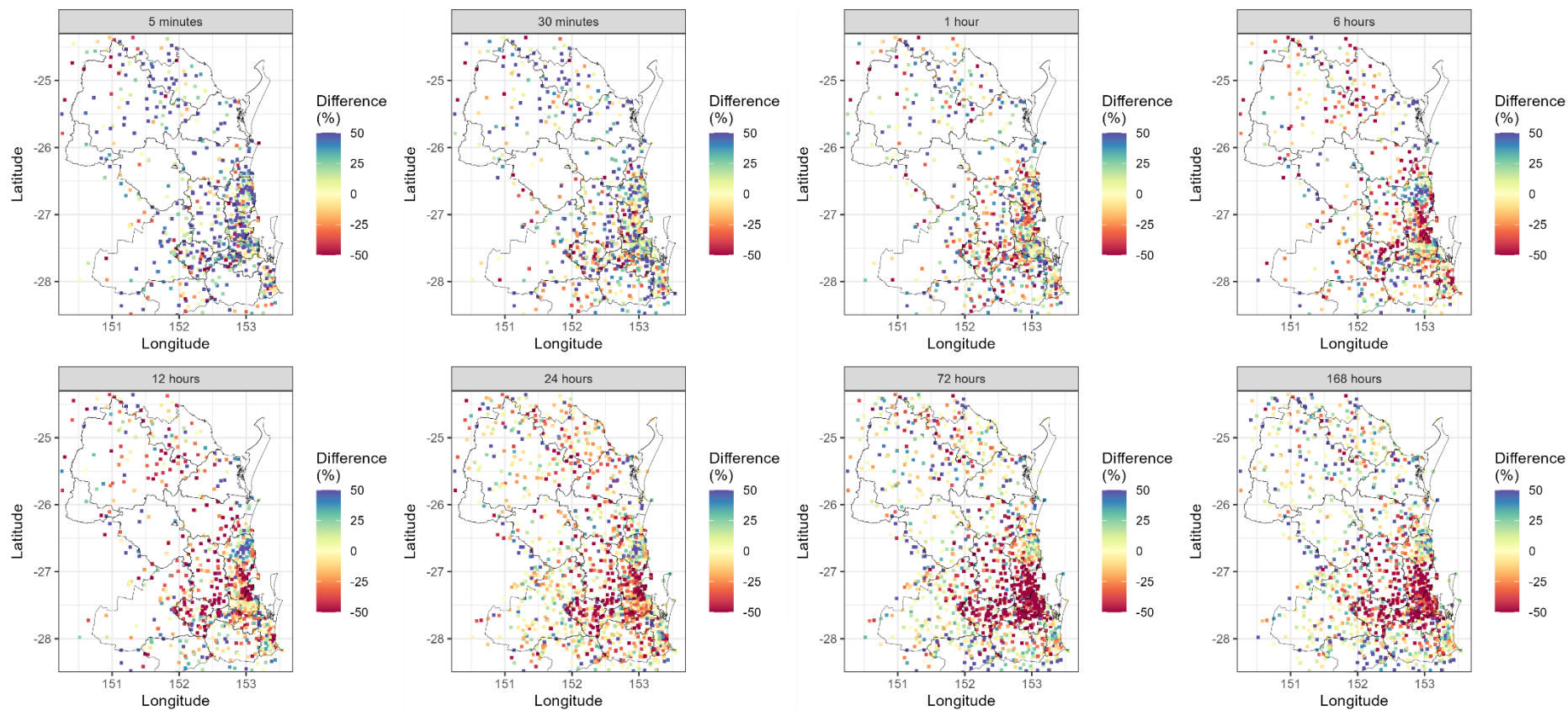


Figure H 8 Percentage changes in at-site and gridded IFDs for 1 in 500 AEP

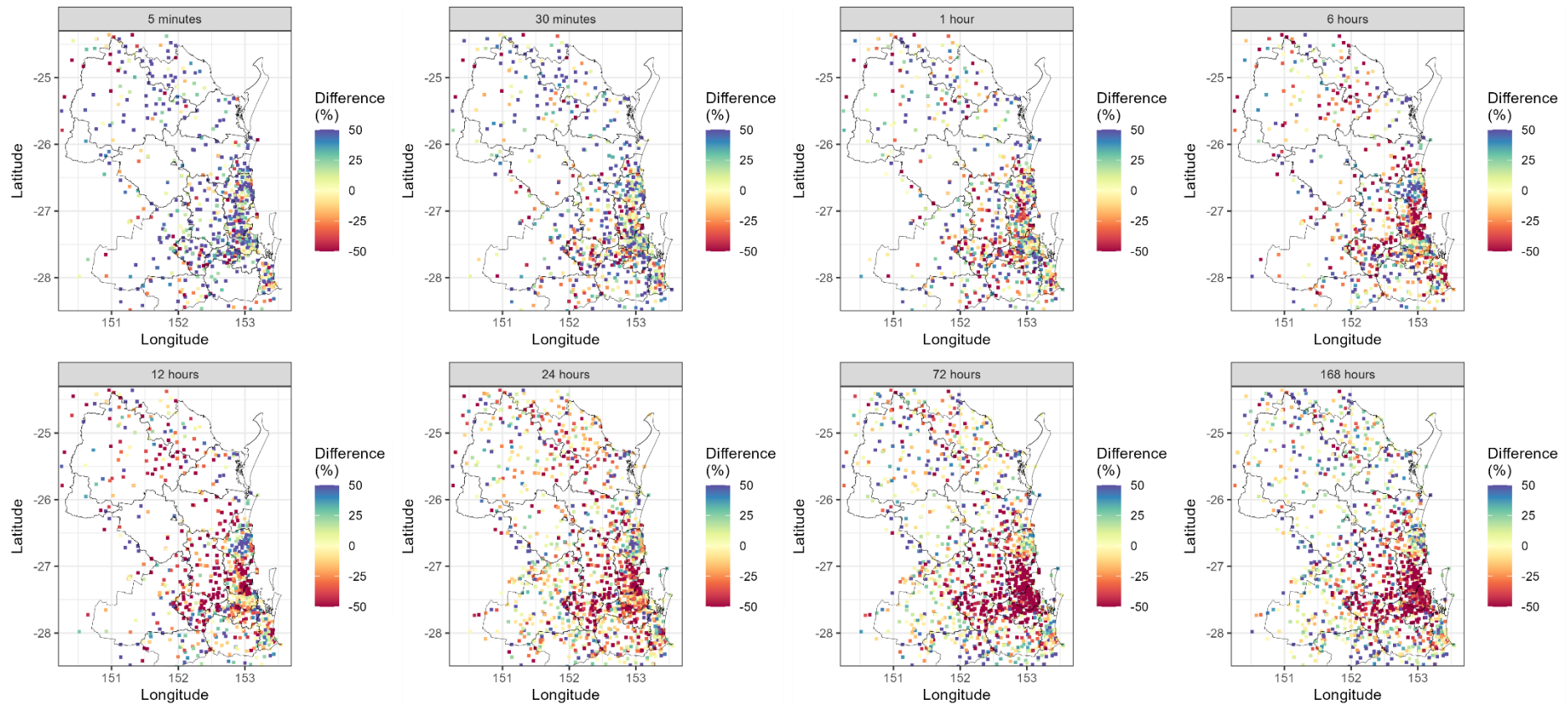


Figure H 9 Percentage changes in at-site and gridded IFDs for 1 in 1,000 AEP

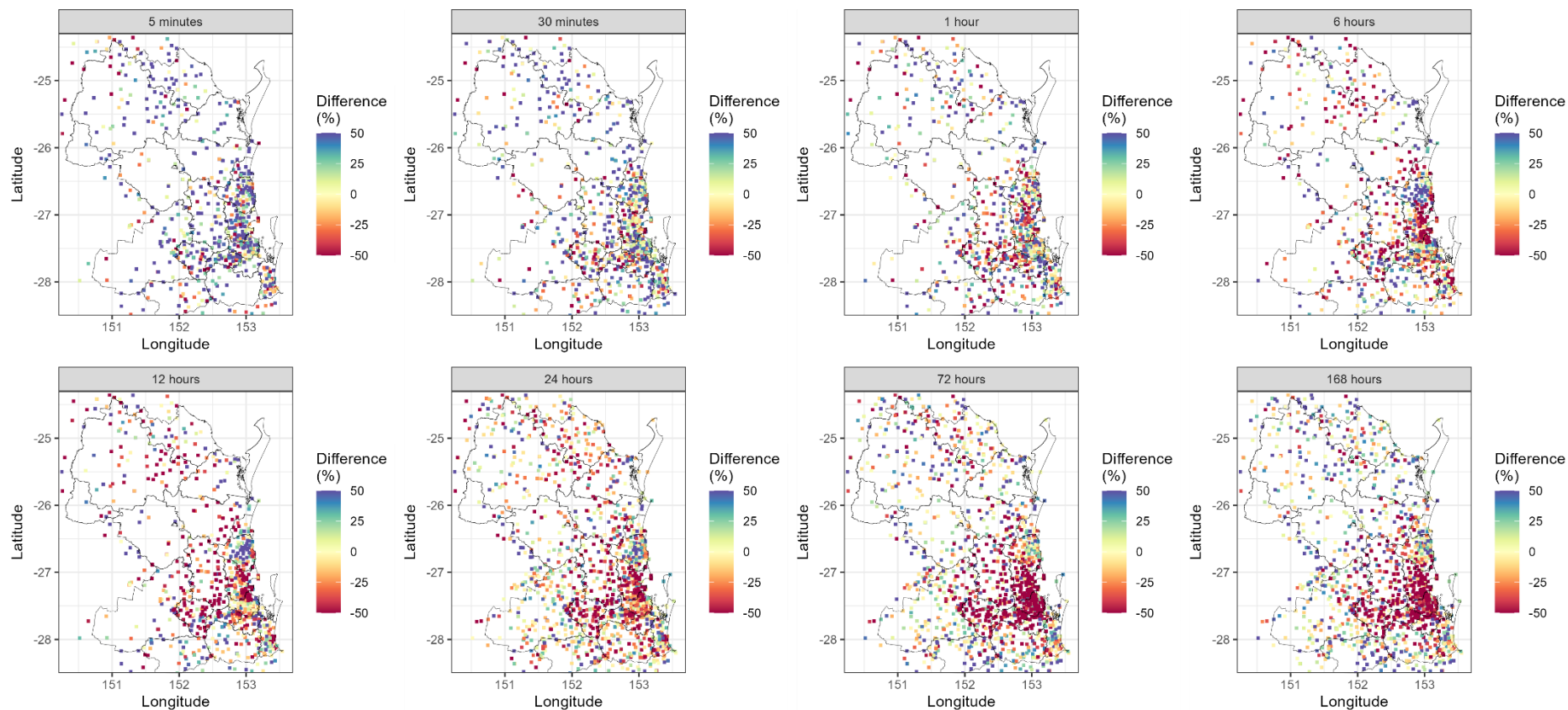


Figure H 10 Percentage changes in at-site and gridded IFDs for 1 in 2,000 AEP

Appendix I Spatial variation of the percentage difference between BoM IFDs (ARR, 2016) and IFDs from this study (HARC, 2024)

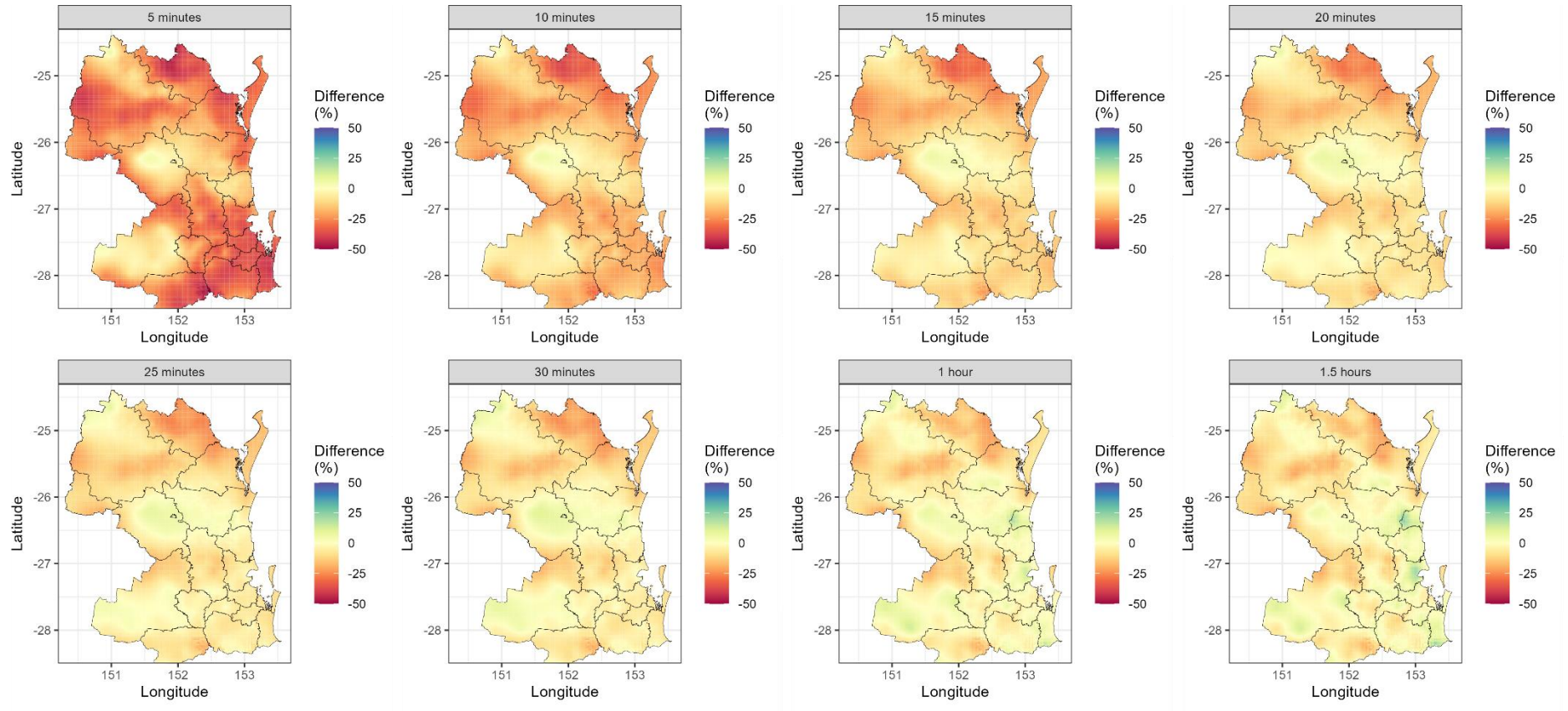


Figure 1 Percentage difference between 50% AEP BoM IFDs (ARR, 2016) and IFDs from this study (HARC, 2024) for durations 5 minutes – 1.5 hours

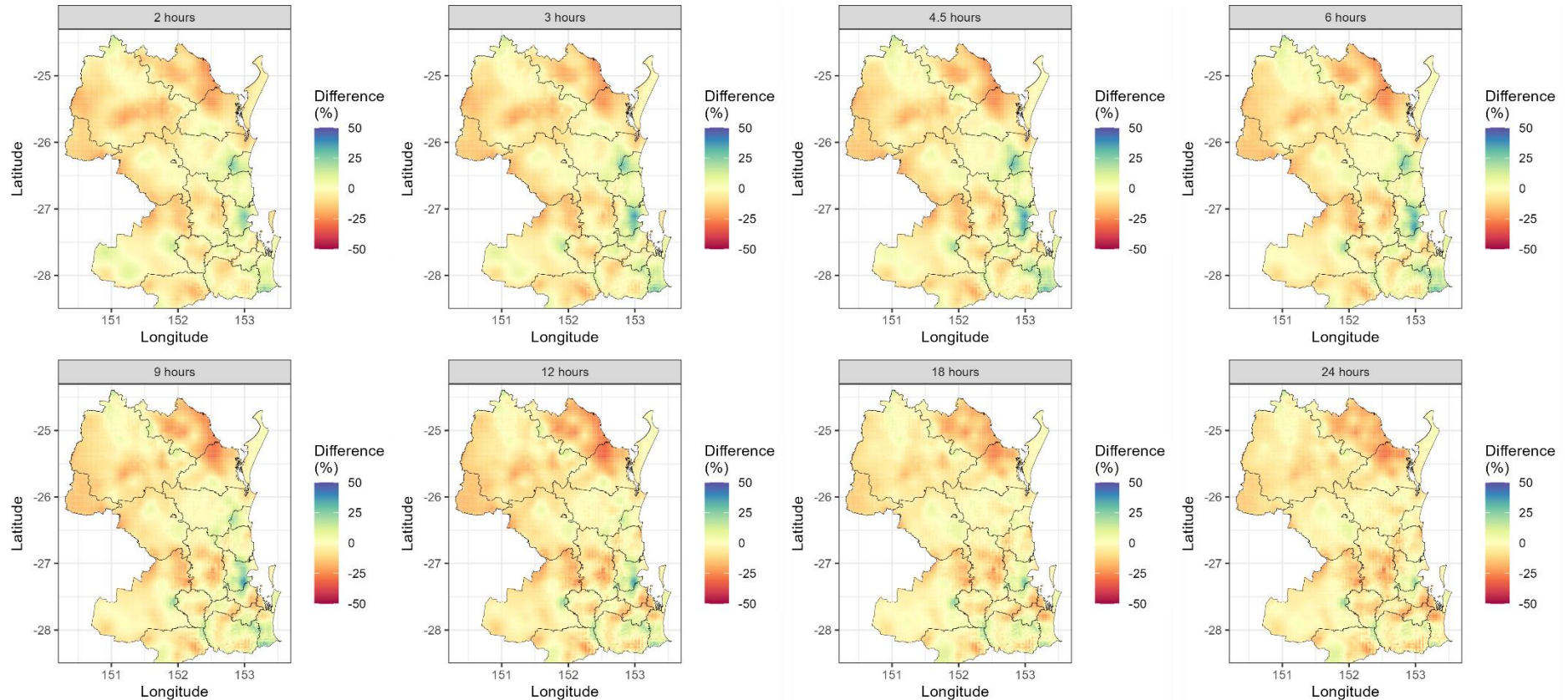


Figure 1.2 Percentage difference between 50% AEP BoM IFDs (ARR, 2016) and IFDs from this study (HARC, 2024) for durations 2 hours – 24 hours

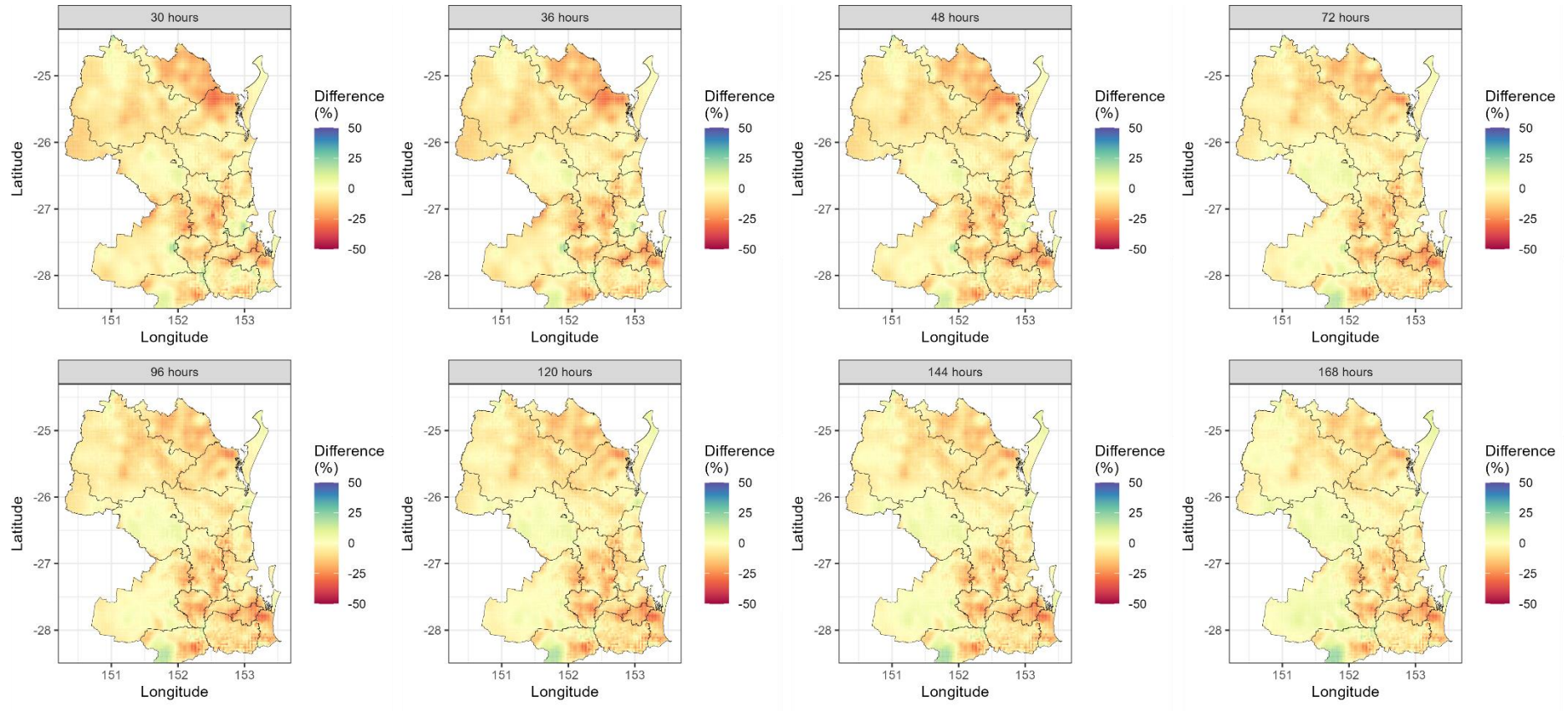


Figure I 3 Percentage difference between 50% AEP BoM IFDs (ARR, 2016) and IFDs from this study (HARC, 2024) for durations 30 hours – 168 hours

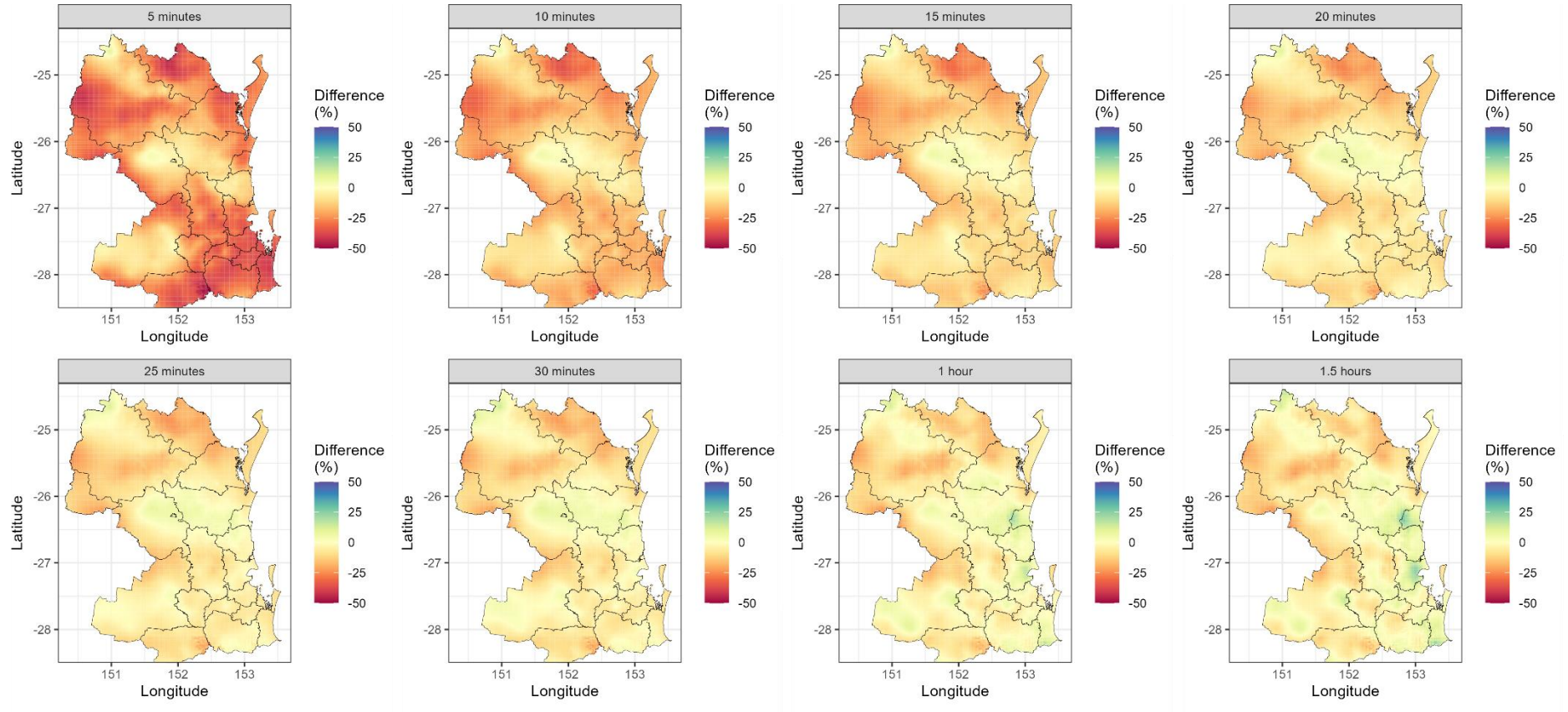


Figure 4 Percentage difference between 20% AEP BoM IFDs (ARR, 2016) and IFDs from this study (HARC, 2024) for durations 5 minutes – 1.5 hours

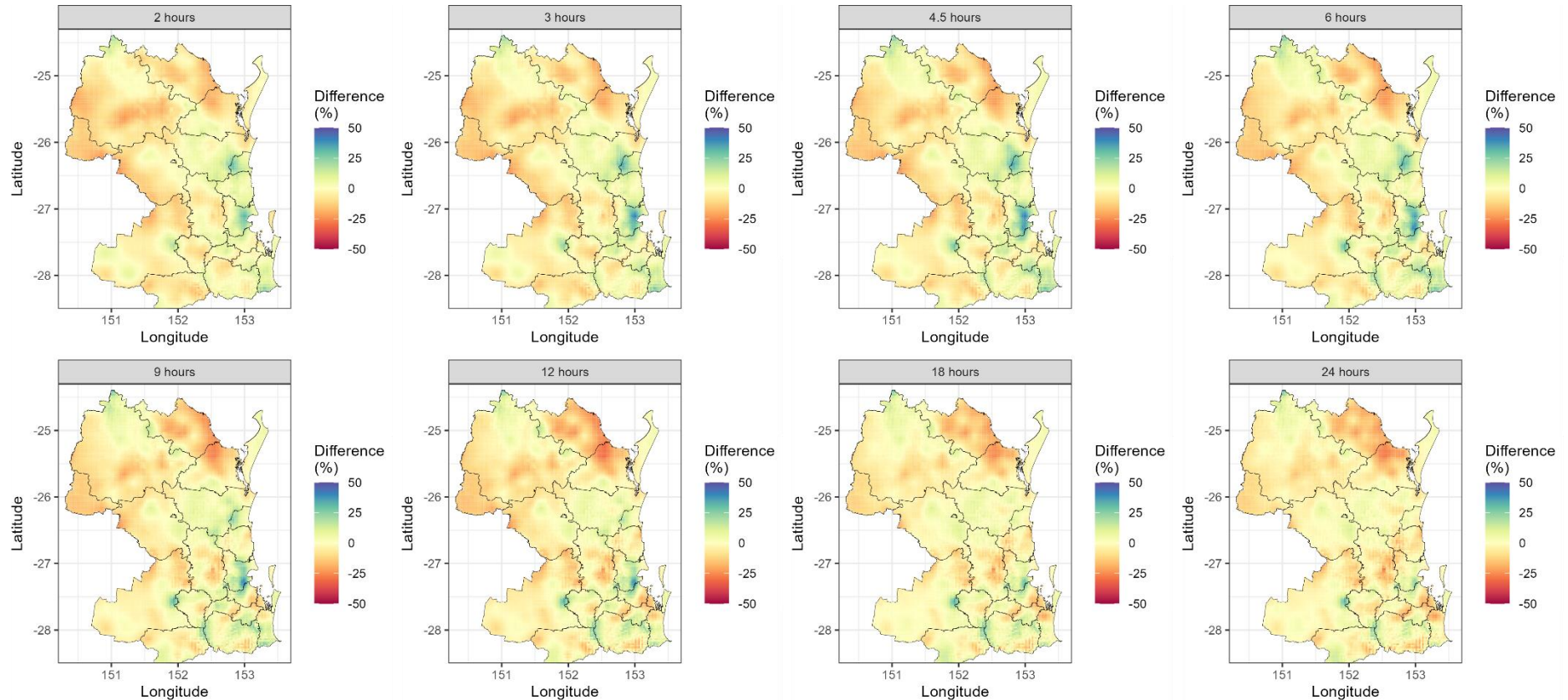


Figure I 5 Percentage difference between 20% AEP BoM IFDs (ARR, 2016) and IFDs from this study (HARC, 2024) for durations 2 hours – 24 hours

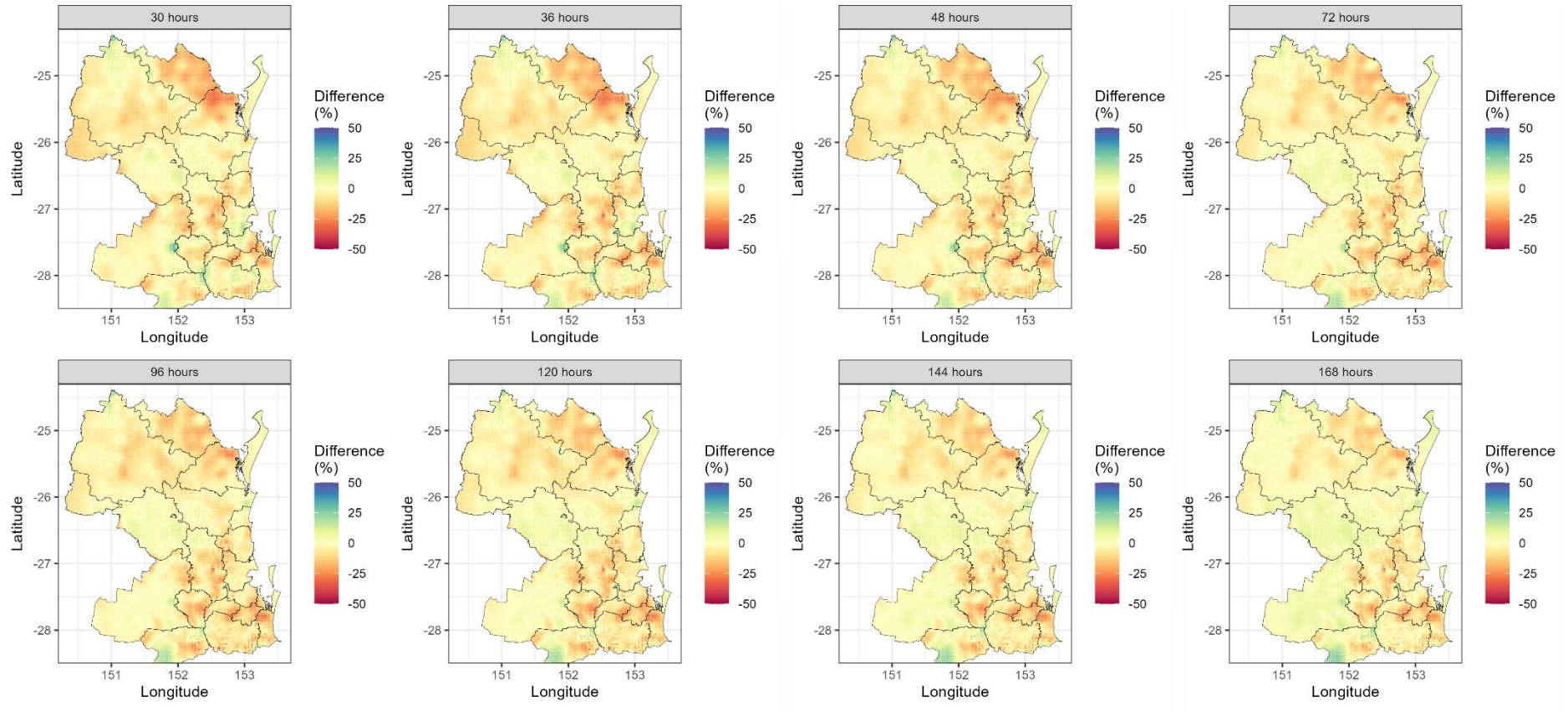


Figure I 6 Percentage difference between 20% AEP BoM IFDs (ARR, 2016) and IFDs from this study (HARC, 2024) for durations 30 hours – 168 hours

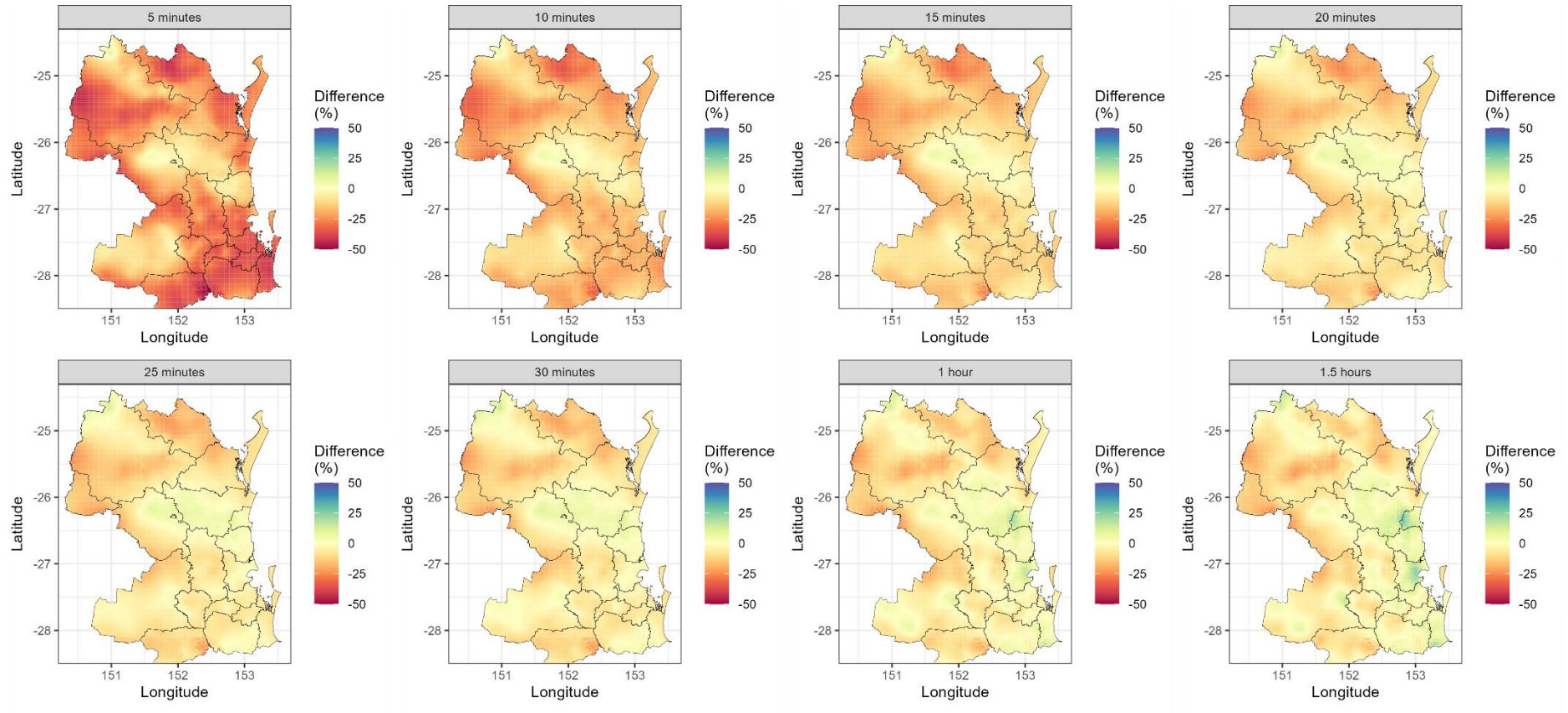


Figure I 7 Percentage difference between 10% AEP BoM IFDs (ARR, 2016) and IFDs from this study (HARC, 2024) for durations 5 minutes – 1.5 hours

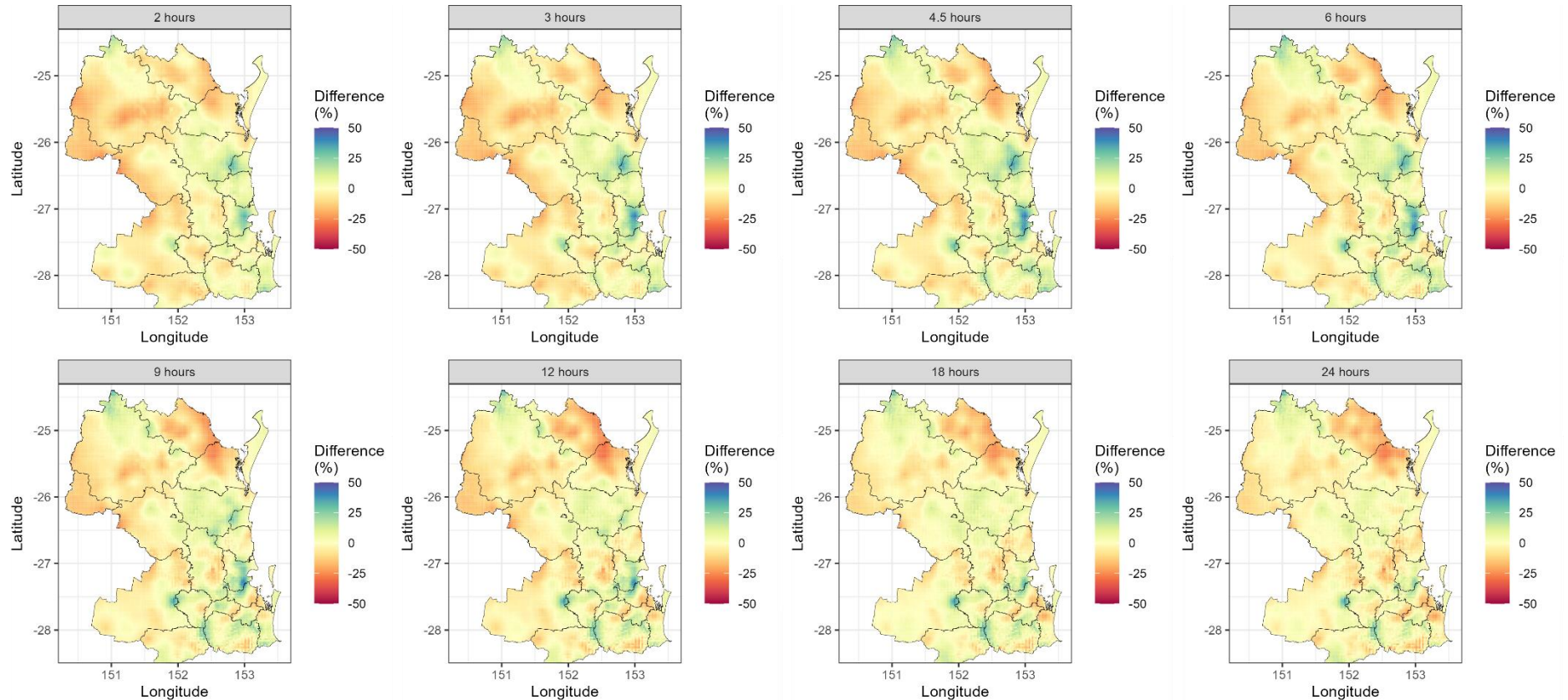


Figure I 8 Percentage difference between 10% AEP BoM IFDs (ARR, 2016) and IFDs from this study (HARC, 2024) for durations 2 hours – 24 hours

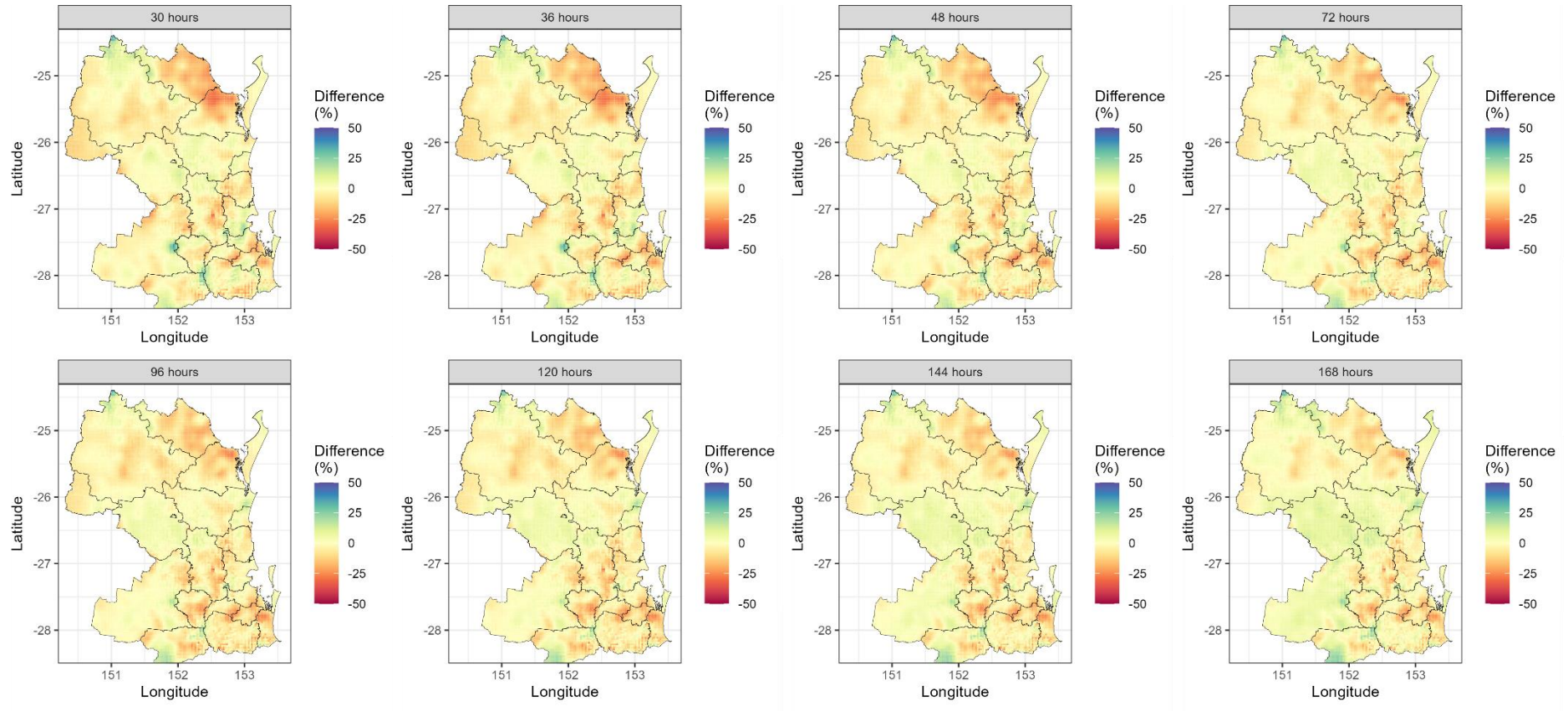


Figure I 9 Percentage difference between 10% AEP BoM IFDs (ARR, 2016) and IFDs from this study (HARC, 2024) for durations 30 hours – 168 hours

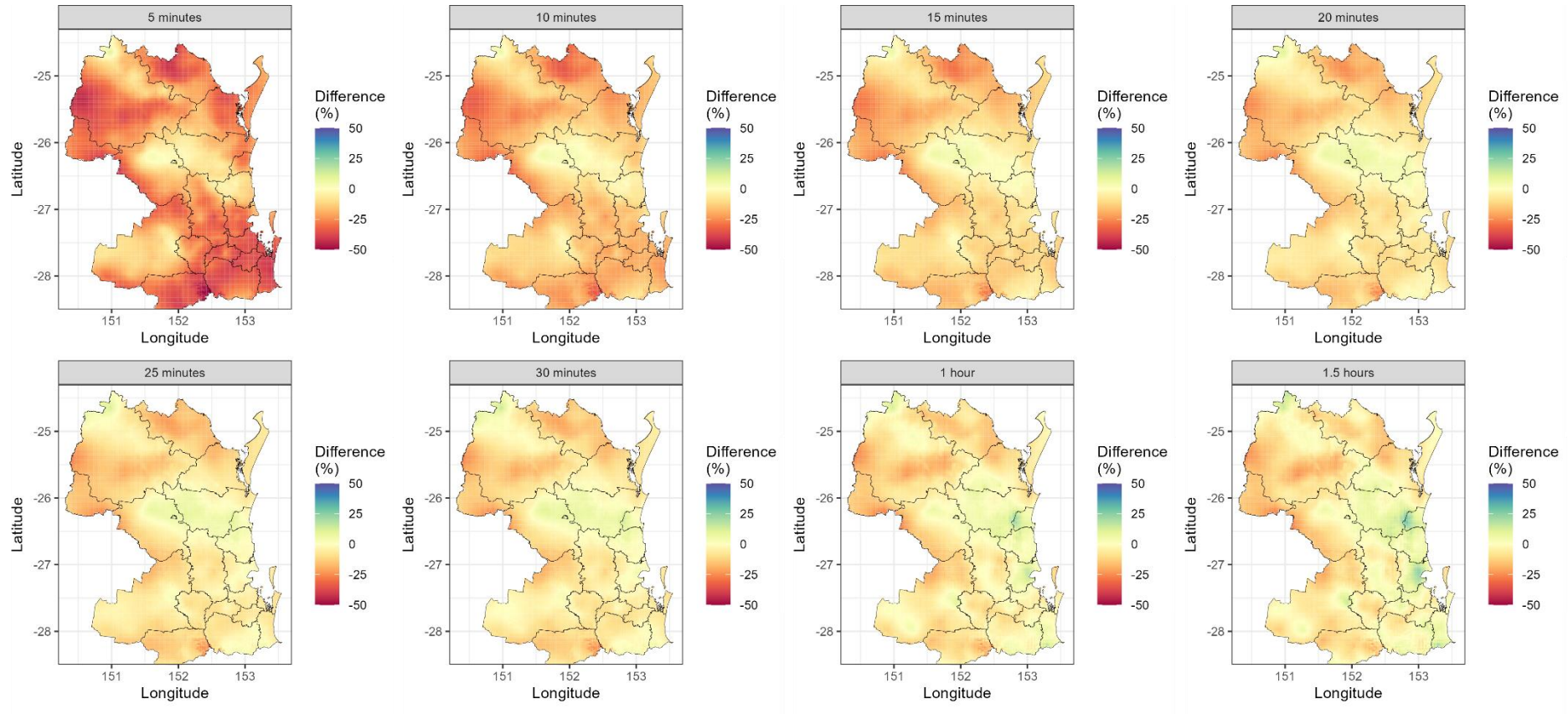


Figure I 10 Percentage difference between 5% AEP BoM IFDs (ARR, 2016) and IFDs from this study (HARC, 2024) for durations 5 minutes – 1.5 hours

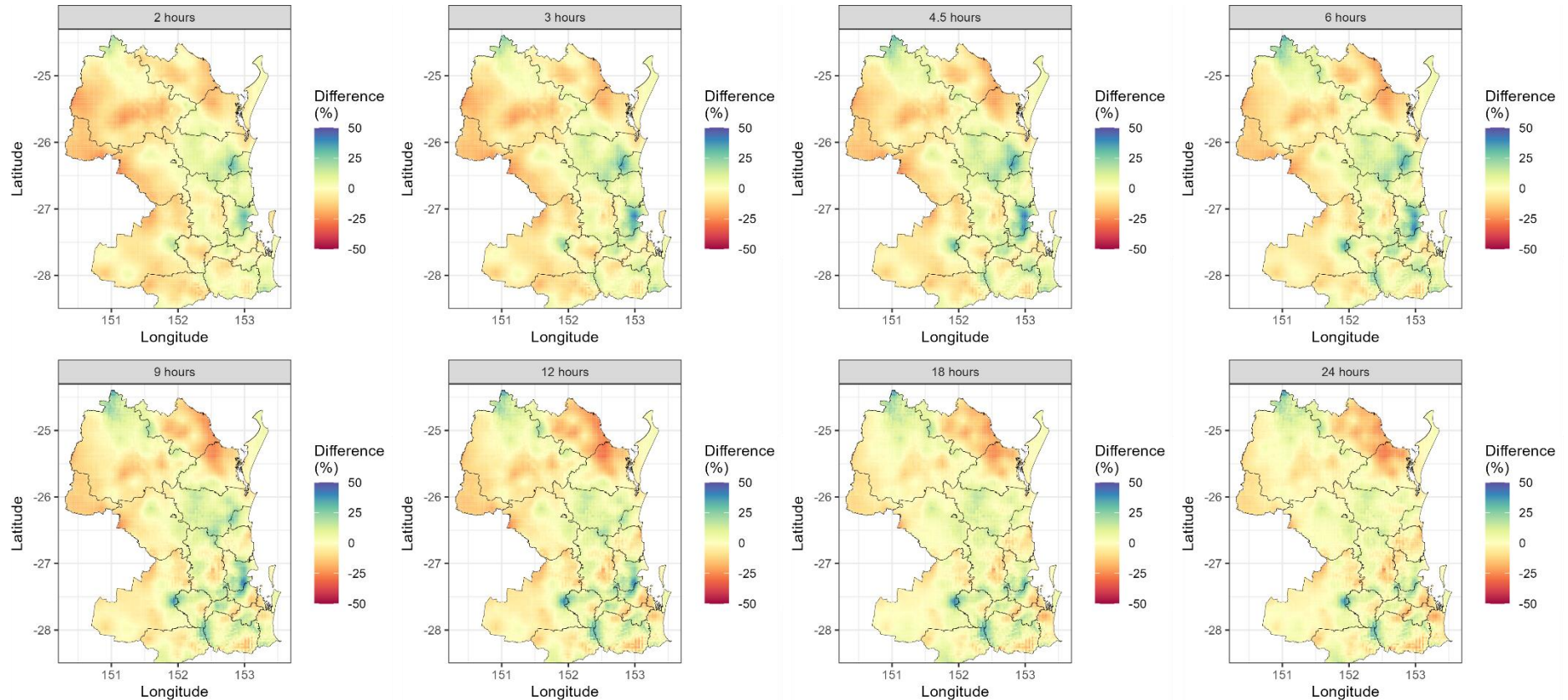


Figure I 11 Percentage difference between 5% AEP BoM IFDs (ARR, 2016) and IFDs from this study (HARC, 2024) for durations 2 hours – 24 hours

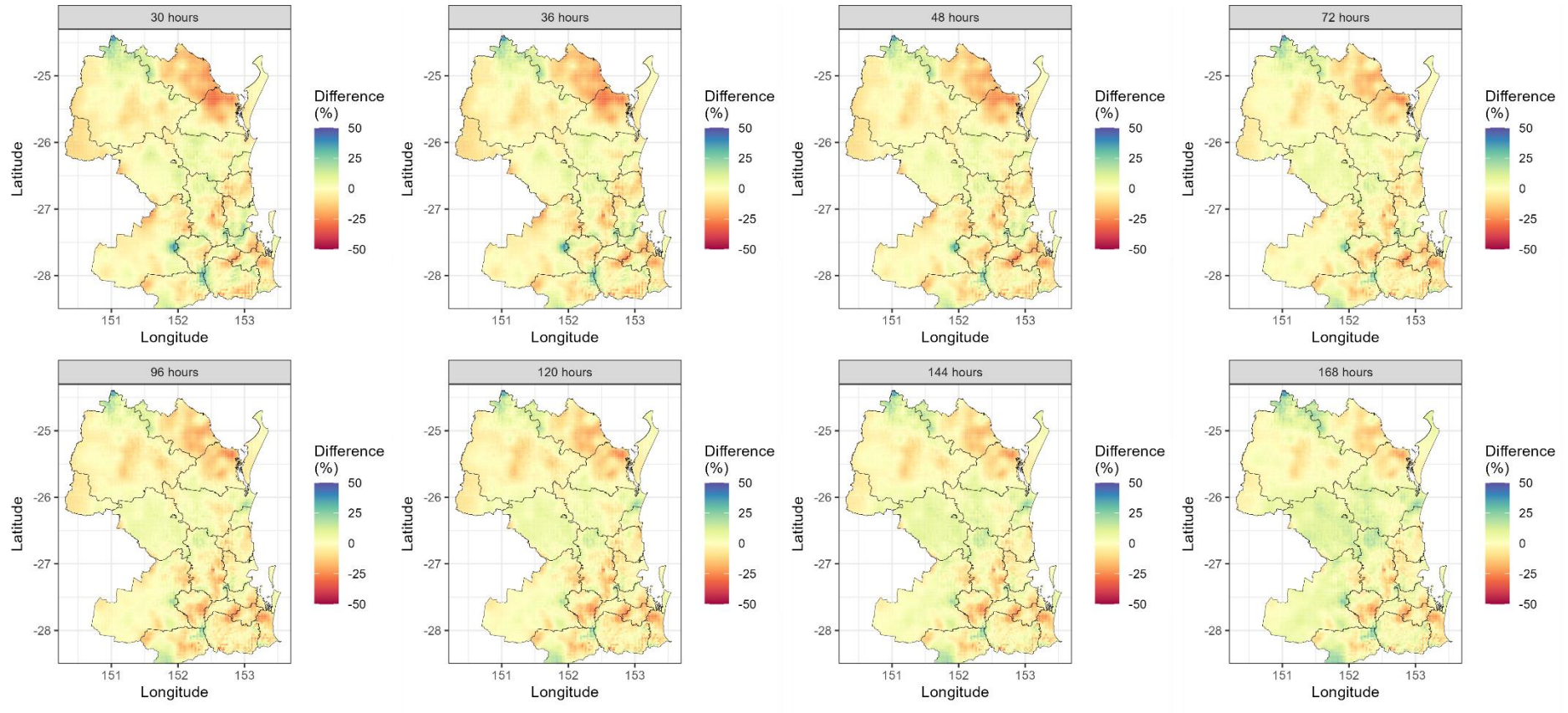


Figure I 12 Percentage difference between 5% AEP BoM IFDs (ARR, 2016) and IFDs from this study (HARC, 2024) for durations 30 hours – 168 hours

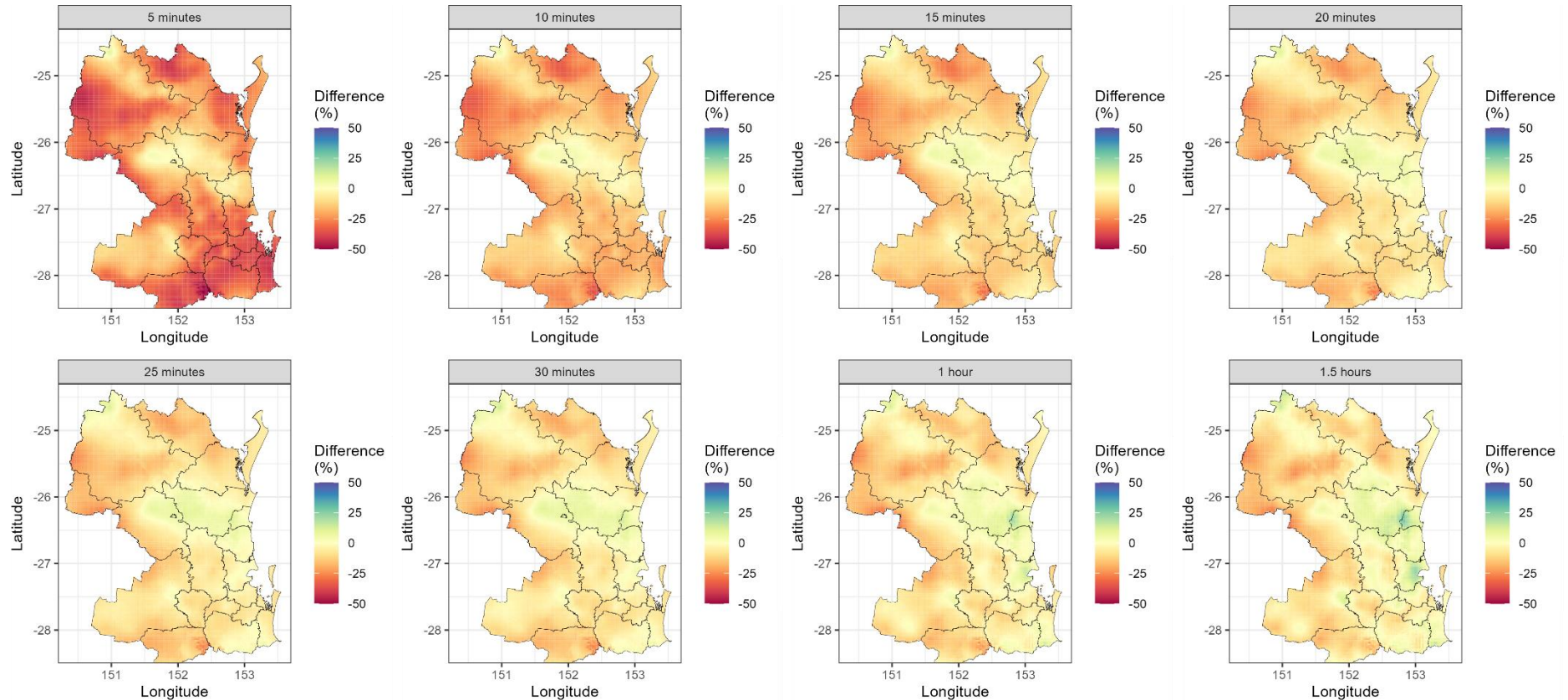


Figure I 13 Percentage difference between 2% AEP BoM IFDs (ARR, 2016) and IFDs from this study (HARC, 2024) for durations 5 minutes – 1.5 hours

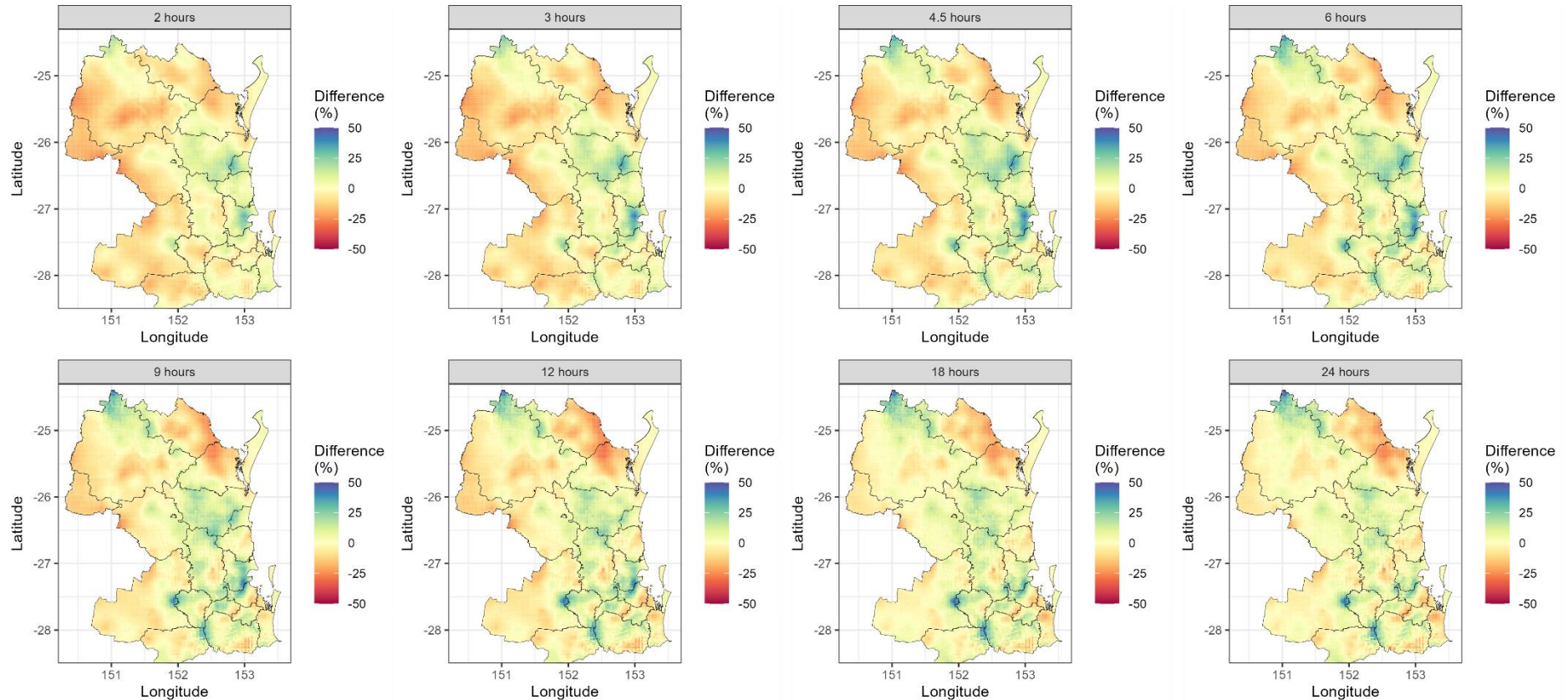


Figure I 14 Percentage difference between 2% AEP BoM IFDs (ARR, 2016) and IFDs from this study (HARC, 2024) for durations 2 hours – 24 hours

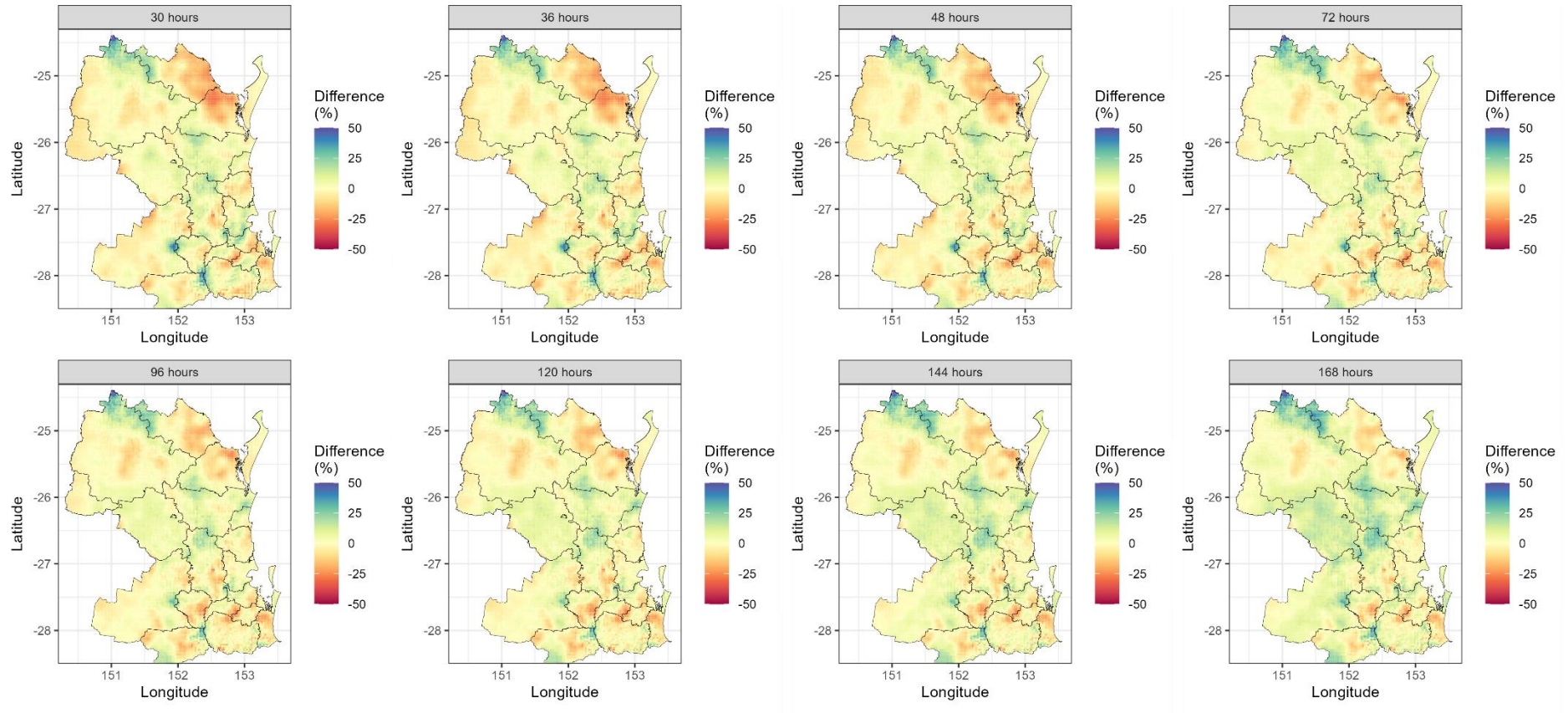


Figure I 15 Percentage difference between 2% AEP BoM IFDs (ARR, 2016) and IFDs from this study (HARC, 2024) for durations 30 hours – 168 hours

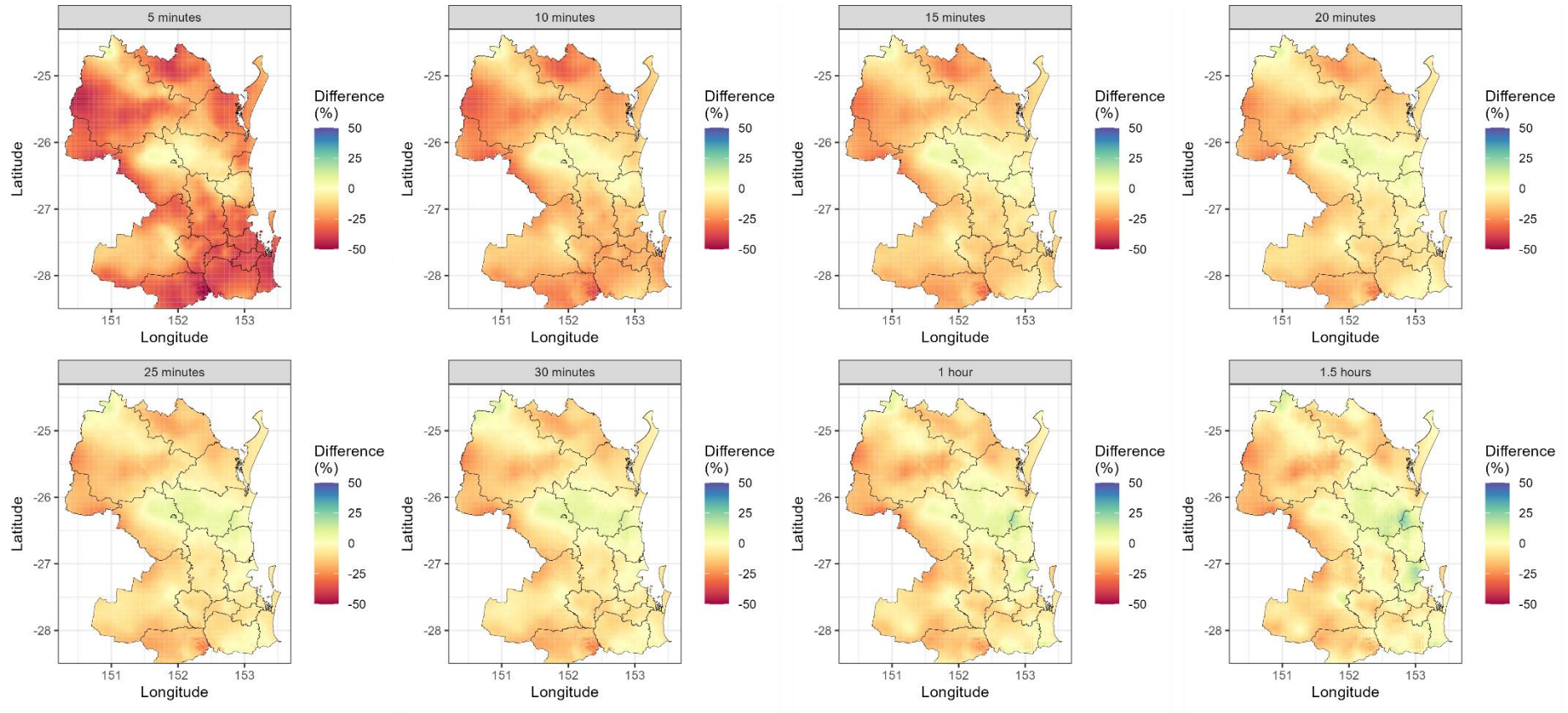


Figure I 16 Percentage difference between 1% AEP BoM IFDs (ARR, 2016) and IFDs from this study (HARC, 2024) for durations 5 minutes – 1.5 hours

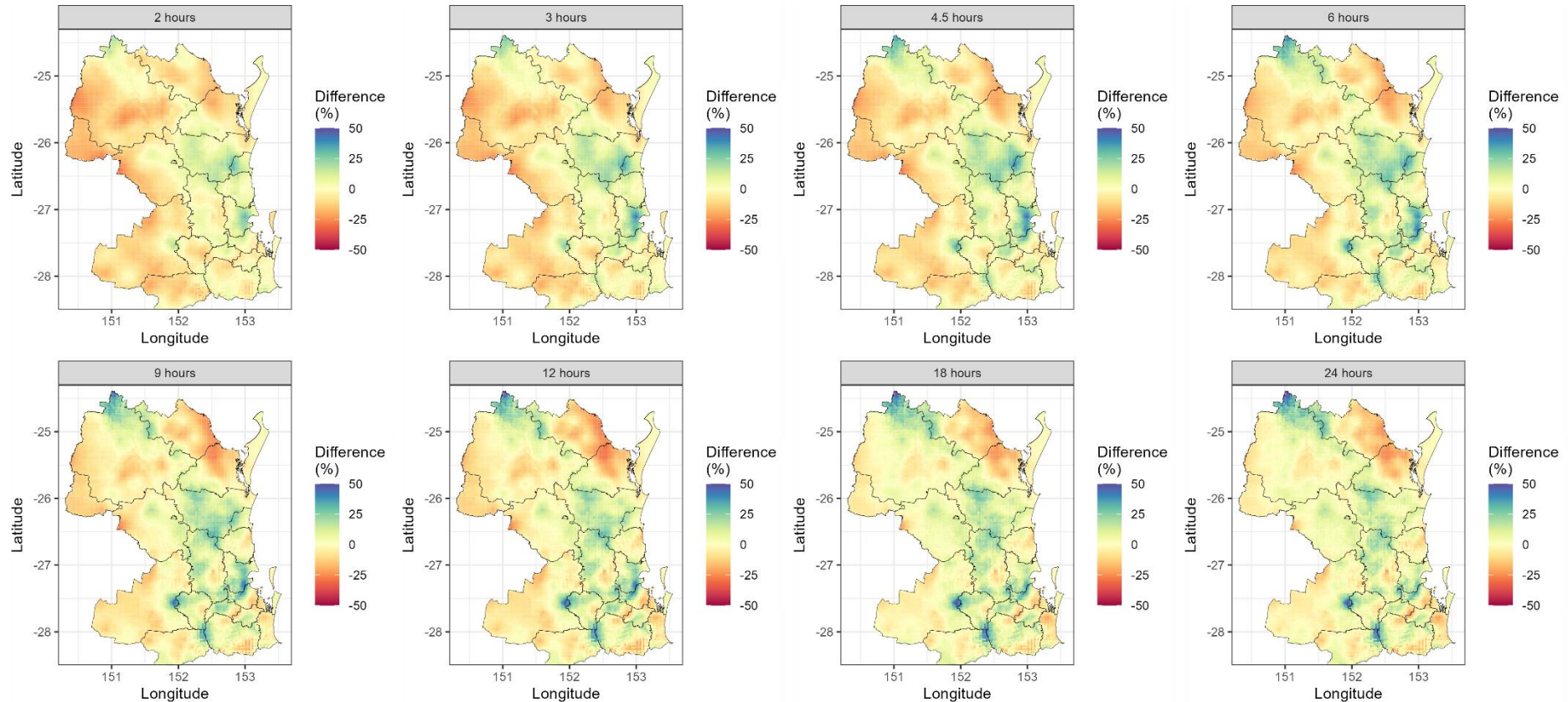


Figure I 17 Percentage difference between 1% AEP BoM IFDs (ARR, 2016) and IFDs from this study (HARC, 2024) for durations 2 hours – 24 hours

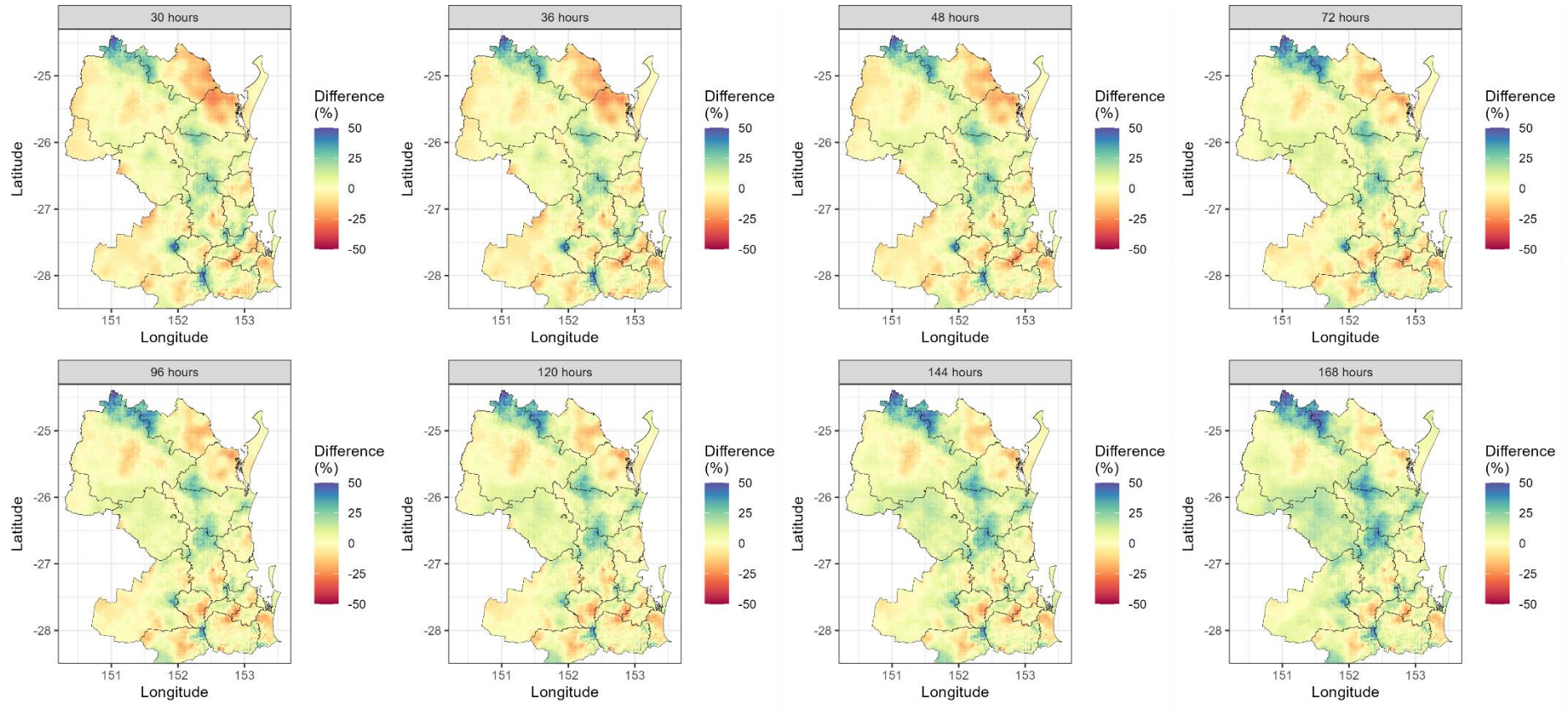


Figure I 18 Percentage difference between 1% AEP BoM IFDs (ARR, 2016) and IFDs from this study (HARC, 2024) for durations 30 hours – 168 hours

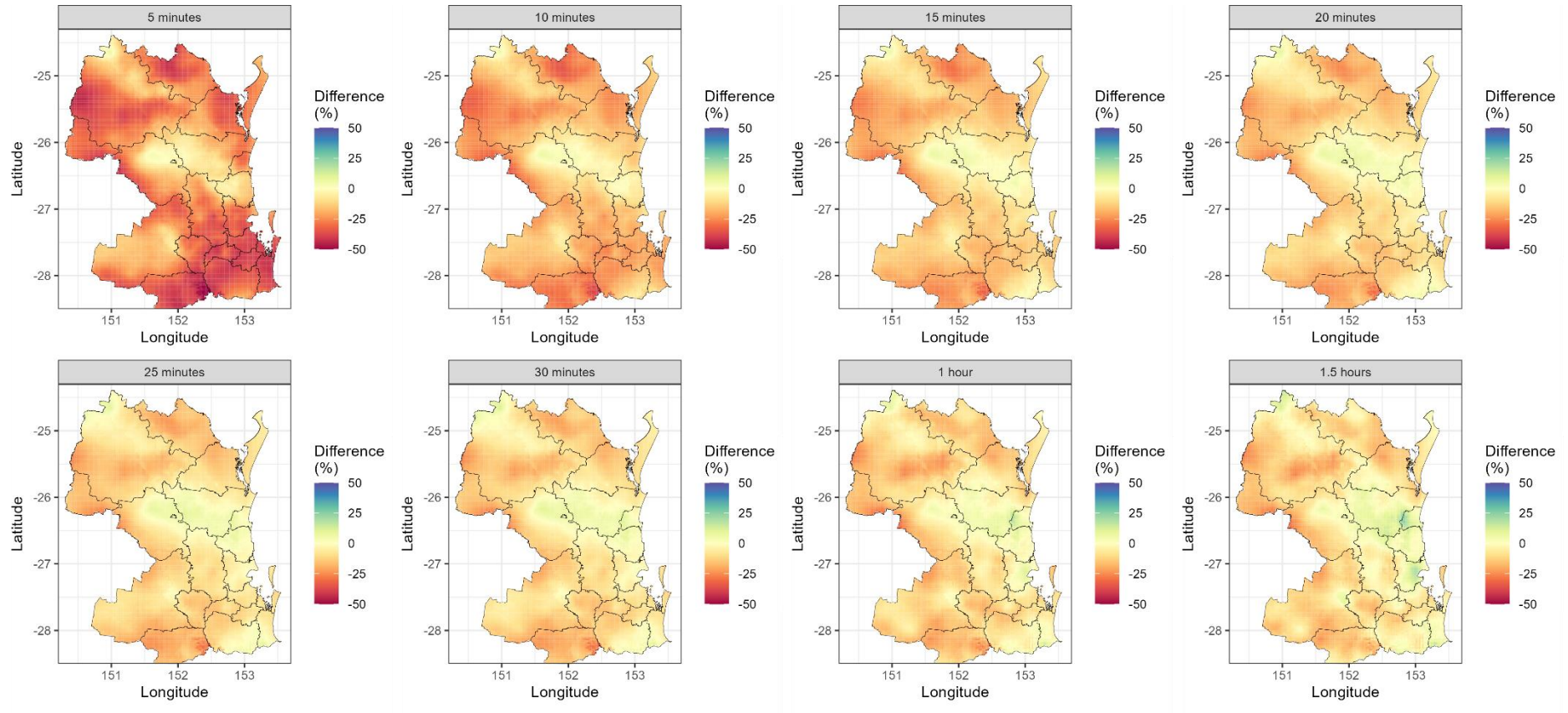


Figure I 19 Percentage difference between 1 in 200 AEP BoM IFDs (ARR, 2016) and IFDs from this study (HARC, 2024) for durations 5 minutes – 1.5 hours

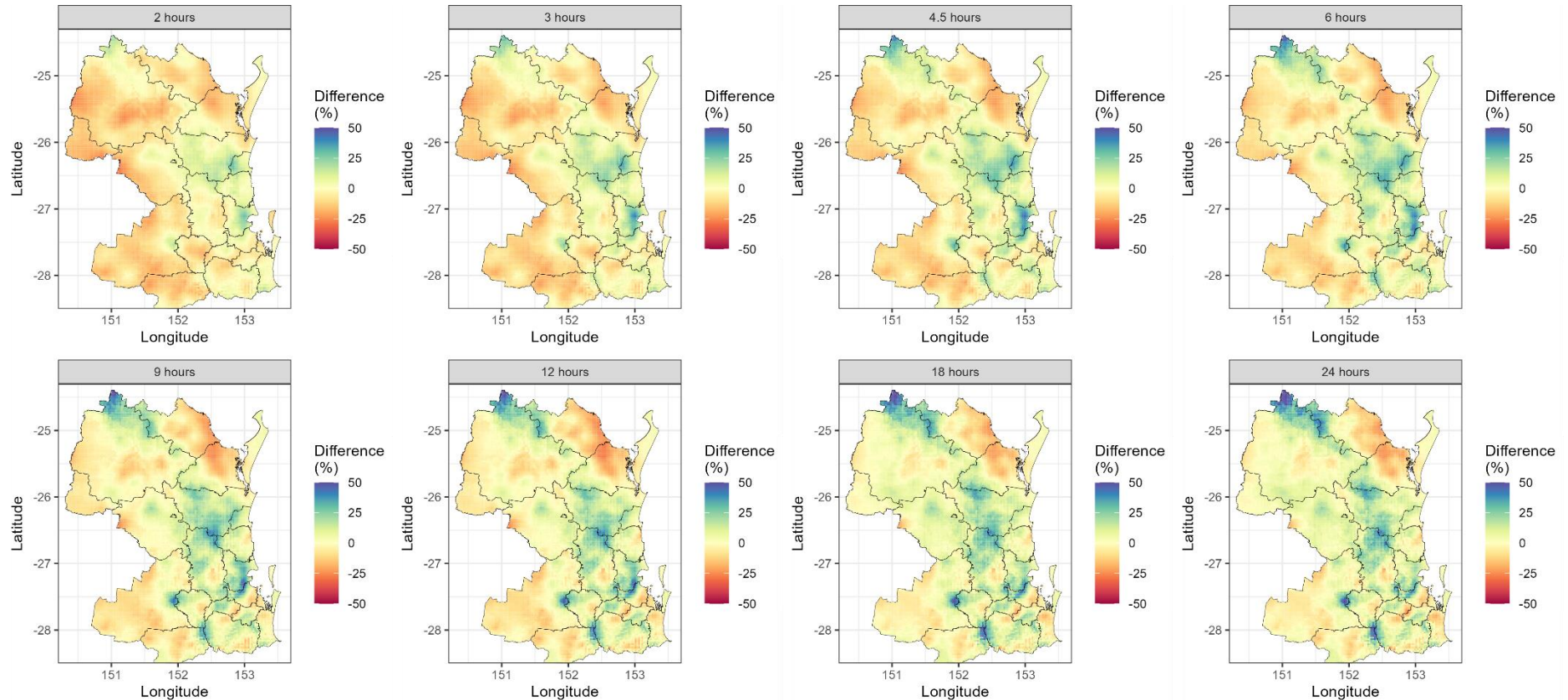


Figure I 20 Percentage difference between 1 in 200 AEP BoM IFDs (ARR, 2016) and IFDs from this study (HARC, 2024) for durations 2 hours – 24 hours

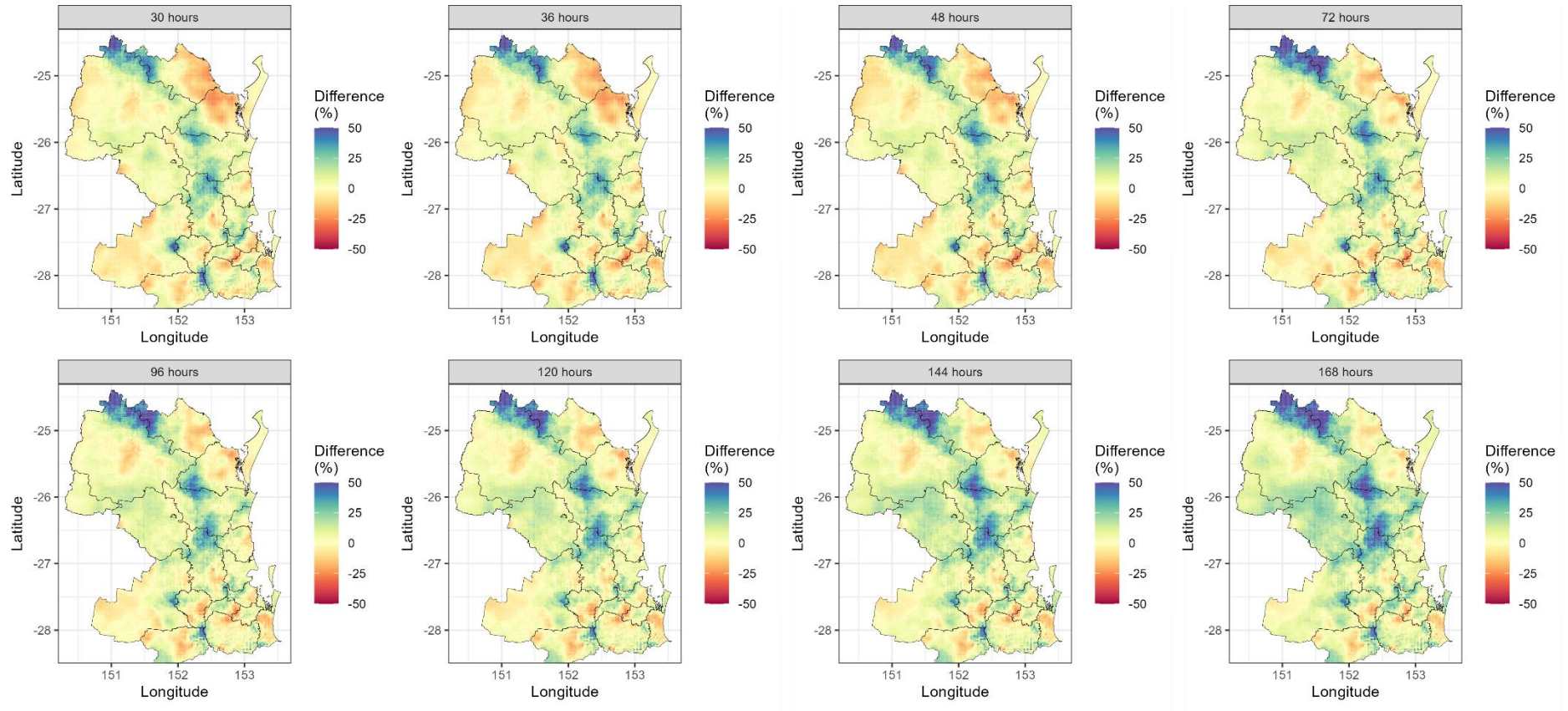


Figure I 21 Percentage difference between 1 in 200 AEP BoM IFDs (ARR, 2016) and IFDs from this study (HARC, 2024) for durations 30 hours – 168 hours

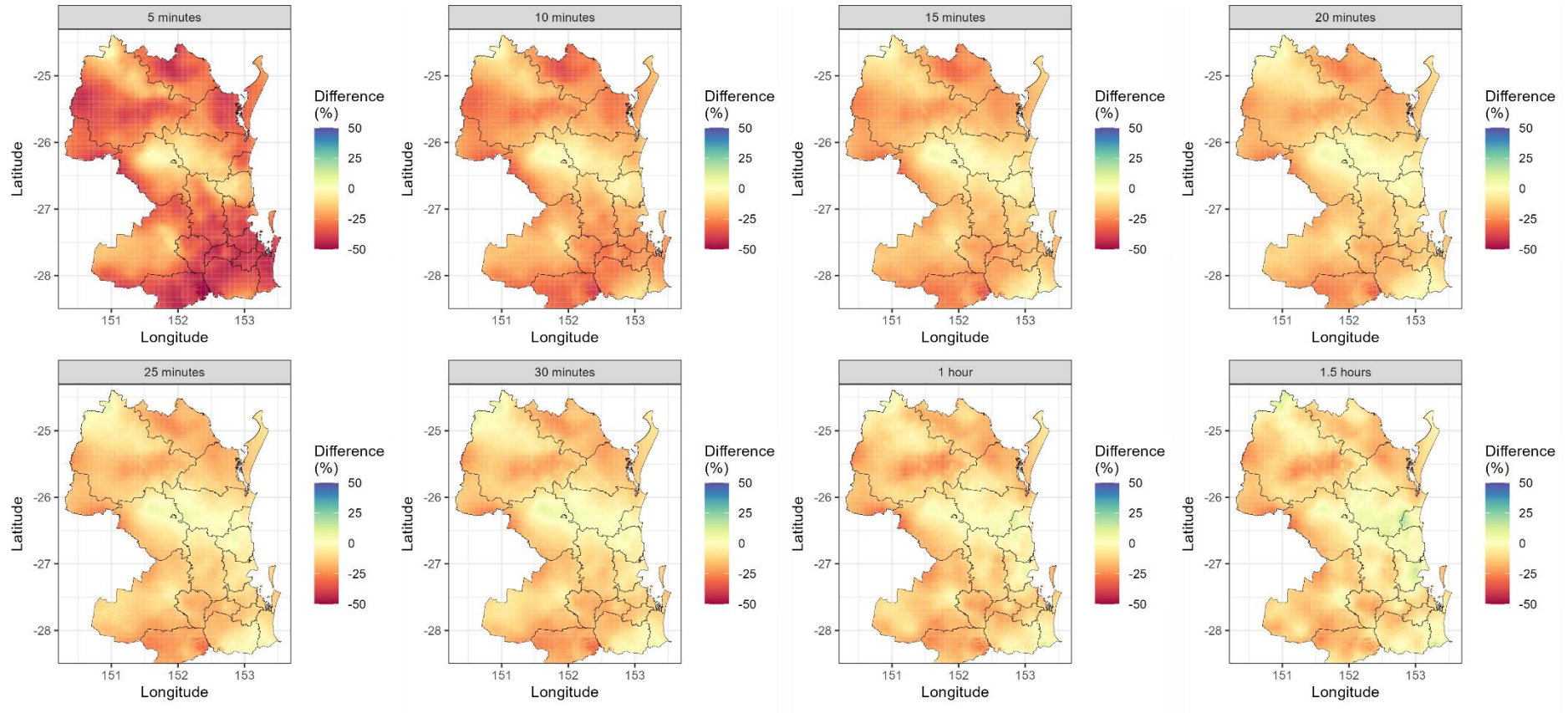


Figure I 22 Percentage difference between 1 in 500 AEP BoM IFDs (ARR, 2016) and IFDs from this study (HARC, 2024) for durations 5 minutes – 1.5 hours

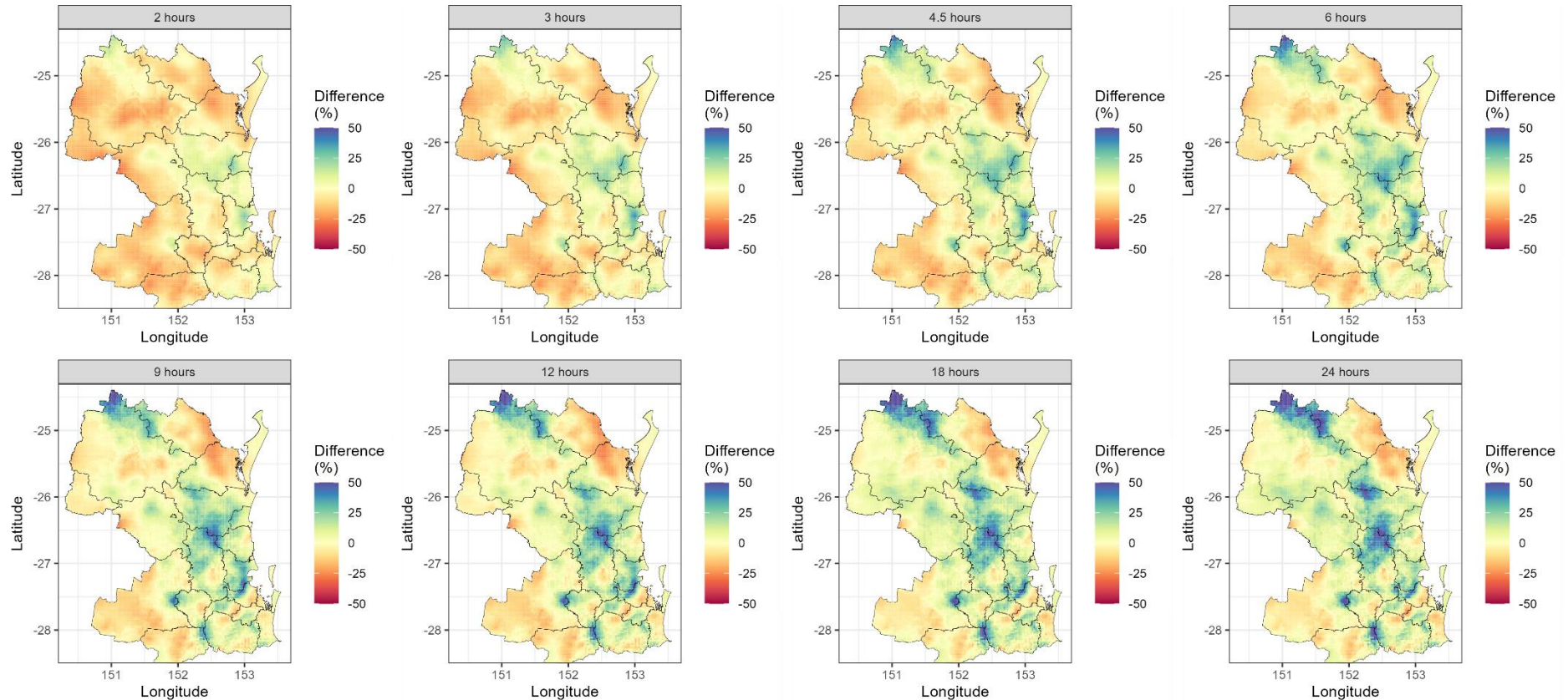


Figure I 23 Percentage difference between 1 in 500 AEP BoM IFDs (ARR, 2016) and IFDs from this study (HARC, 2024) for durations 2 hours – 24 hours

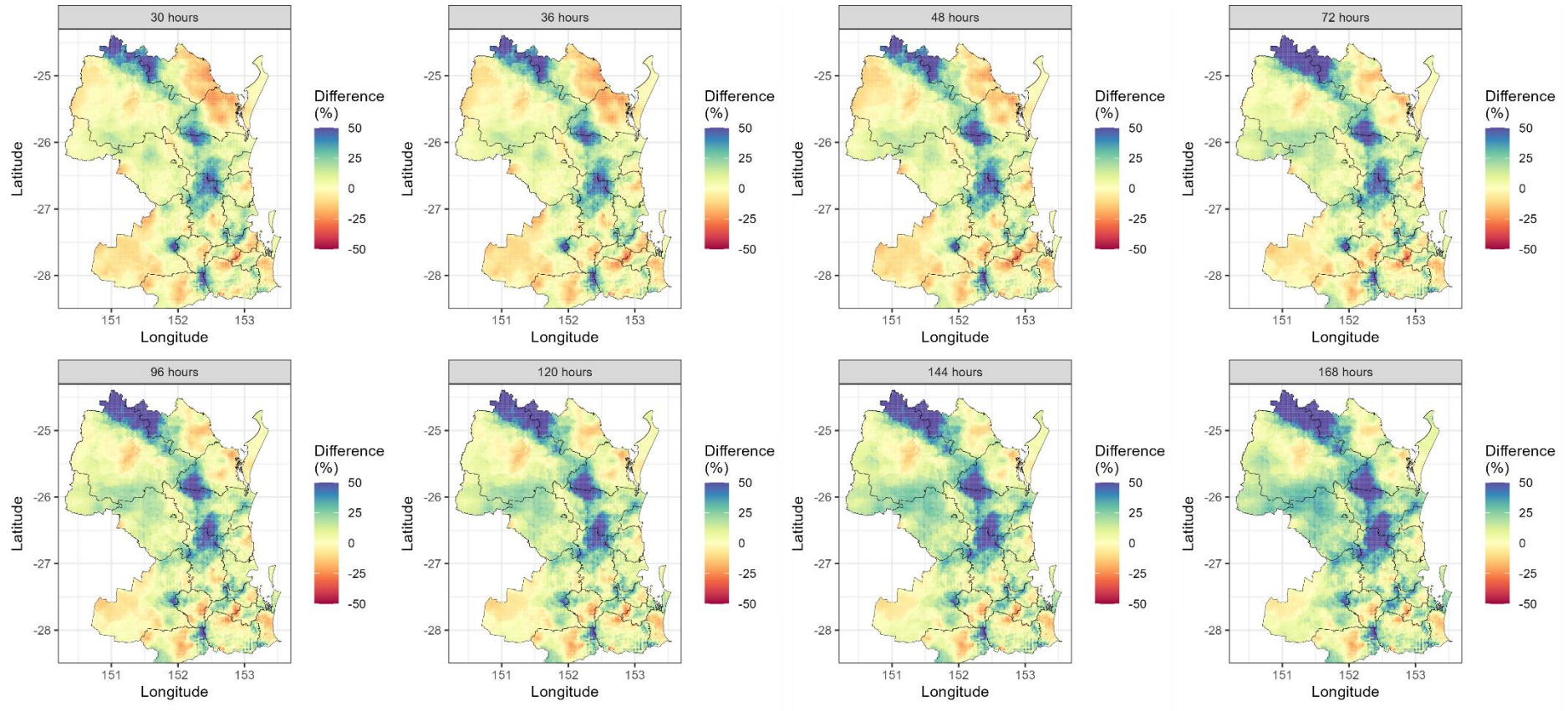


Figure I 24 Percentage difference between 1 in 500 AEP BoM IFDs (ARR, 2016) and IFDs from this study (HARC, 2024) for durations 30 hours – 168 hours

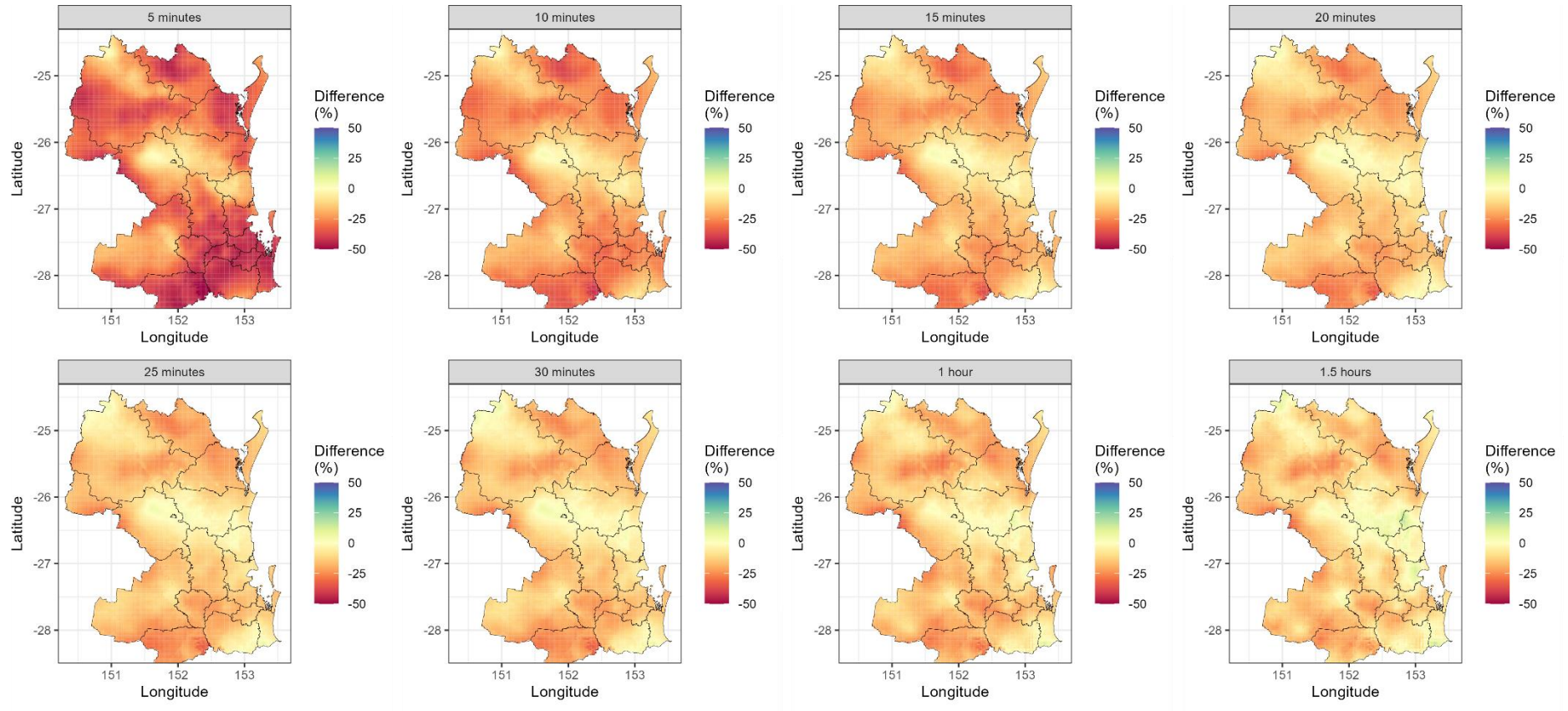


Figure I 25 Percentage difference between 1 in 1,000 AEP BoM IFDs (ARR, 2016) and IFDs from this study (HARC, 2024) for durations 5 minutes – 1.5 hours

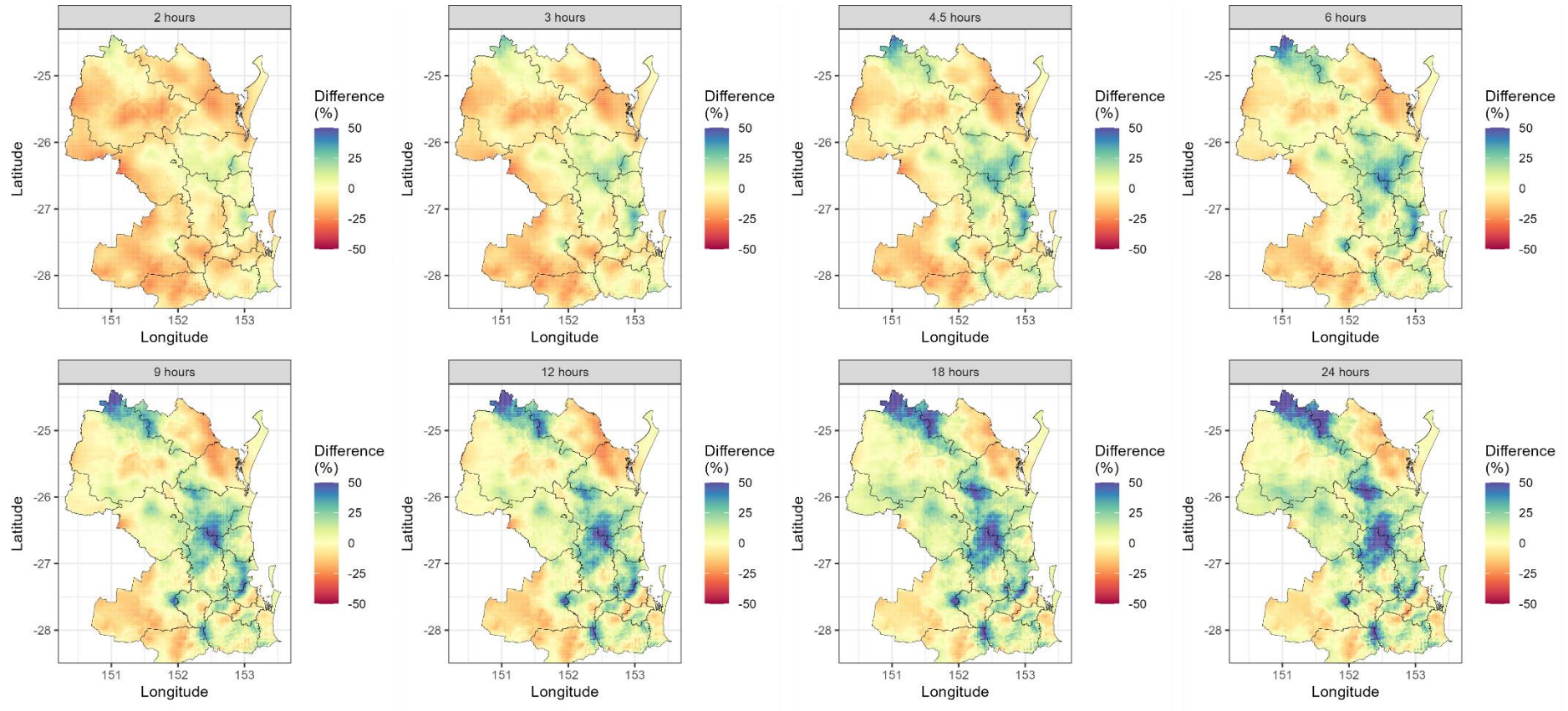


Figure I 26 Percentage difference between 1 in 1,000 AEP BoM IFDs (ARR, 2016) and IFDs from this study (HARC, 2024) for durations 2 hours – 24 hours

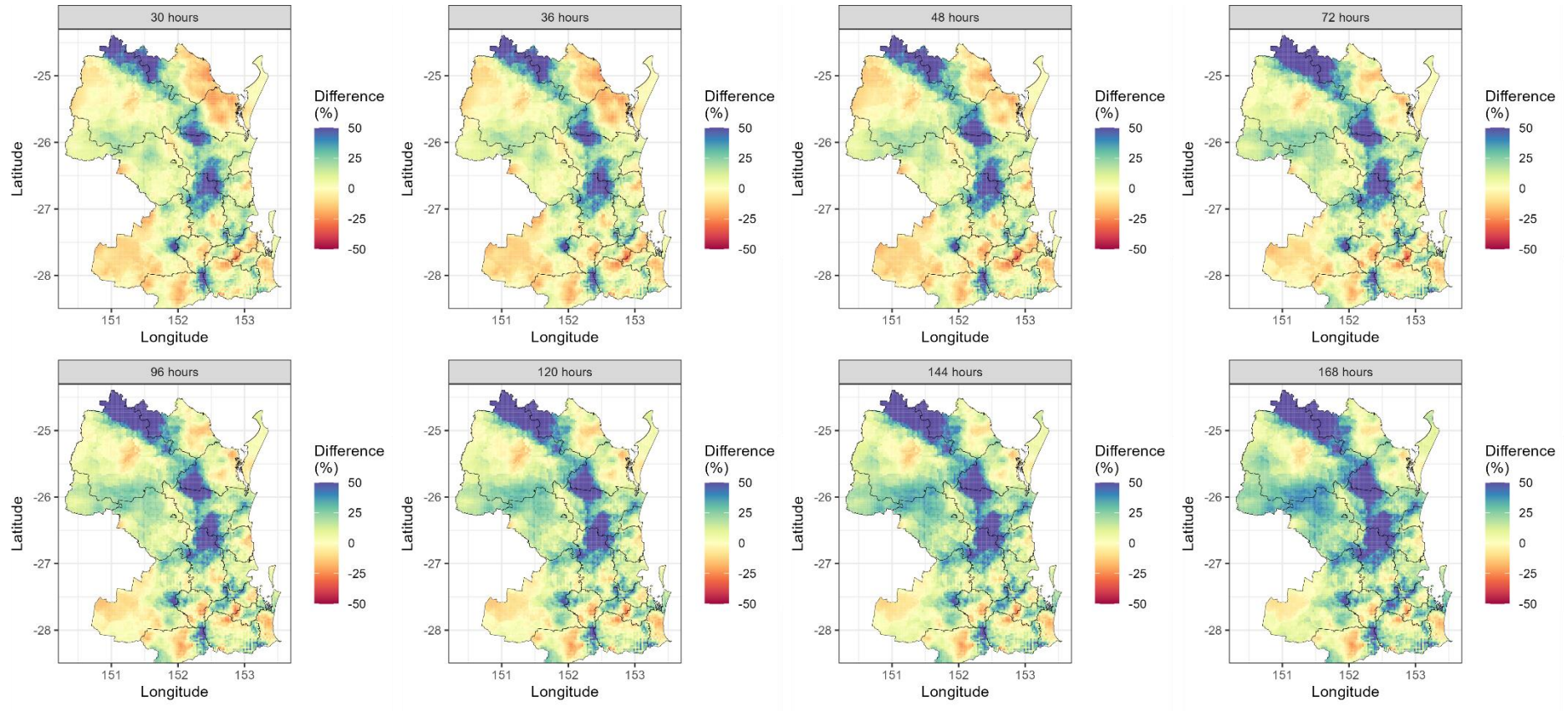


Figure I 27 Percentage difference between 1 in 1,000 AEP BoM IFDs (ARR, 2016) and IFDs from this study (HARC, 2024) for durations 30 hours – 168 hours

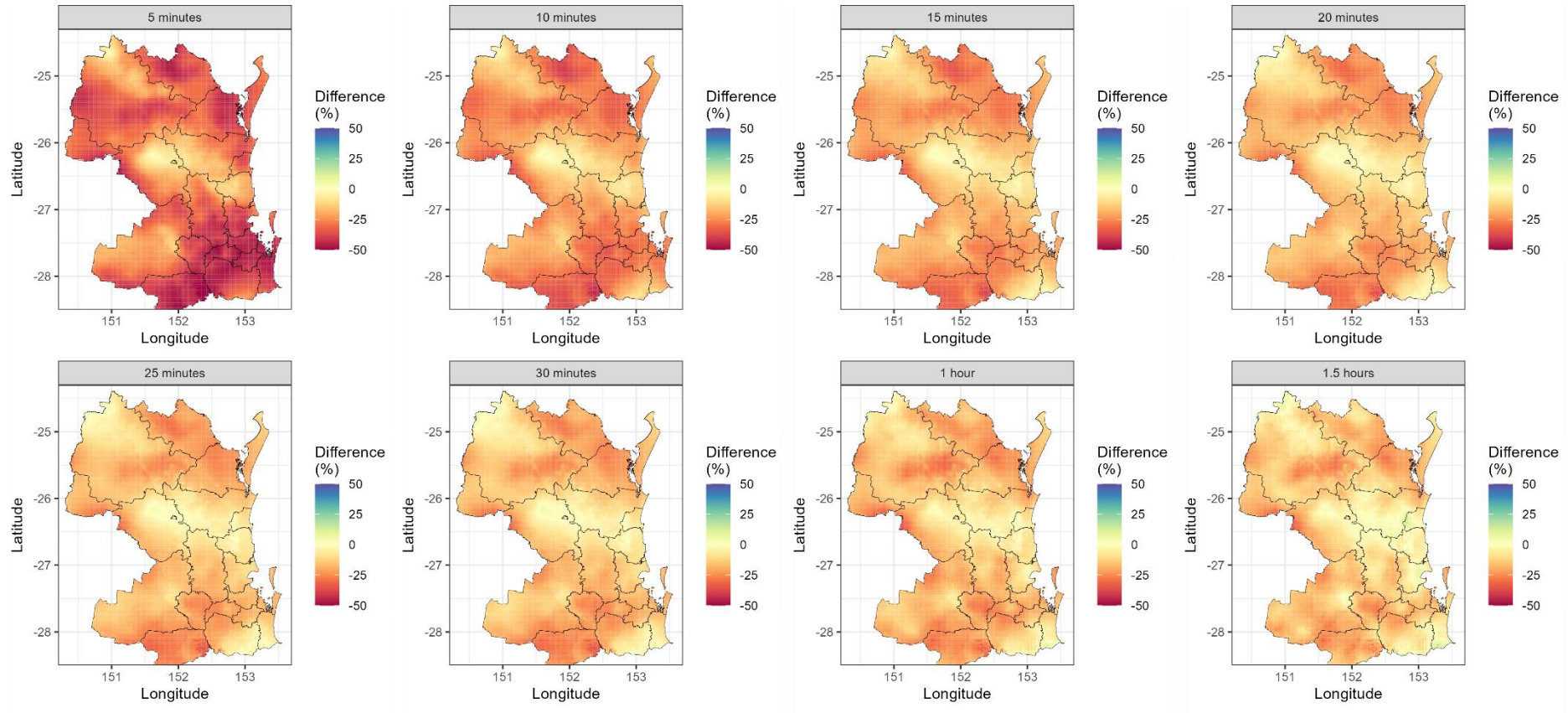


Figure I 28 Percentage difference between 1 in 2,000 AEP BoM IFDs (ARR, 2016) and IFDs from this study (HARC, 2024) for durations 5 minutes – 1.5 hours

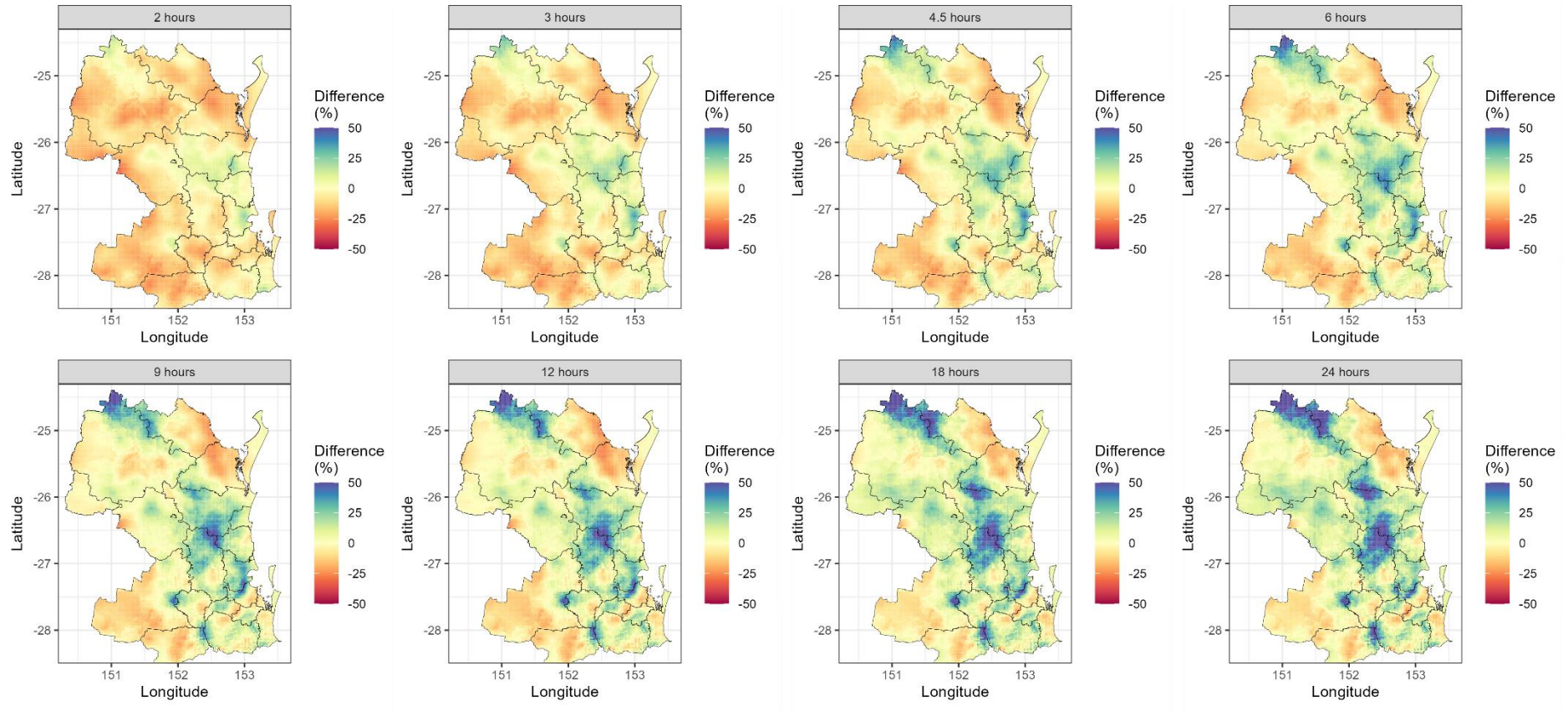


Figure I 29 Percentage difference between 1 in 2,000 AEP BoM IFDs (ARR, 2016) and IFDs from this study (HARC, 2024) for durations 2 hours – 24 hours

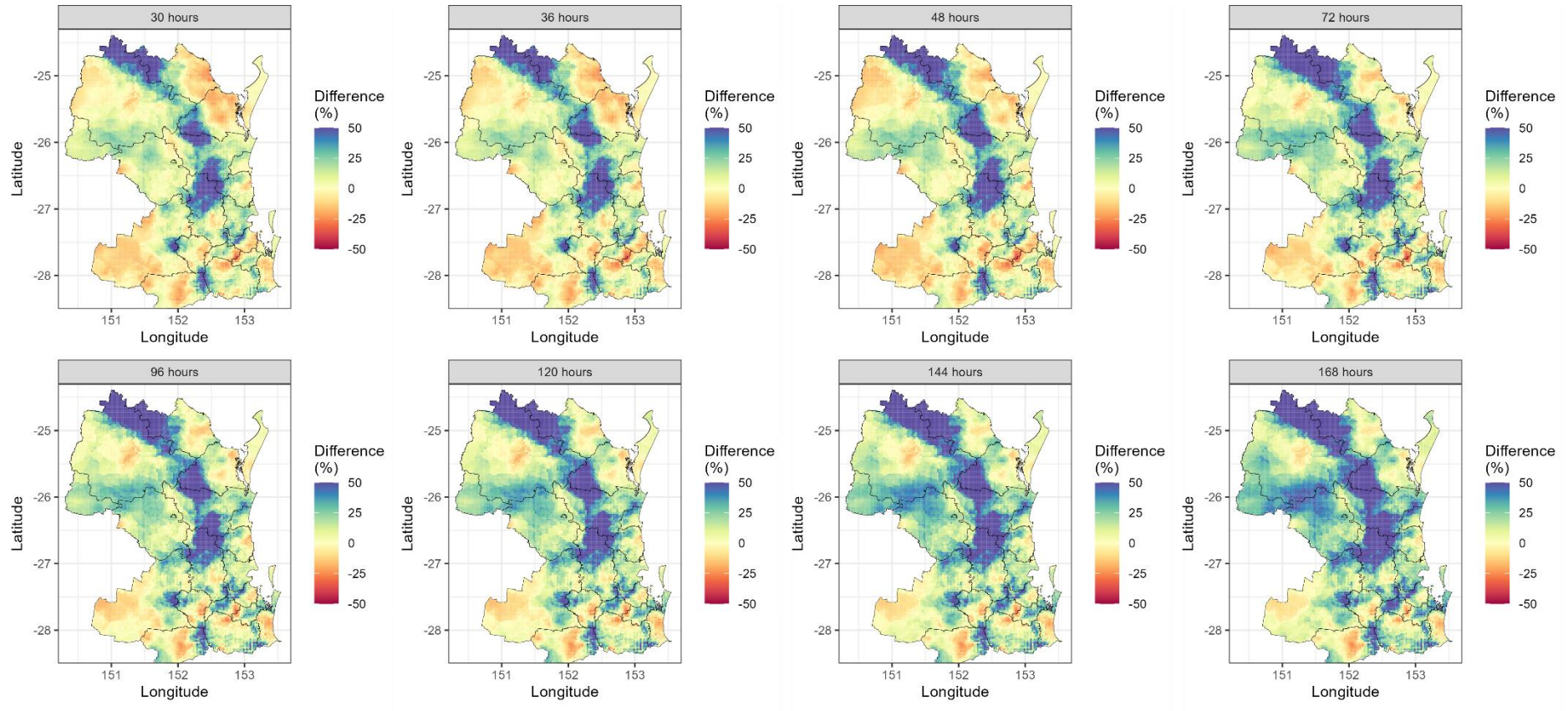


Figure I 30 Percentage difference between 1 in 2,000 AEP BoM IFDs (ARR, 2016) and IFDs from this study (HARC, 2024) for durations 30 hours – 168 hours

Appendix J Summary of the percentage difference between BoM IFDs (ARR, 2016) and IFDs from this study (HARC, 2024) across different AEPs and durations



Figure J 1 Summary of percentage changes across different AEPs and durations (5 minutes – 30 minutes). The median change for the given durations and AEPs is displayed in the respective tiles.



Figure J 2 Summary of percentage changes across different AEPs and durations (1 hour – 6 hours). The median change for the given durations and AEPs is displayed in the respective tiles.

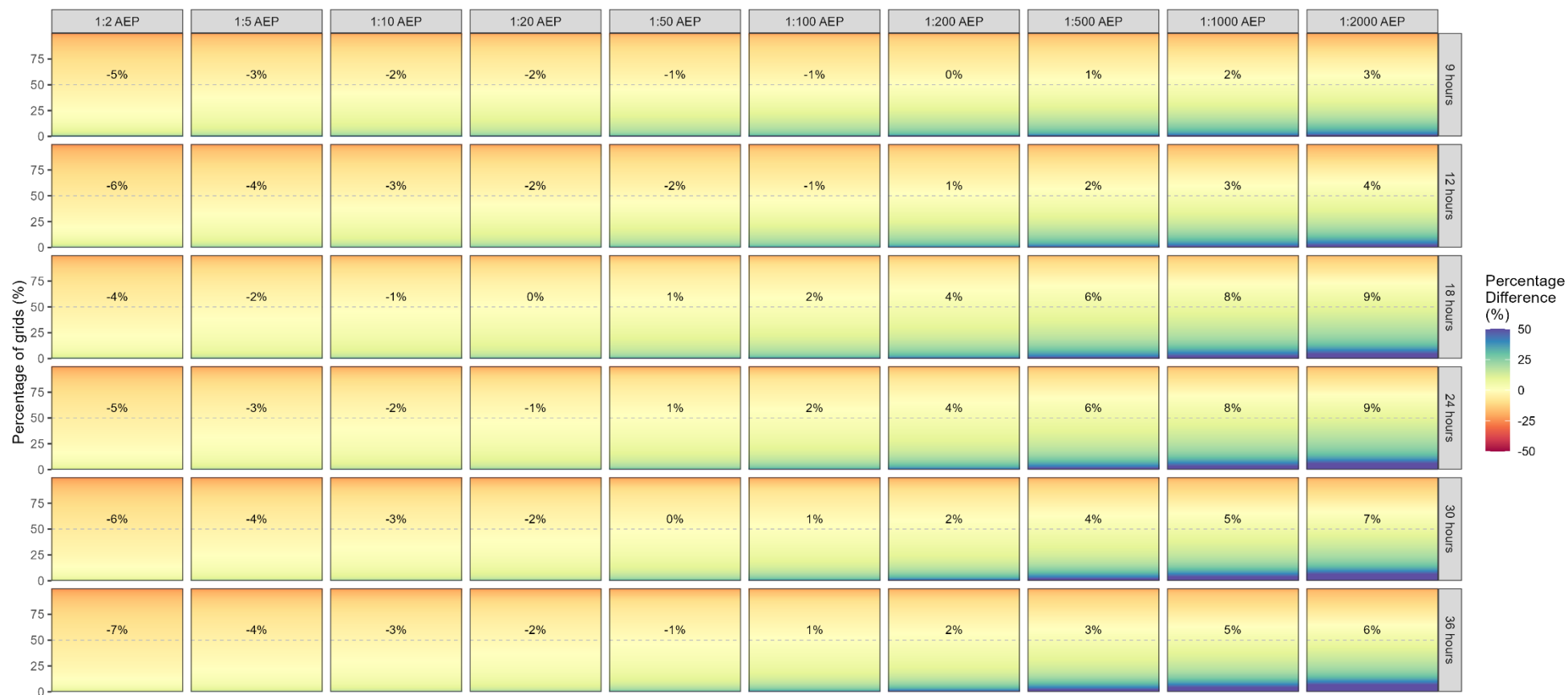


Figure J 3 Summary of percentage changes across different AEPs and durations (9 hours – 36 hours). The median change for the given durations and AEPs is displayed in the respective tiles

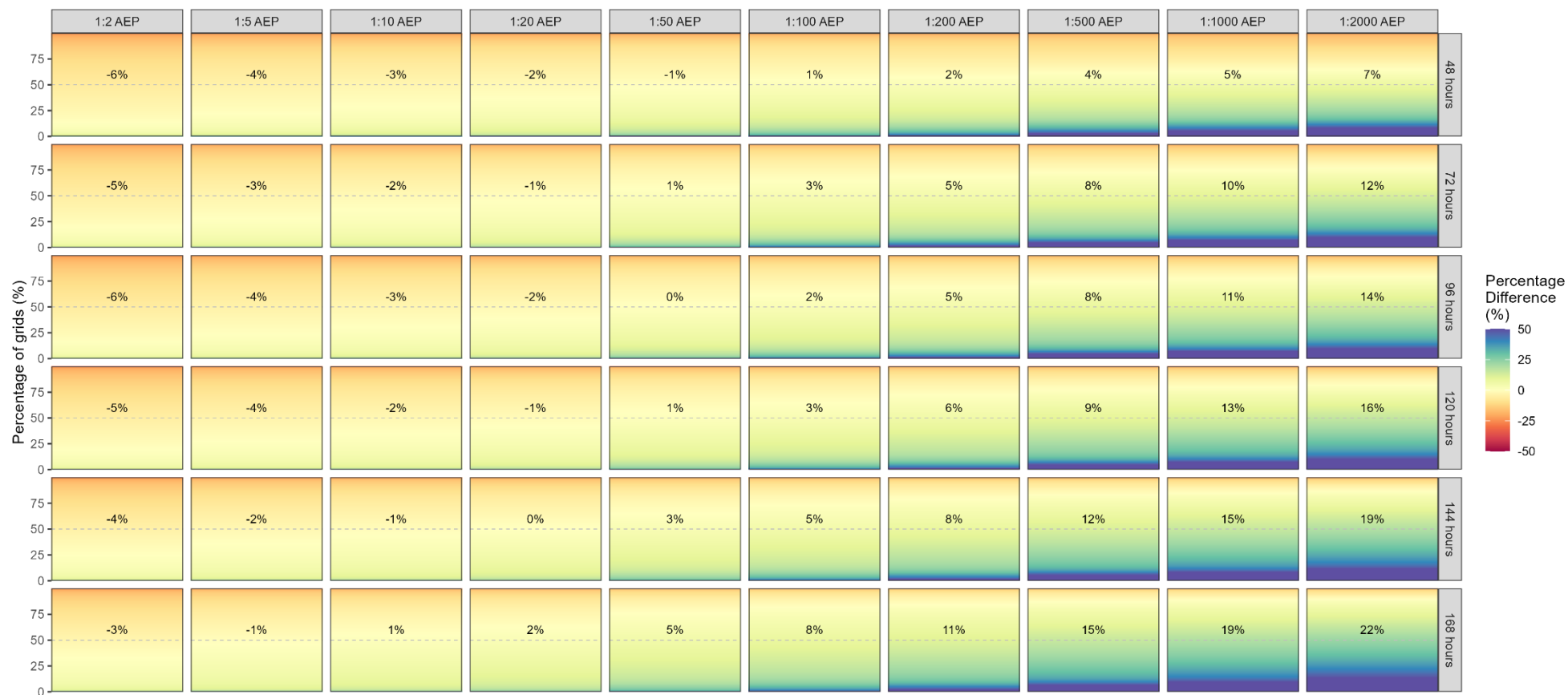


Figure J 4 Summary of percentage changes across different AEPs and durations (48 hours – 168 hours). The median change for the given durations and AEPs is displayed in the respective tiles

Appendix K Description of rainfall data file formats

A.1 Bureau of Meteorology pluviograph gauges

BoM pluviograph gauge format:

- 6 minute resolution
- One day of data per line, commencing at mid-night local time
- 3 header lines
- Fixed width format – no commas:
 - Station ID
 - YYYYMMDD
 - followed by 240 values for the entire day
- Uses station local time zone
- Error codes:
 - -9999.0 for missing data Don't use
 - -8888.0 for accumulated data (with accumulated value at end of period): Uniformly distribute over accumulated period. Further steps in QA process will determine (comparison with nearby sites and other data sets) will determine whether this is acceptable for use

K.1 Bureau of Meteorology one minute AWS gauges

BoM one minute AWS format:

- 1 minute resolution
- 1 minute of data per line
- 1 header line
- Comma delimited:
 - 'hd'
 - Station Number
 - Year,
 - Month,
 - Day,
 - Hour (local time with DST adjustment),
 - Minutes,
 - Year,
 - Month,
 - Day,
 - Hour (local time without DST adjustment),
 - Minutes,
 - Precipitation since last (AWS) observation in mm,
 - Quality of precipitation since last (AWS) observation value,
 - Period over which precipitation since last (AWS) observation is measured in minutes,

- #
- Uses station local time zone
- Quality codes:
 - F for missing data
 - Y for good data

K.2 Bureau of Meteorology daily rainfall gauges

BoM daily rainfall gauge format:

- 1 day resolution
- 1 day of data per line
- 1 header line
- Comma delimited:
 - BoM Product code,
 - Station Number,
 - Year,
 - Month,
 - Day (End of 9 am local time period),
 - Rainfall amount in mm,
 - Period over which rainfall is measured in days,
 - Quality code
- Uses station local time zone
- Quality codes:
 - N for not yet completed quality control process OK (initially)
 - Y for good data OK

K.3 Bureau of Meteorology event data

BoM flood warning event data format:

- Variable resolution – time of bucket tip or update of accumulated value
- 1 period of data per line (variable period)
- 1 header line
- Comma delimited:
 - End of observation period in UTC format: YYYY-MM-DD HH:mm:ss,
 - Rainfall depth for day (mm)
 - Void data flag
- Uses UTC – need to convert to Qld local time +10 hours mostly, +11 hours during rare periods of DST in Queensland
- Daylight saving time conversions are available from here:
http://www.bom.gov.au/climate/averages/tables/dst_times.shtml
- Void data flag:
 - Y for flagged as bad data Don't use

- N for good data OK

K.4 Bureau of Meteorology rolling accumulated data

BoM flood warning rolling accumulated data format:

- Variable resolution – time of bucket tip or update of accumulated value
- 1 period of data per line (variable period)
- 1 header line
- Comma delimited:
 - End of observation period in UTC format: YYYY-MM-DD HH:mm:ss,
 - Accumulated rainfall depth (mm) as a rolling total accumulation for the day. Rolling total seems to reset with first reading after 21:00 UTC, which would be 9 am Qld time (normally)
 - Void data flag
- Uses UTC – need to convert to Qld local time +10 hours mostly, +11 hours during rare periods of DST in Queensland
- Daylight saving time conversions are available from here:
http://www.bom.gov.au/climate/averages/tables/dst_times.shtml
- Void data flag:
 - Y for flagged as bad data Don't use
 - N for good data OK

K.5 Queensland Water Monitoring Information Portal

QWMIP format:

- Variable resolution – time of bucket tip or update of value
- 1 period of data per line (variable period)
- 4 header lines
- Comma delimited:
 - End of observation period format: HH:mm:ss DD/MM/YYYY,
 - Rainfall depth in period (mm) (this will normally be 1 mm, the volume of the tipping bucket)
 - Quality code
- Uses station local time zone
- Quality codes:
 - 1 Good (actual) OK
 - 9 CITEC Normal Reading OK
 - 10 Good OK
 - 20 Fair OK
 - 30 Poor Don't use (initially)
 - 40 Unverified data OK
 - 60 Estimate Don't use (initially)
 - 80 BOM data OK

- 83 Non standard rainfall OK
- 130 Not coded value OK
- 150 Unknown Don't use
- 151 Data not yet available Don't use
- 160 Suspect Don't use
- 200 Water level below threshold Don't use initially (not sure how this is relevant for rainfall)
- 250 Missing data Don't use
- 255 No data exists Don't use

K.6 Scenic Rim Regional Council

Scenic Rim Regional Council format:

- 1 hour time step
- One 1 hour period of data per line
- 38 header lines:
 - Line 27 of the header contains an abbreviated site name (up to four characters)
 - Line 28 of the header contains a four digit site number (ALERT identification number)
 - Line 29 of the header indicates whether the data in that column is rainfall (R), water level (H) or battery voltage (B)
 - Line 30 of the header contains the units of the data (always mm for rainfall data)
- Comma delimited:
 - Start of observation period format: DD/MMM/YYYY HH:mm:ss,
 - End of observation period format: DD/MMM/YYYY HH:mm:ss,
 - Rainfall depth in 1 hour period (mm), for each gauge
- Uses station local time zone
- No quality codes

K.7 South Burnett Regional Council

Data received in standard Bureau of Meteorology formats:

- Daily rainfall data, see Section K.2
- One minute AWS data, see Section K.1

K.8 Sunshine Coast Council

Sunshine Coast Council format:

- 5 minute time step
- One 5 minute period of data per line
- 1 header lines
- Comma delimited:
 - End of observation period format: DD MMM YYYY HH:mm,
 - Rainfall depth in 5 minute period (mm) (appears to normally be a multiple of 1 mm),

- BoM site ID number
- Uses station local time zone
- No quality codes

K.9 Toowoomba Regional Council

Toowoomba Regional Council format:

- 5 minute time step
- 1 period of data per line (variable period)
- No header lines
- Comma delimited:
 - Rainfall depth in period (mm) (appears to normally be a multiple of 0.5 mm)
 - End of observation period format: YYYY-MM-DD HH:mm:ss.sss,
 - TRC site ID number,
 - TRC site name,
 - R (for rainfall)
- Uses station local time zone
- No quality codes

K.10 Gympie Regional Council

Gympie Regional Council format:

- 1 day time step
- Spreadsheets – one spreadsheet per calendar year
- Header row has site names
- No site numbering
- Daily value recorded, for the day **starting** on the date provided
- Day start time is variable.
 - Gympie Sewage, Gympie Water and Cooloola Cove Water: day starts at 6 am (on the date recorded) and ends at 6 am the next day.
 - As all other plants are visited daily the time periods could vary due to when operator arrives to site – assume day starts between 6 am and 9 am on the day recorded and ends at a similar time the next day.

K.11 SILO patched point data daily rainfall

SILO patched point data daily rainfall gauge format:

- 1 day resolution
- 1 day of data per line
- 1 header line
- Comma delimited text file:
 - Station Number,
 - YYYY-MM-DD (End of 9 am local time period),

- Rainfall amount in mm,
 - Quality code
- Uses station local time zone
- Quality codes:

▫ 0	Station data, as supplied by the Bureau	OK
▫ 13	Deaccumulated using nearby station	OK (initially)
▫ 15	Deaccumulated using interpolated data	OK (initially)
▫ 23	Nearby station, data from Bureau	Don't use
▫ 25	Interpolated daily observations	Don't use
▫ 75	Interpolated long-term average	Don't use

K.12 Seqwater raw and processed point data

Seqwater supplied rainfall gauge data in series of compressed data files, stored in Network Common Data Form (NetCDF). The data files contained 15 minute time resolution data, with about 1 year of rainfall data stored in each file. Each file contained either raw or processed rainfall data – with the raw rainfall data containing all gauge records and the processed rainfall data having removed recordings that were identified by Seqwater as likely being low quality or suspect data. Each record contained:

- Time of observation, in minutes since 1 January 1970, relative to UTC
- Rainfall observation, in mm
- For some rainfall records had been flagged as suspect, a comment was provided

Appendix L Sub-daily gauges used for unrestricted to restricted duration factor calculations

Site	Number of water year maxima	Site Name	Start water year	End water year
BO140010	6	Tin Can Bay (Defence)	2018	2022
BO39066	14	Gayndah Airport	2010	2022
BO140010	6	Tin Can Bay (Defence)	2018	2022
BO39066	14	Gayndah Airport	2010	2022
BO39128	14	Bundaberg Aerodrome	2010	2022
BO40004	23	Amberley Airport Meteorological Office	2001	2022
BO40068	19	Double Island Point Lighthouse	2005	2022
BO40082	14	University of Queensland Gatton	2010	2022
BO40126	13	Maryborough	2011	2022
BO40284	5	Beerburrum Forest Station	2019	2022
BO40405	13	Hervey Bay Airport	2011	2022
BO40555	11	Toolara (Kelly)	2005	2015
BO40861	15	Sunshine Coast Airport	2009	2022
BO40908	12	Tewantin RSL Park	2012	2022
BO40922	13	Kingaroy Airport	2011	2022
BO40988	14	Nambour Department of Agriculture Forestry and Fisheries-Hillside	2010	2022
BO41359	20	Oakey Aerodrome	2004	2022
BO41522	12	Dalby Airport	2012	2022
BO41529	15	Toowoomba Airport	2009	2022
BP39034	7	Delubra	1963	1969
BP39066	17	Gayndah Airport	2003	2018
BP39128	54	Bundaberg Aerodrome	1964	2017
BP39171	29	Narayan Research Station	1970	1997
BP39297	32	Builyan Gum St	1984	2015
BP39330	13	Monto Airport	1993	2005
BP39340	5	Mingo Creek ALERT	1997	2000
BP39341	6	Byrnestown ALERT	1997	2002
BP39342	5	Mt Yeatman TM	1997	2000
BP40004	56	Amberley Airport Meteorological Office	1962	2017
BP40013	2	Bauple	1972	1972
BP40063	30	Dayboro Post Office	1969	1998
BP40068	15	Double Island Point Lighthouse	2003	2017
BP40076	18	Esk Dale West	1972	1989
BP40082	62	University of Queensland Gatton	1956	2017
BP40093	54	Gympie	1963	2016
BP40101	20	Ipswich	1975	1994
BP40102	29	Jimna Composite	1972	2000

Site	Number of water year maxima	Site Name	Start water year	End water year
BP40111	45	Kilkivan Post Office	1972	2016
BP40112	39	Kingaroy Prince St	1963	2001
BP40121	15	Maleny Tamarind St	2002	2016
BP40126	53	Maryborough	1964	2016
BP40152	37	Murgon Post Office	1972	2008
BP40241	38	Samford CSIRO	1967	2004
BP40282	56	Nambour DPI	1954	2009
BP40308	48	Mt Glorious Fahey Rd	1968	2015
BP40311	3	Nukinenda	1990	1992
BP40318	31	Kirkleagh	1960	1990
BP40334	3	Biggenden ALERT	1998	2000
BP40382	17	Crows Nest	1965	1981
BP40428	23	Brian Pastures	1995	2016
BP40457	9	Wacol DPI	1972	1979
BP40464	7	Teewah Creek Site Number 1	1972	1978
BP40467	7	Teewah Creek Site Number 4	1972	1978
BP40469	46	Marodian Homestead	1972	2017
BP40496	39	Caloundra WTP	1973	2011
BP40528	3	BCC 3 Catchments	1970	1972
BP40553	10	Beerwah CSIRO Research Station	1974	1983
BP40624	7	Gigoom Post Office	1973	1979
BP40651	15	Jimna Forestry	2001	2015
BP40759	5	Corbould Park Racecourse	2012	2016
BP40769	12	Blackbutt Forestry Station	1988	1999
BP40856	26	Rainbow Beach	1992	2017
BP40908	15	Tewantin RSL Park	2003	2017
BP40915	8	Sugarloaf Mountain	2008	2015
BP40922	19	Kingaroy Airport	2001	2019
BP40960	12	Clear Mountain Buranda Rd	2004	2015
BP40988	10	Nambour Department of Agriculture Forestry and Fisheries-Hillside	2008	2017
BP40991	8	Esk White Rock	2008	2015
BP41018	45	Clifton Post Office	1972	2016
BP41060	39	Leyburn	1959	1997
BP41082	8	Pittsworth	1959	1966
BP41090	4	Darr Creek ALERT	1998	2000
BP41092	3	Ballon ALERT	1999	2000
BP41140	34	Dalby Regional Council	1959	1992
BP41359	45	Oakey Aerodrome	1973	2017
BP41361	16	Pittsworth DPI	1970	1985
BP41467	28	Toowoomba City Council	1957	1984

Site	Number of water year maxima	Site Name	Start water year	End water year
BP41480	3	Dalby CSIRO Field Station	1983	1984
BP41497	29	Australian Agricultural College Dalby Campus	1985	2013
BP41522	26	Dalby Airport	1992	2017
BP41529	17	Toowoomba Airport	2003	2018
BP42054	19	Cadarga DPI	1971	1989
BP42059	40	Auburn	1972	2011
QG1303P003	32	Kroombit Tops Standalone Pluvio	1992	2023
QG1303P006	60	Blue Hills Standalone Pluvio	1964	2023
QG134001B	34	Baffle Creek at Mimdale	1990	2022
QG135002A	32	Kolan River at Springfield	1992	2023
QG1350P002	31	Bania Standalone Pluvio	1993	2022
QG136001B	29	Burnett River at Walla	1995	2023
QG136006A	32	Reid Creek at Mungy	1992	2023
QG136007A	27	Burnett River at Figtree Creek	1997	2023
QG136011A	34	Degilbo Creek at Coringa	1990	2023
QG136106A	29	Burnett River at Eidsvold	1995	2023
QG136108A	33	Monal Creek at Upper Monal	1991	2023
QG136111A	26	Splinter Creek at Dakiel	1998	2023
QG136112A	34	Burnett River at Yarrol	1990	2023
QG136118A	30	Eastern Creek at Lands End	1994	2023
QG1361P002	32	Boolaroo Tops Standalone Pluvio	1992	2023
QG136203A	33	Barker Creek at Brooklands	1991	2023
QG136207A	32	Barambah Creek at Ban Ban	1992	2023
QG136213A	28	Barambah Creek at West Barambah	1996	2023
QG1362P001	41	Mortimer Standalone Pluvio	1983	2023
QG136304A	29	Stuart River at Proston Rifle Range	1995	2023
QG136305A	32	Auburn River at Dykehead	1992	2023
QG136306A	33	Cadarga Creek at Brovinia Station	1991	2023
QG136319A	29	Boyne River at Cooranga	1995	2023
QG138002C	28	Wide Bay Creek at Brooyar	1996	2023
QG138004B	31	Munna Creek at Marodian	1993	2022
QG138010A	31	Wide Bay Creek at Kilkivan	1993	2023
QG138014A	31	Mary River at Home Park	1993	2022
QG138107B	31	Six Mile Creek at Cooran	1993	2022
QG138110A	32	Mary River at Bellbird Creek	1992	2022
QG138111A	31	Mary River at Moy Pocket	1993	2022
QG140002A	30	Teewah Creek at Coops Corner	1994	2022
QG141009A	33	North Maroochy River at Eumundi	1991	2023
QG142001A	33	Caboolture River at Upper Caboolture	1991	2022
QG143007A	29	Brisbane River at Linville	1995	2023
QG143010B	31	Emu Creek at Boat Mountain	1993	2022

Site	Number of water year maxima	Site Name	Start water year	End water year
QG143108A	30	Warrill Creek at Amberley	1994	2023
QG143110A	31	Bremer River at Adams Bridge	1993	2022
QG143203C	29	Lockyer Creek at Helidon Number 3	1995	2022
QG143921A	29	Cressbrook Creek at Rosentreter's Crossing	1995	2022
QG422310C	30	Condamine River at Warwick	1994	2023
SC540094	30	Picnic Point ALERT	1994	2022
SC540136	30	Eerwah Vale ALERT	1994	2022
SC540137	29	Nambour ALERT	1995	2022
SC540190	29	Ferris Knob ALERT	1995	2022
SC540191	29	West Bellthorpe ALERT	1995	2022
SC540218	27	Doonan Creek ALERT	1997	2022
SC540219	27	Palmwoods ALERT	1997	2022
SC540221	27	Coolum ALERT	1997	2023
SC540222	27	Eudlo ALERT	1997	2022
SC540223	27	Yandina Creek ALERT	1997	2023
SC540224	27	Upper Doonan ALERT	1997	2022

Appendix M Independent peer reviewers' statement

Peer Review Statement for the HARC report “Review and update of design rainfall-intensity-frequency-duration for eleven local government areas in South East Queensland” Version 3 dated 23rd October 2024

By Don Carroll, RPEQ 3634, 31st October 2024

Introduction

This peer review report accompanies the subject report and is a summary of an on-going peer review for the entire project duration. It is assumed that the reader has read the report, details of which are not replicated in this review, unless review comment is warranted. This statement includes comment on the methodology adopted by HARC, an overall assessment of the project work, implications for flood studies and urban infrastructure design and concludes with a discussion on the comparative analysis undertaken by the reviewer followed by recommendations regarding application of the new IFD tables for South-East Queensland.

Methodology

HARC have adopted the GEV distribution in their fitting of QA'd burst data across south-east Queensland. This was done by estimating L1 moments (data means) for a range of durations and spatially interpolating each duration's L1 value across the entire area. The L1 moments generated for daily rainfall stations were adjusted for present day climate change according to the recently issued ARR 2024 guidelines. L1 values derived from more recent shorter series (predominantly sub-daily stations) were not adjusted. Mean Annual Rainfall was used as a covariate in the interpolation process. L-CV (variation surrogate) and L-Skew (skew surrogate) moments were fixed across the region for durations less than 2 hours, and pooled L-CV (L2/L1) and L-Skew (L3/L1) moments were estimated using 500 data years from surrounding gauges (weighted by surrounding station data years) for burst durations ≥ 48 hours. L-CV and L-Skew values for burst durations greater than 2 hours and less than 48 hours were log-linearly interpolated which enabled L1, L2 and L3 values to be calculated for every grid cell throughout the region. For the shorter durations, the L-skew value was constrained so that the distribution skew was always greater than zero. Compensating adjustments to L-CV values were made where the L-Skew value was constrained. The reviewer agrees with methodological approach adopted by HARC noting however that differing spatial interpolation methodologies are likely to result in different estimates determined in other studies particularly for high elevation areas.

Overall Methodological Assessment

The HARC (2024) IFD data set represents the most up to date IFD analysis for S-E Queensland. This reviewer can find no fault with the QA process, the adopted methodology and the numerical analysis used to parameterize IFD estimation throughout the region. This conclusion was reached through on-going review of the work undertaken by HARC throughout the project life, spot checking station analysis and reviewing generated data sets. Nonetheless there is inherent uncertainty in IFD estimation, ranging from field instrumentation, station density, spatial interpolation techniques, statistical distribution selection, parameter interpolation assumptions, unrestricted/restricted factor estimation, grid sizing, implicit climate change effects etc. Nathan (2021) found as part of the IFD update to the City Of Gold Coast, that quantile intensity estimates could range between $\pm 20\%$ assuming 90% confidence limits.

The differences between HARC, BoM 2016 and LIMB methodologies are presented in Table 13-1 in the HARC report. The most significant are (i) the inclusion of climate changes effects (v. BoM 2018, LIMB), use of Kriging in the grid interpolation process (v. BoM 2016), (iii) regionalization of L-CV values, and (iv) smoothing of IFD tables. In terms of L-CV regionalization, HARC used a hybrid approach; averaged to 2 hours, pooled using 500 data years from neighboring sites for durations ≥ 48 hours and interpolated in between, whereas the LIMB pooled 100 data years for all durations separately. In regards to IFD smoothing, HARC adopted the a-priori assumption that L1, L-CV and L-skew should increase with duration (the reviewer finds this is a sound assumption), whereas LIMB used predominantly fitted polynomials as did BoM 2016.

It is difficult to assess how these methodological differences affect IFD estimates across comparative regions as they can be masked by use of differing data sets. Suffice to say, that both data and methodological differences contribute to divergent IFD estimates, and importantly they are not systematic across comparative regions.

Flood Studies

Practitioners in the past have found it necessary to use scalers to adjust grid based IFD estimates in order to achieve Flood Frequency calibration for regional flood studies; the Coomera, Gold Coast, the Bremer River, Ipswich, the Bohle River, Townsville, Pine rivers immediately come to this reviewer's mind and there are likely many more reported by others. Adjustment factors were typically in the order of 20% to 30% and were generally required in upland and high elevation catchment areas. This was primarily the case when using the BoM 2016 IFD grids, which were largely based on daily data and compared to latter day regional studies used relatively sparse sub-daily rainfall datasets. At the time of issue the BoM 2016 data sets represented best practice, notwithstanding the aforementioned calibration issues. The latest HARC South-East Queensland data sets generally show a marked increase in design rainfall depths for the mid to long durations compared to BoM 2016. This is largely due to the additional data since 2012 (the end date for the BoM 2016 data set) and inclusion of additional ALERT data sets which are locationally skewed to higher elevations compared to non-Alert rainfall stations.

Urban Drainage Infrastructure

Flood studies aside, the case for urban drainage infrastructure also comes in to play which involves considerable investment by LGA's and state government agencies. Its design relies on statistical rainfall intensity and depth estimates for the shorter durations.

The rational method is the most common tool used in urban drainage design. Typically AEP: of 1:2 street drainage, 1:10 trunk drainage, 1:100 major drainage including overland flow paths are considered. Calculations are typically done from prescribed tables provided by LGA's. The key parameter is the rainfall burst intensity for a specified design AEP and Time of Concentration. Total rainfall depth comes into play for retention basin design. Previous statistical estimates of short duration bursts were based on scaling methodologies due to the paucity of sub-daily data sets. The latest work undertaken by HARC (2024) and those undertaken by WMA Water addresses this issue through inclusion of ALERT data, and although not WMO compliant in terms of instrumentation, provides an order of magnitude increase in sub-daily data in urban areas.

The HARC dataset for short durations is generally lower than the BOM2016 for the same AEP and duration. For durations less than 30 minutes (approx.) the HARC IFD curves tend to a constant intensity suggesting that for a given AEP there is a maximum intensity limit irrespective of the duration, i.e. design rainfall depths decreases linearly with duration. This is more evident for coastal regions due to higher rainfall intensities than those further west.

The BoM2016 dataset methodology for the shorter durations was based on simple power scaling pivoted on the calculated 1 hour intensity for a given AEP. This methodology was used because of the relative paucity of sub-daily data available to the BoM when undertaking their analysis. Using this methodology infers that as the burst duration tends to zero the burst intensity tends to infinity. Accordingly, this approach is considered to be conservative for the very short durations (< 30 minutes). However, there is a case for LGA's to use the Max(HARC,BoM2016^u) data set for urban drainage design in order to retain current serviceability.

Comparative Analysis Discussion

Several comparative analyses were undertaken as part of this review. These were:

1. Comparison of HARC and BOM2016 IFD's for key urban areas within participating Councils
2. Comparison of LIMB and HARC IFD's for LIMB selected locations and key urban areas
3. Comparison of HARC and Max(HARC, BoM2016^u) for S-E Queensland
4. Comparison of HARC and DCPM for DCPM 3, selected locations;

These data sets can be provided on request from the Queensland Reconstruction Authority.

This comparative analysis resulted in the following interpretations:

Focusing on the 1% AEP curve, for key urban areas where elevations are generally low, the HARC curves look reasonable. In the majority of cases the HARC curves for the short durations (<1 hour) are lower than BoM 2016 curves primarily due to power scaling methodology as previously mentioned. The HARC curves for the long durations (> 24 hours) were generally greater than the BoM2016 curves.

For some high elevation areas (e.g. within LIMB area and 2 DCPM locations) the HARC curves were 20 to 30% lower for the mid-range durations (1 hour to 24 hours). A comparison with Max(HARC, BoM2016^u) curves did improve agreement but not to a sufficient extent. It is moot, as whether there are sufficient sampling points to draw a conclusion that the HARC curves are systemically lower in the higher elevation areas, Toowoomba is a case in point where HARC curves are significantly higher for the mid to long durations.

It is more likely than not that for higher elevation locations there will be a tendency to under-estimate IFD curves when they are smoothed in the gridding process, e.g. pooling to 500 data years. This under estimation has been for some catchments significant and required scalers to adjust the IFD's to enable matching with local flood frequency analysis assuming all other factors have been considered. Adopting the envelope curves will somewhat address this issue but not sufficiently for every high elevation catchment. Further it can be argued that blending the 2024 HARC IFD data set with a 2016 BoM IFD data set that had limited sub-daily data is questionable in itself; differing methodologies, datasets etc. and secondly if it should be used as a mechanism to address the potential issue of under-estimated IFD's for high elevation areas. One of the most common ways of addressing this issue is to analyze individual stations and derive a set of duration based scalers to adjust the affected grid based IFD tables. It is worth noting that two high elevation DCPM locations; Fairlies Knob and Nambour DPI were markedly higher than the HARC grid based IFD's. These curves were derived from local data analysis using different methodologies (PoT extraction, GPA and constrained/smoothed intensity duration curve fitting based on Koutsoyiannis et al (1998)). Further the LIMB curves also exhibited the same behavior for some high elevation locations, refer comparative plots for the Lockyer, Ipswich and Moreton Bay regional council areas available from the Queensland Reconstruction authority. It is noted that the LIMB dataset used 100 data years pooling data that included elevation factors, which may have contributed to the higher LIMB estimates.

In summary, the HARC IFD data set is a significant improvement on the BoM 2016 dataset due to increase in sub-daily data, incorporation of climate change uplift for the longer durations and the application of systematic methodology based on the GEV distribution for all durations. As such their use should decrease bias in previous statistical flood peak estimates, nevertheless there will be instances for high elevation catchments where further adjustment of the IFD's may be required. However, the occurrences of applying these adjustments are likely to be significantly reduced when using the HARC IFD dataset compared to the BoM 2016 dataset.

Recommendations:

1. That for the LIMB LGA areas that the maximum of HARC generated IFD tables and LIMB IFD tables be adopted. The LIMB IFD tables will need to be uplifted for climate change according to the ARR 2024 guidelines for the longer durations (≥ 24 hours)
2. For all other areas the HARC tables are sufficient. However for urban areas LGA's may wish to use the $\text{Max}(\text{HARC}, \text{BoM2016}^u)$ IFD tables for urban drainage design. Apart from retaining serviceability, this has the added advantage in providing reasonable agreement between the LIMB urban areas and the non-LIMB urban areas, as LIMB short durations intensities are similar to BoM 2016 estimates.
3. In regional studies where it is found, when all else considered, difficulty in achieving calibration with local flood frequency analysis, then $\text{Max}(\text{HARC}, \text{BoM2016}^u)$ IFD tables should also be trialed, in addition to revisiting local rainfall data statistical analyses.
4. That the ARR datahub host the additional IFD datasets; HARC, $\text{Max}(\text{HARC}, \text{BoM2016}^u)$ and the $\text{Max}(\text{HARC}, \text{LIMB}^u)$ but in such a way that the default IFD output is as per recommendations made above, however still allowing the user to select an alternative dataset as the user sees fit.