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Characterisation of the 2022 floods in the Northern Rivers region

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Contents

Acknowledgments vii
Executive summary viii
1 Introduction 1
1.1 Context and aim of this report 1
1.2 Methods adopted throughout this report 2
1.3 Limitations of the report 5
2 The Northern Rivers region 7
2.1 Demographics 7
2.2 Current industries and land use 8
2.3 Key water related infrastructures 9
3 Hydro-meteorological environment of the Northern Rivers region 12
3.1 Topography 12
3.2 Climate of the Northern Rivers region 12
3.3 Surface water in the Northern Rivers region 19
3.4 Groundwater in the Northern Rivers region 24
3.5 Estuaries and coastal data 24
4 Flooding in the Northern Rivers region 26
4.1 Overview of major historical flood events 26
4.2 Flood modelling studies 28
5 Analysis of the February/March 2022 flood event 30
5.1 Antecedent conditions 30
5.2 Climate conditions during the event 37
5.3 Frequency analysis of 2022 rainfall 42
5.4 Summary of climate conditions 46
5.5 River levels and flows during the 2022 flood 46
5.6 Frequency analysis of 2022 peak flows 57
5.7 Summary of surface water conditions 63
6 Conclusion and recommendations 65
6.1 Key characteristics of the February/March 2022 event 65
6.2 Recommendations 65

Appendix A List of rainfall, water level and streamflow gauging stations retained for data analysis 67
Appendix B List of rainfall and streamflow gauging stations excluded from data analysis..........85
Appendix C Interpolation of hourly point rainfall data..........89
Appendix D Processing of radar images..........92
Appendix E AWRA-L model performance against observed streamflow data..........95
Appendix F Major and minor flood events in the Northern Rivers region..........99
Appendix G Published studies related to flooding in the Northern Rivers region..........101
Appendix H Method used in flood frequency analysis for the 2022 event..........119
H.1 Clarification on flood frequency analysis method..........119
H.2 Mathematical assumptions underlying the fitting of AMS probability distribution 124
H.3 Prior distribution..........125
H.4 Likelihood function..........126
H.5 Inference and estimation of AEP for the 2022 flood..........129
H.6 Validation of the copula model..........130
H.7 Overview of fitting configurations..........130
H.8 Fitting results..........131
References..........138

Figures

Figure 1 Overview of the Northern Rivers region 2

Figure 2 Richmond River profile 12

Figure 3 Quality check of rainfall records for the Cudgera Lake hourly rain gauge (station ID H558046) 14

Figure 4 Active climate (daily) and flood (sub-daily) rain gauges across the Northern Rivers region 15

Figure 5 Mean annual rainfall and potential evapotranspiration for the 1991-2020 period. Maximum value in each map is shown as a pink dot. 17

Figure 6 Monthly statistics for rainfall and potential evapotranspiration across the Northern Rivers region..18

Figure 7 Intensity-Frequency-Duration rainfall data for 1, 2 and 3 days duration, 1% and 0.1% AEP. Maximum value in each plot is shown as a pink dot 18

Figure 8 Streamflow data and rating curves for the Wilsons River at Eltham station (203014) ..20

Figure 9 Active streamflow gauging stations in the Northern Rivers region..............................22

Figure 10 Mean monthly runoff and root zone soil moisture level for the four basins of the region 23

Figure 11 Extent of two-dimensional hydrodynamic models 29

Figure 12 Comparison between initial soil moisture level and runoff coefficient for historical flood events in the region 31

Figure 13 Rainfall totals prior to the 2022 floods across the Northern Rivers region 33

Figure 14 Filling level of the AWRA-L root zone soil moisture layer across the Northern Rivers region 35

Figure 15 Groundwater levels prior to the 2022 flood events. The plots show the water level below the measuring points for four telemetered bores in the Richmond catchment. 36

Figure 16 Mean Sea Level pressure charts for the 27, 28 February and 1 March 2022 at 6 AM and 6 PM generated by the Bureau of Meteorology..38

Figure 17 Rainfall total and daily maximum during the 2022 flood along with dates of maximum daily rainfall in the AGCD archive 40

Figure 18 Hourly interpolated and radar rainfall across the Richmond Basin during the 2022 flood event..41

Figure 19 Frequency analysis of 24 hours and 72 hours rainfall maximum for the 2022 flood ...44

Figure 20 Peak flow of 2022 flood compared to maximum streamflow (figure a) and maximum gauged streamflow (figure b) for streamflow gauging stations across the Northern Rivers region 47

Figure 21 Flood volumes for the 2022 flood at streamflow gauging stations across the Northern Rivers region 48

Figure 22 Water levels of historical floods at the Lismore gauge (Rowing Club, H058176).........51

Figure 23 Hydrographs of the 2022 flood across the Northern Rivers region. The highlighted lines correspond to period when the water level was above the major flood level....................52

Figure 24 Longitudinal profiles of the Wilsons River during the rising limb of the 2017 and 2022 floods....54

Figure 25 Wave height and tide data from coastal stations in the Northern Rivers region.........56

Figure 26 Annual maximum series computed from instantaneous streamflow for the Wilsons River at Eltham (203014)....57

Figure 27 Location of the two stations of Rock Valley (203010) and Eltham (203014) used to compute Lismore partial inflows 58

Figure 28 Fitting of the GEV distribution to AMS data from Lismore partial inflows (sum of flow from 203014 and 203010) excluding (figure a) and including (figure b) the 2022 event. 60

Figure 29 Expected AEP of the 2022 flood for gauging stations across the Northern Rivers region when the event is excluded (figure a) and included (figure b) in the fitting. 62

Figure 30 Comparison between catchment average rainfall derived from interpolation and AGCD for four catchments and two flood events 91

Figure 31 Example of blended images for Grafton, Marburg and Mount Staplton using Equation 1 (figure a), and overlap area (figure b), used to create the image with additional blend (figure c)....93

Figure 32 Comparison between hourly rainfall from rain gauge and blended radar...................94

Figure 33 Relationship between AMS data computed from Lismore water levels (H058176) and AMS data computed from Lismore partial inflows (sum of streamflows from Eltham and Rock Valley stations)....120

Figure 34 Comparison between AMS data from observed and AWRA-L streamflow for the Lismore partial inflows....121

Figure 35 Distribution of GEV and copula parameters for the Lismore partial inflows when fitting ignores streamflow errors and includes the 2022 event..132

Figure 36 Expected KS test p-value for fitting ignoring streamflow errors and including the 2022 event....133

Figure 37 Comparison of AEP values generated with a model including AWRA covariate (dark blue) against values generated from a univariate model (light blue). Streamflow errors are ignored for all configurations shown in this figure. A logarithmic scale is used for the y-axis in figures (a) and (b). Dotted lines in figure (a) and (b) shows fitting results when excluding the 2022 flood. Plain line show results of fitting including 2022 flood. 134

Figure 38 Comparison of AEP of the 2022 peak flow between fittings ignoring (dark blue) and including (light blue) streamflow errors. All fittings include the 2022 event and use AWRA covariates. 135

Tables

Table 1 Correspondence between Annual Exceedance Probability and Average Recurrence Interval 5

Table 2 Probability of observing a certain number of 1% AEP floods during a certain number of years 5

Table 3 Major towns in the Northern Rivers region 7

Table 4 Major demographic indicators for the LGA in the Northern Rivers region 8

Table 5 Proportion of employed persons by industry of employment† – top 10 industries (in percentage) 8

Table 6 Proportion of LGA area by land use class (in percentage of the total area)† 9

Table 7 Principal levee systems across the Northern Rivers region 10

Table 8 Major dams in the Northern Rivers region 11

Table 9 Number of active rain gauges per basins with station density in bracket expressed in km^2 per station 13

Table 10 Number of active surface water stations retained for data analysis in this report 19

Table 11 Average performance of the AWRA-L model against observed streamflow data across the region 23

Table 12 Groundwater bore selected for data analysis 24

Table 13 Tidal gauges selected for data analysis 25

Table 14 List of major flood events in the Northern Rivers region 27

Table 15 Number of studies per basins and decade in the region 28

Table 16 AEP of catchment rainfall maximums for the 2022 event 45

Table 17 Peak time difference between the Woodlawn College station on the Wilsons River and upstream gauging stations 49

Table 18 Expected AEP of the 2022 flood and associated 90% credible interval in brackets for two configurations excluding and including the 2022 event during the fitting 62

Table 19 Bureau of Meteorology climate rain gauges 68

Table 20 Bureau of Meteorology flood rain gauges 73

Table 21 BoM flood water level stations 78

Table 22 Manly Hydraulics Laboratories water level stations 79

Table 23 WaterNSW streamflow gauging stations 81
Table 24 List of rain gauges discarded from data analysis 86
Table 25 Streamflow gauging stations excluded from data analysis 88
Table 26 Performance metrics for AWRA-L simulated streamflow 96
Table 27 Major and minor flood events in the Northern Rivers region 99
Table 28 List of studies related to flooding in the Northern Rivers region 101
Table 29 Streamflow gauging stations where flood frequency analysis is performed along with censoring thresholds applied 122
Table 30 Cases considered in the likelihood function related to censored and missing variables 126
Table 31 Expected GEV and copula parameters when the fitting includes streamflow data from the 2022 flood 136

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This report was reviewed by Prof. Rory Nathan who has forty years of experience in engineering and environmental hydrology and is currently a professor of Hydrology and Water Resources in Infrastructure Engineering at the faculty of Engineering and Information Technology in the University of Melbourne. Prof Rory Nathan is also a core author and a member of the technical committee overseeing the Australian Rainfall and Runoff guidelines.

Executive summary

An exceptional flood event affected the Northern Rivers region in NSW between the end of February and the beginning of March 2022 which saw rainfall totals and water levels exceeding historical records by a significant amount in many parts of the region. The flood impacted riverine communities experienced considerable damages in towns such as Lismore, Coraki and Woodburn, and this triggered a range of actions by local communities, local government authorities, State, and Australian Federal government to address emergency circumstances and strategies to mitigate the impact of future floods in the region. In this context, the National Emergency Management Agency, Australian Federal Government, commissioned CSIRO to undertake the "Northern Rivers Resilience Initiative" project. The project area covers the Clarence, Richmond, Tweed and Brunswick river basins (and some of the coastal creeks which drain to the ocean) and seven Local Government Areas included in these catchments: Clarence Valley Council, Kyogle Council, Richmond Valley Council, Lismore City Council, Tweed Shire Council, Byron Shire Council, Ballina Shire Council.

The 2022 flood event was remarkable by many accounts. The antecedent conditions including rainfall totals, soil moisture and groundwater levels were significantly wetter than average across the Northern Rivers region. During the event, rainfall totals between the 23rd of February and the 1st of March were the highest daily rainfall on records for many parts of the Richmond, Tweed and Brunswick basins. The rainfall was centred on the mid-Richmond and Wilsons River catchment around Lismore and reached daily rainfall totals that are estimated to be significantly higher than a 1% Annual Exceedance Probability event which constitutes a reference for design purposes. Extreme rainfalls translated into record high streamflows, volumes and water levels for stations in the mid and lower Richmond, Wilsons catchment, Tweed and Brunswick basins. Major flood levels were exceeded by more than 2m in several locations including in Lismore where the flood reached 14.37m, a level that exceeds the major flood level of 9.7m by 4.67m.

The flood frequency of the 2022 event was estimated and analysed in terms of its Annual Probability of Exceedance. The 2022 peak flow was estimated to be significantly higher than the 1% Annual Exceedance Probability event at seven gauging stations in the region and for the Lismore partial inflows (a partial estimate of streamflow at Lismore based on the sum of flows at two upstream stations). A high degree of uncertainty is associated with these frequency estimates which were found to vary between slightly less than a 1 in 100 year frequency (1% AEP) to 1 in several thousand years (up to 0.01% AEP for one station).

This study revealed several issues with the data used to monitor and analyse flood events in the region. Both climate and flood rain gauge networks suffered from numerous failures during the 2022 flood effectively reducing the number of rain gauges considerably in certain parts of the region. The first recommendation of this report is to increase the redundancy and robustness of rain gauge networks to reduce the risk of failure during extreme weather events.

Multiple sources of rainfall data were used in this study and revealed significant differences in terms of rainfall magnitude. Consequently, it is recommended to develop a gridded hourly rainfall product blending on-ground observations with radar and atmospheric models at a resolution equal to or finer than 1km. The blending should also report associated uncertainty in the form of ensembles where uncertainty is expected to increase as we move away from rain gauges.

Finally, it is recommended to increase the current effort of acquiring streamflow data to improve rating curves at existing streamflow gauging stations especially stations with limited gauging data, develop rating curves for additional stations including the Lismore gauge, and repair or install a station to measure streamflow on Terania Creek upstream of Lismore.

1 Introduction

1.1 Context and aim of this report

An exceptional flood event affected the Northern Rivers region in NSW between the end of February and the beginning of March 2022. During this event, the rainfall totals and water levels exceeding historical records by a significant amount in many parts of the region. There was considerable damage in towns such as Lismore, Coraki and Woodburn which triggered a range of actions by local communities, local government authorities, state, and Australian governments to address emergency circumstances and strategies to mitigate the impact of future floods in the region. In this context, the National Emergency Management Agency, Australian Federal Government, commissioned CSIRO to initiate the “Northern Rivers Resilience Initiative” project. The project area covers the entire Northern Rivers region including the Clarence, Richmond, Tweed and Brunswick river basins (and some of the coastal creeks which drain to the ocean) and seven Local Government Areas included in these catchments: Clarence Valley Council, Kyogle Council, Richmond Valley Council, Lismore City Council, Tweed Shire Council, Byron Shire Council, Ballina Shire Council. The project area is presented in Figure 1.

The project is sequenced in two Parts with a first part of six months analysing the drivers of the 2022 flood (this report), reviewing previous flood mitigation studies, and identifying and prioritising options for mitigating flood risks in the region (Weber et al., 2022). Part 2 of the project will follow after this initial assessment and involve detailed modelling over the next two years of the project. This program of work will collate and generate high quality Light Detection and Ranging (LiDAR) data to provide spatial analysis and to underpin hydrological/hydrodynamic modelling of water movement for the Northern Rivers region. It will also collect detailed bathymetry for the Richmond and Tweed rivers, and their main tributaries. Detailed hydrological and hydrodynamic models will be developed and implemented for the entire Richmond River Catchment to investigate scenarios and actions to mitigate flood risk in the Richmond River catchment. It will involve examining and evaluating possible events or scenarios that could take place in the future and predict possible outcomes, drawing on local knowledge and expertise on the catchment and flooding.

This report which was prepared between July and November 2022 constitutes the first part of the Northern Rivers Resilience Initiative. The report aims at characterising the physical factors that led to the February/March 2022 floods including climate, surface water and groundwater. It provides a general introduction to the Northern Rivers region in section 2 along with a presentation of its physical environment in section 3 with a focus on topography, surface water and groundwater, and coastal areas. Section 4 reviews major historical floods and flood mitigation programs in the region. Finally, Section 5 analyses the 2022 flood event from initial catchment conditions to rainfall and river flows during the event. The section closes with a frequency analysis of the streamflow peaks for key river gauges.

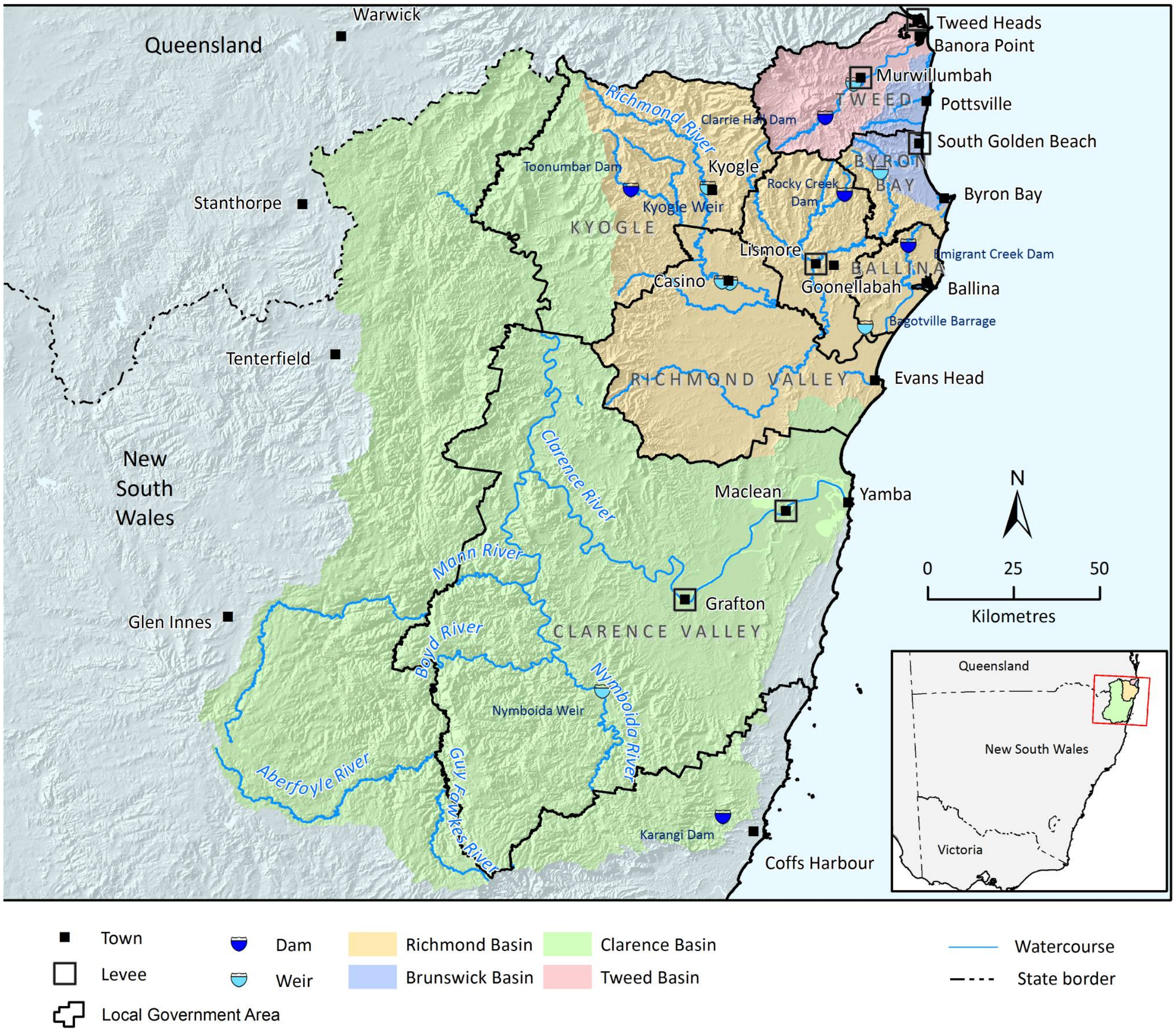

Figure 1 Overview of the Northern Rivers region

1.2 Methods adopted throughout this report

1.2.1 Reporting areas

As indicated in the previous section, the project covers the entire Northern Rivers region including the four major river basins (and smaller coastal creeks which drain to the ocean) and seven Local Government Areas (LGA). The word "basin" is used throughout this report to distinguish the four high-level physical reporting areas (Clarence, Richmond, Tweed and Brunswick) from sub-areas defined by catchments drained at a particular point in a river (for example the Wilsons River catchment at Lismore).

The basins and LGA boundaries partly overlap with important exceptions such as in the Kyogle LGA which is split between the Richmond and Clarence basin, and the Clarence Valley LGA which only covers the lower part of the Clarence basin (see Figure 1).

To simplify the analysis in this report, two types of reporting areas are used to present specific aspects of the region. The presentation of socio-economic information in sections 2 is based on LGA boundaries whereas the climate and hydrological information is based on basin boundaries for the rest of the report (sections 3 to 5).

1.2.2 Time periods

In this report, the flood that occurred between the end of February and beginning of March 2022 is assumed to start on the 22^{nd} February and end on the 15^{th} March 2022. These dates are arbitrary and defined based on the authors analysis of when rainfall, water level and streamflow data remained above average values. This event will be referred to as the “2022 flood event” in the rest of the report.

It is acknowledged that a second major flood occurred later in 2022 which will also be discussed in this report, but not given the same amount of scrutiny as the end February and early March major event. It is also highlighted that the Northern Rivers have seen numerous flood events in the past that are discussed in section 4.1 including start and end dates of these events. These events are used throughout the report to provide a historical context to the 2022 flood event.

1.2.3 Data sources and analysis

This report characterises the 2022 flood event using data collected by CSIRO from National and State providers detailed below.

Hydro-meteorological data sources

To complete data acquisition, processing, analysis and interpretation for this rapid assessment within the duration of this study (five months), data collection effort was focused on the three main providers of hydro-climate data in the region: WaterNSW, Bureau of Meteorology (BoM) and Manly Hydraulics Laboratories (MHL). It is acknowledged that more data is available from other data providers such as LGAs or privately owned networks.

Socio-economic data sources

Socio-economic data presented in this report are extracted from Australian Bureau of Statistics (ABS) published datasets and from technical reports covering the Northern Rivers region (see Appendix G for a list of reports).

Model data

The analysis and conclusions provided in this report are based on measurements and exclude the use of hydrological and hydro-dynamic models. The main motivation for this approach is to focus on factual evidence extracted from verifiable data sources while modelling work is left to subsequent phases of this project. It is acknowledged that modelling brings more opportunities for understanding certain hydro-meteorological factors at play during a major flood such as the 2022 event that often pushes measurement networks beyond their accuracy limits. However, models remain imperfect representations of reality and rely on specific assumptions which require thorough analysis and discussion that are out of scope in this rapid assessment phase of the project.

An exception to this approach was made in the use of the AWRA-L national water balance model (Vaze et al., 2013) for estimates of certain variables with no equivalent field measurements. The use of AWRA-L bridges important knowledge gaps and reduces uncertainty related to flood frequency analysis. AWRA-L was not specifically built for this study. It is a model covering the whole Australian continent, relying on open-source software technology, and for which data are accessible publicly and in near-real time through the Bureau of Meteorology website. More information about AWRA-L is provided in section 3.3.1.

1.2.4 Reporting uncertainty

The analysis of large flood events is complex because of their rarity and due to the limited amount of data available to describe them. Consequently, many facts presented in this report are associated with a high level of uncertainty. Reporting uncertainty is a core recommendation of the Australian Rainfall and Runoff guidelines (Ball et al., 2019) that underpins Flood modelling studies in Australia.

This report describes uncertainty by using percentile values which are defined as thresholds below which a certain fraction of a data sample falls. For example, when analysing 80 years of annual rainfall in a catchment, the 25% percentile is the rainfall value that is greater than 25% of the data sample, i.e. it is the 20^{th} value when sorting the record in ascending order.

Five percentiles are generally reported in this report: 5%, 25%, 50% (also referred to as the median), 75% and 95%.

1.2.5 Frequency analysis

In flood studies such as the ones described in section 4.2 of this report, the approach taken to qualify the rarity of a flood event relies on what is called “frequency analysis” which aims at estimating the probability of occurrence of a flood using long records of past historical events and statistical models. In this report, this probability is defined as the chance for a rainfall amount or a flood peak to be equalled or exceeded during a particular year and at a particular location. This probability is referred to as “Annual Exceedance Probability” or AEP in short.

Sections 5.3 and 5.6 of this report present AEP estimates of the 2022 rainfall and peak flows across the Northern Rivers. It is highlighted that the AEP of the 2022 flood is expected to show large uncertainty due to both errors in observed data and short duration of data records. The 2022 flood AEP is also highly variable spatially across the Northern Rivers region as the flood did not reach similar magnitude across the entire region as discussed in section 5.

Sections 5.3 and 5.6 refer to the 1% AEP threshold because it often constitutes the most extreme level of protection adopted in flood risk management plans. It is highlighted that this threshold remains arbitrary and reflects a particular level of risk accepted by the communities more than a physical characteristic of rivers and floodplains. This corresponding rainfall and peak flow values are also a function of the length of available observations and the number of extreme events recorded during this period.

As an alternative to the concept of AEP, flood occurrence can also be described in terms of the average intervals separating two flood events. This is generally referred to as “Average

Recurrence Interval" or, more commonly, "return period". Table 1 provides a correspondence between AEP and Average Recurrence Interval.

Table 1 Correspondence between Annual Exceedance Probability and Average Recurrence Interval

ANNUAL EXCEEDANCE PROBABILITY		AVERAGE RECURRENCE INTERVAL
(%)	**(1 in y years)**	**(years)**
10	1 in 10	10
5	1 in 20	20
1	1 in 100	100
0.5	1 in 200	200
0.1	1 in 1000	1000

The use of return periods is generally discouraged because it suggests that large floods occur at regular intervals, which is not consistent with observations. In fact, it can be shown that the exact number of floods occurring during a given period with a specific AEP is highly variable. As an illustration, Table 2 provides the chances of observing exactly 0 to 5 floods reaching a 1% AEP over a period of 50, 100 and 150 years[1]. This table suggests that there is a non-negligible chance of observing up to 4 events reaching 1% AEP during a 100 year-period (probability of 0.01, see third column and fifth row in the table). Consequently, the term return period will be avoided as much as possible in this report.

Table 2 Probability of observing a certain number of 1% AEP floods during a certain number of years

NUMBER OF FLOODS	PERIOD OF 50 YEARS	PERIOD OF 100 YEARS	PERIOD OF 150 YEARS
0	0.61	0.37	0.22
1	0.31	0.37	0.34
2	0.08	0.18	0.25
3	0.01	0.06	0.13
4	0	0.01	0.05
5	0	0	0.01

1.3 Limitations of the report

The focus of this report is the analysis of antecedent catchment characteristics and hydro-climatic data related to the 2022 event. Several other factors which contributed to or are related to the flood event are not covered in this report as discussed below.

[1] Probability is computed as follows:

$$P = C_N^k \alpha^k (1-\alpha)^{N-k}$$

Where α is the AEP (1% here), k is the number of events (0 to 5), N is the duration of the period (50, 100 and 150) and C_N^k is the number of possible combinations when selecting k items out of N (binomial coefficient).

1.3.1 Impact of the 2022 flood on socio-economic and environmental factors

The 2022 flood caused extensive damage to communities with large scale destruction and long-lasting impacts on fragile eco-systems. These aspects remain at the core of the CSIRO project but are not part of the present report which remains focused on hydro-climate analysis.

1.3.2 Impact of climate change

Climate change resulting from elevated CO_2 concentration in the atmosphere is now increasingly recognised as an aggravating factor for flooding and its associated impacts (Masson-Delmotte et al., 2021). Despite the mounting evidence confirming this trend, it remains difficult to relate climate change to a single event such as the 2022 flood. The approach generally applied to investigate this point relies on attribution studies that simulate various scenario of CO_2 concentration and analyse their impact on a particular event (Pall et al., 2011). These studies require complex numerical simulations that are not compatible with the short-time frame available for the present investigation. Consequently, climate change impact on the 2022 flood is not covered in this report.

This report relies on historical observed data to-date and assumes that they remain representative of the current climate in which the 2022 flood occurred.

1.3.3 Flood frequency analysis of the 2022 event and design floods

As indicated in section 1.2.5, this report contains frequency analysis of the 2022 flood based on observed streamflow data to compare this event against historical events. This analysis is undertaken for this flood only and does not replace the design flood levels (for example the 1% AEP flood level) defined by flood studies across the region.

2 The Northern Rivers region

This section describes the main characteristics of the Northern Rivers region including its demographic, current industries, land use and key water related infrastructures. The data was extracted from census data published by the Australian Bureau of Statistics.

2.1 Demographics

The region falls entirely within the New South Wales state with a border to Queensland state in its Northern part. Table 3 lists the towns in the region having a population above 10,000 according to the 2021 census (ABS, 2022). Five towns out of nine in this table are located along the coast, suggesting an important concentration of population in the coastal parts of the region.

Table 3 Major towns in the Northern Rivers region

NAME	LGA	TOTAL POPULATION 2021†
Tweed Heads	Tweed	20,563
Grafton	Clarence Valley	19,255
Ballina	Ballina	18,629
Banora Point	Tweed	16,320
Lismore	Lismore	15,229
Pottsville	Tweed	14,086
Goonellabah	Lismore	13,591
Casino	Richmond Valley	12,298
Byron Bay	Ballina	10,914

† Data sourced from ABS (2022)

The demographic profiles of the seven LGA sourced from the 2011 and 2021 censuses are provided in Table 4. This table highlights a sharp contrast between coastal LGAs (Ballina, Byron and Tweed) exhibiting a higher population density and median weekly income compared to inland LGAs (Clarence Valley, Kyogle and Richmond Valley). The Lismore LGA appears as an intermediate between these two groups. The table also shows that these differences between the two coastal and inland LGAs increased between 2011 and 2021. For example, the population increase between the two censuses ranges between 14.4% to 23.6% for the coastal LGAs against a range of 1.4% to 9% for the inland LGAs.

Compared to Australia, the LGAs in the region show a higher median age in 2021 varying between 43 to 52 against 38 for Australia, and a lower median weekly income that is lower than $1,602 compared to $1,746 for Australia. The population density in the region is much higher than Australia with 2021 values ranging from 5.2 people/km^2 for Kyogle to 95.5 people/km^2 for Ballina against 3.3 people/km^2 for Australia. However, population density for Australia is not really representative due to the important concentration of population in a few urban areas and the large size of the Australian continent. Nonetheless, the population density for the coastal

LGAs is remarkably high, suggesting a much denser population than most regional areas of Australia.

Table 4 Major demographic indicators for the LGA in the Northern Rivers region

INDICATOR NAME	UNITS	AUSTRALIA	BALLINA	BYRON	CLARENCE VALLEY	KYOGLE	LISMORE	RICHMOND VALLEY	TWEED
Total population, 2011†	number	21,507,717	39,274	29,209	49,665	9,228	42,766	22,037	85,105
Total population, 2021‡	number	25,422,788	46,296	36,116	54,115	9,359	44,334	23,565	97,392
% change **in total population**	%	18.2	17.9	23.6	9	1.4	3.7	6.9	14.4
Population density, 2011†	people/ km^2	2.8	81	51.7	4.8	2.6	33.2	7.2	65.1
Population density, 2021‡	people/km^2	3.3	95.5	63.9	5.2	2.6	34.4	7.7	74.5
Indigenous population, 2011†	number	548,369	1,225	516	2,845	487	1,916	1,453	2,940
Indigenous population, 2021‡	number	812,728	1,804	685	4,391	525	2,600	1,858	4,329
% change in indigenous population	%	48.2	47.3	32.8	54.3	7.8	35.7	27.9	47.2
Median age, 2011†	years	37	45	42	46	45	40	42	45
Median age, 2021‡	years	38	48	43	49	52	44	46	47
change in Median age	years	1	3	1	3	7	4	4	2
Median weekly total household income, 2011†	$	1,234	930	885	768	714	907	789	845
Median weekly total household income, 2021‡	$	1,746	1,429	1,602	1,123	983	1,319	1,137	1,296
% change in median weekly total household income	%	41	53.7	81	46.2	37.7	45.4	44.1	53.4

† Data sourced from ABS (2012)
‡ Data sourced from ABS (2022)
§ Data sourced from GA (2022)

2.2 Current industries and land use

The proportion of employed persons by industry for Australia and the seven LGAs presented in Table 5 suggests that the ranking of employment by industries in the region is similar to the one prevailing across Australia with top employment in the health care and social assistance sector. Noticeable differences from the national figures are observed in Kygole LGA with a high proportion of employment in Agriculture, forestry and fishing and in Byron, Tweed, and Ballina LGAs with a high proportion of employment in the accommodation and food services industry.

Table 5 Proportion of employed persons by industry of employment† – top 10 industries (in percentage)

INDUSTRY OF EMPLOYMENT	AUSTRALIA	BALLINA	BYRON	CLARENCE VALLEY	KYOGLE	LISMORE	RICHMOND VALLEY	TWEED
Health care and social assistance	12.6	16.9	14.2	15.4	14.4	19	13.6	15.7
Retail trade	9.9	11.6	10.2	11.8	9.2	12.5	10.2	11.2
Education and training	8.7	11.1	9.8	7.9	9	11.2	8.1	8.6
Accommodation and food services	6.9	8.6	12	9.2	4.4	7.1	7.2	10.3

INDUSTRY OF EMPLOYMENT	AUSTRALIA	BALLINA	BYRON	CLARENCE VALLEY	KYOGLE	LISMORE	RICHMOND VALLEY	TWEED
Construction	8.5	8.9	8.5	8.7	8.3	6.8	6.3	11.2
Agriculture, forestry and fishing	2.5	4.4	3.8	6.4	18.7	6	8.2	2.6
Manufacturing	6.4	4.7	4	5.5	8.1	5.9	14.7	4.3
Public administration and safety	6.7	5.7	3.2	7.9	4	5.1	5	5.3
Professional, scientific and technical services	7.3	5.4	7.1	3.3	3.2	4.4	3.2	4.7
Transport, postal and warehousing	4.7	2.9	2.7	4.3	3.3	3.1	4.7	3.9

† Data sourced from ABS (2016)

Table 6 shows that the land use in the region is characterised by a higher proportion of grazing and nature conversation areas in LGAs away from the coast (for example Kyogle) and a predominance of urban intensive use areas in coastal LGAs (Ballina, Byron and Tweed).

Table 6 Proportion of LGA area by land use class (in percentage of the total area)†

LAND USE CLASS	BALLINA	BYRON	CLARENCE VALLEY	KYOGLE	LISMORE	RICHMOND VALLEY	TWEED
Dryland cropping	15.7	1.9	1.5	0.8	7.4	3.9	7.5
Dryland horticulture	12.2	5.4	0.1	0.1	5.1	0.2	3.7
Grazing modified pastures	20.4	24.3	6.8	15.5	30.5	15.5	19.8
Grazing native vegetation	14.4	26.4	20.9	29.7	29.0	16.8	14.2
Nature conservation	2.2	11.5	22.4	20.6	6.5	11.5	16.4
Other minimal use	12.1	9.1	22.1	13.7	6.6	24.4	18.5
Plantation forests	0.2	1.1	1.8	4.7	1.2	4.4	0.9
Production native forestry	0.0	0.0	18.1	11.4	0.8	16.1	0.0
Urban intensive use	14.5	17.5	1.8	1.2	8.0	3.0	15.6
Water	7.9	2.8	4.4	2.1	4.3	3.3	3.1

† Data sourced from NSW (2020)

2.3 Key water related infrastructures

This section provides a brief overview of key infrastructures potentially affecting flood dynamic in the Northern Rivers.

2.3.1 Flood levees

Levees are the main infrastructures built to protect communities from damaging floods. Several towns across the Northern Rivers identified in Figure 1 are equipped with levee systems that have been built progressively since 1960 as indicated in Table 7. The description of the levees provided in this table is obtained from published documents listed in the reference section and in Appendix G. It is acknowledged that this description remains brief and may not provide a consistent level of details across the region due to the lack of documented references for many levees. This knowledge gap is currently being addressed by the NSW Flood Levee Repair and Maintenance Program team with whom CSIRO NRRI team is collaborating actively.

Table 7 Principal levee systems across the Northern Rivers region

BASIN	LOCATION	DESCRIPTION
Clarence		
	Grafton	Seven levees surround the town of Grafton with varying design criteria due to their progressive construction. The levees are expected to be overtopped when Clarence River flows exceeds 20,000 m^3/sec (Clarence Valley Floodplain Management Committee, 2014). In addition, a series of levees protect South Grafton and adjoining rural areas with a similar design criteria following a levee upgrade completed in 1996 (Clarence Valley Floodplain Management Committee, 2014)
	Maclean	A levee was constructed in 1975 and covers 3.5 km along the bank of the Clarence River in Maclean (Clarence Valley Floodplain Management Committee, 2014).
Richmond		
	Lismore	The majority of Central Lismore is protected by a levee built in 2005 up to a 10% AEP flood (Lismore City Council, 2014; NSW SES, 2018).
Tweed		
	Murwillumbah	A series of levees on the banks of the Tweed River protect the town centre with protection level varying from 2% to 20% AEP (NSW SES, 2014, p. A9)
	Tweed Heads	In South Tweed Heads a system of levees protect the town from floods at an AEP of approximately 5% (NSW SES, 2014, p. A10)
Brunswick		
	South Golden Beach	Levees along both banks of Yelgun Creek for 500 m and Redgate road for 500 m protect the town from flooding up to a level of 4.2 m (NSW SES, 2013a). The design level of this protection could not be identified from published documents.

2.3.2 Transport infrastructures affecting flooding

Transport infrastructure such as roads, railways and bridges constitute important obstacles to flood propagation with often a significant impact on flooding levels. Road networks are also critical during flood events by providing evacuation routes as described in the appendices of SES flood emergency sub plans (NSW SES, 2013a, 2013b, 2014, 2017, 2018). Finally, the impact of embankments from decommissioned railways are widespread in rural areas and not often as documented as the impact of major roads or operational railways projects.

The main transport infrastructure project with a potentialimpact on flood dynamic in the region is the upgrade of the M1 highway which intended to increase flood immunity of the highway to a level varying between the 5% and the 1% Annual Exceedance Probability event (Leslie et al., 2017a, 2017b). Reviewing the impact of this upgrade on the 2022 flood is beyond the scope of this report.

2.3.3 Water storages

There are six major dams in the regions as listed in Table 8 and shown in Figure 1. The principal purpose of all these dams is water supply to nearby towns, except Toonumbar dam which was built to support local irrigation. Their storage capacity provided in Table 8 remains small compared to river flows in flood conditions. In addition, the six dams are ungated with no active management during flood conditions, and had their stored volumes close to full storage capacity at the beginning of the 2022 flood following several months of higher-than-average rainfall (see section 5.1.1).

Consequently, the six dams are considered to have a negligible impact on downstream flooding during the 2022 flood and won't be discussed further in this report.

Table 8 Major dams in the Northern Rivers region

BASIN	NAME	OPERATOR	RIVER	STORAGE CAPACITY (GL)	YEAR OF COMPLETION	DATA SOURCE
Clarence						
	Shannon Creek dam	Coffs Harbour City Council	Offstream	30.0	2002	ANCOLD (2022)
	Karangi dam	Coffs Harbour City Council	Unknown	5.6	Unknown	Coffs Harbour City Council (2022)
Richmond						
	Rocky Creek dam	Rous County Council	Rocky Creek	14.0	1953	ANCOLD (2022)
	Emigrant Creek dam	Rous County Council	Emigrant Creek	0.8	1968 with upgrade in 2022	Rous County Council (2022)
	Toonumbar dam	WaterNSW	Iron Pot Creek	11.1	1971	ANCOLD (2022)
Tweed						
	Clarrie Hall	Tweed Shire Council	Doon Doon Creek	15.0	1983	ANCOLD (2022)

3 Hydro-meteorological environment of the Northern Rivers region

3.1 Topography

The Northern Rivers region is bound in the West by the Great Dividing Range where altitudes remain above 500 m, reaching up to 1450 m in the South-West of the Clarence Basin. Rivers in the upper parts of the region are steep with deeply incised valleys. The rivers then flow towards the coast and meander through wide floodplains in the lower parts of their basin. A typical river profile in the region is shown in Figure 2 for the Richmond River where the steep gradient in the first 50 km of the river can be seen to transition progressively to a nearly flat topography for the last 100 km before the river mouth.

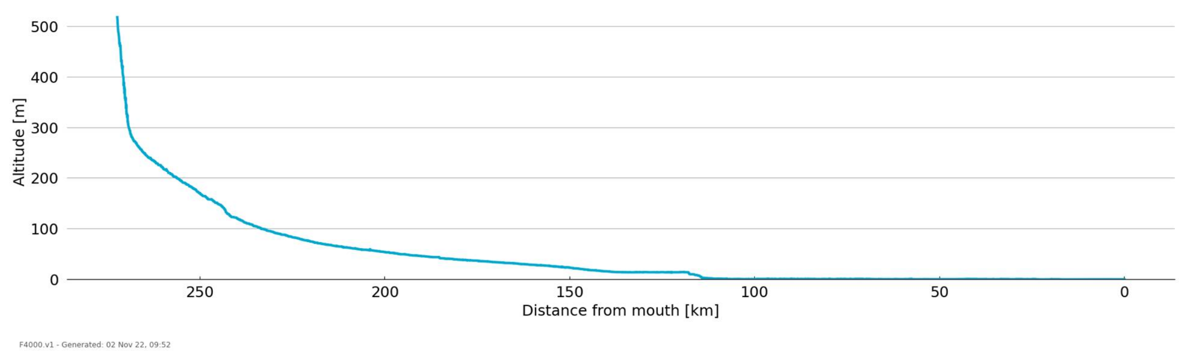

Figure 2 Richmond River profile

Data source: NSW Spatial Services (2022)

It is worth noting that the Northern Rivers floodplains exhibit a pronounced tidal influence that reaches long distances inland. For example, the city of Lismore that is located more than 100 km from the ocean following the Wilsons and then the Richmond River (total river length of approximately 106 km) is under tidal influence. Therefore, ocean conditions like tide levels have a significant impact on flooding with an increasing effect closer to the ocean. It also complicates the measurement of streamflow for the gauges located in the floodplain because streamflow cannot be computed directly from water levels as is generally done for most rivers.

3.2 Climate of the Northern Rivers region

This section overviews the climate of the Northern Rivers region with a focus on rainfall data and rainfall extremes. Information presented in this section form the basis for the analysis of the rainfall during the 2022 flood described in section 5.2.

3.2.1 Rainfall stations

Data related to the climate of the Northern Rivers region is obtained from several networks of measurement stations owned and operated by various data providers. The Bureau of Meteorology operates a large fraction of the stations grouped into two principal networks described hereafter and in appendices A and B. A first set of stations aims at providing long-term data for climate analysis that will be referred to in the rest of this report as the "climate network". The stations in this network include automatic weather stations that measure a range of atmospheric variables such as rainfall, temperature, and atmospheric pressure at a high frequency (sub-hourly). The maintenance cost of these stations is high, consequently they only cover the main urban centres and critical infrastructures (e.g., airports). The climate network is complemented with stations that collect a smaller number of variables (essentially rainfall and temperature) at a daily time step. All climate stations generally possess long historical records spanning multiple decades.

Alongside its climate network, the Bureau of Meteorology uses rainfall stations that are focussed on supporting its flood warning service. These stations measure rainfall at a high frequency (sub-hourly) and have a short historical record often starting in the 2000s. This second network is referred to as the "flood network" in the rest of this report. More details on the climate and flood networks can be obtained from Evans et al. (2020).

Other networks include the climate stations operated by WaterNSW to complement its surface water network described in 3.3.1, stations operated by the LGAs to support the management of water infrastructures such as dams or sewage treatment plants, and privately owned networks to support the daily management of local businesses.

It is acknowledged that these networks often overlap: a station can be owned by one stakeholder (for example a LGA) and maintained and monitored by another stakeholder (for example Bureau of Meteorology). Describing these complex arrangements is out of scope for this report.

Table 9 summarises the number of active rain gauges by basins in the region. Detailed station characteristics are provided in Appendix A. Additional historical stations that are now closed are available from the Bureau of Meteorology databases, but they are not reported here as they cannot be used to characterise the 2022 flood. Table 9 distinguishes stations that are retained for data analysis from stations that are excluded following quality checks. The process of checking rain gauge data is detailed hereafter.

Table 9 Number of active rain gauges per basins with station density in bracket expressed in km^2 per station

BASIN	CLIMATE RAIN GAUGES		FLOOD RAIN GAUGES	
	RETAINED	EXCLUDED	RETAINED	EXCLUDED
Clarence	58 (535 km^2/st)	5	22 (1410 km^2/st)	5
Richmond	32 (219 km^2/st)	1	30 (234 km^2/st)	6
Tweed	14 (77 km^2/st)	1	21 (52 km^2/st)	2
Brunswick	4 (127 km^2/st)	0	12 (42 km^2/st)	9
TOTAL	108	7	86	21

Data source: Climate Data Online, BoM (2022d) and Australia Rainfall and River Conditions, BoM (2022a)

Overall, the densities of stations reported in Table 9 appear reasonable. The Clarence Basin and the Richmond basin are close to the minimum standard of 575 km^2/station for climate stations, as recommended by the World Meteorological Organisation (WMO, 2020, pp. I.2-24). Further analysis would be required to ensure that high altitude areas in the region where rainfall variability is generally higher are covered by enough rain gauges.

As indicated in Table 9, certain stations are excluded from the analysis. This process is based on the inspection of double mass curves which compares the accumulated rainfall at two neighbouring sites in order to detect non-stationarities (WMO, 2018, p. 82). Figure 3 shows the double mass curves for the hourly rainfall at the Cudgera Lake station (H558046) from the flood network compared against daily data at Murwillumbah (58158, Figure 3.a) and Mullumbimby (58040, Figure 3.b) stations, both located less than 16 km away. The third plot in the figure shows a comparison against the average of the first two neighbouring stations which is often added to increase the robustness of the test. The three curves reveal that significant non-stationarities occurred in 2009 and 2012 due to large rainfall reported by the Cudgera Lake station but not for its neighbours (breaks in the curve in Figure 3). These discrepancies flag the Cudgera lake station data as erroneous and prompted their exclusion from the present data analysis.

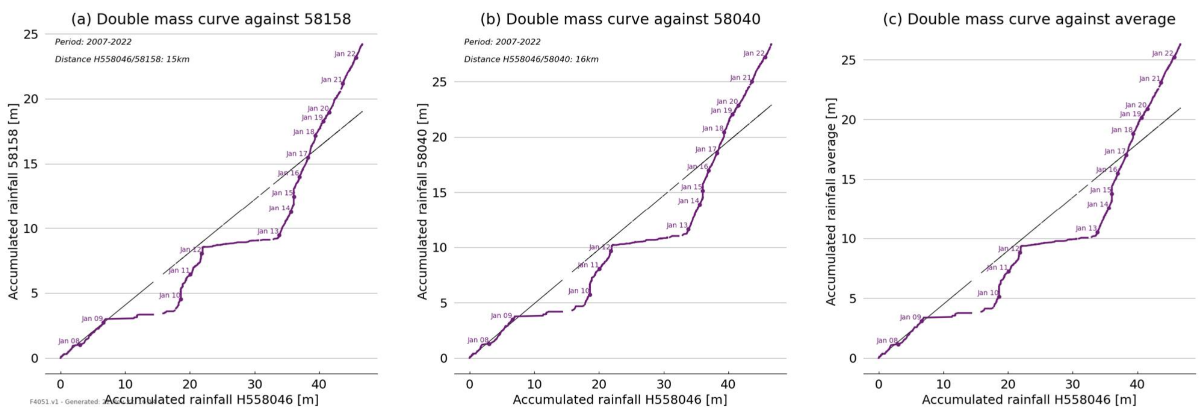

Figure 3 Quality check of rainfall records for the Cudgera Lake hourly rain gauge (station ID H558046)

Data source: Climate Data Online, BoM (2022d) and Australia Rainfall and River Conditions, BoM (2022a)

A similar process was conducted for all other stations listed in Appendix A, which led to the exclusion of 7 climate gauges and 21 flood gauges. It is acknowledged that double-mass curve analysis is a generic test of rainfall data quality that was chosen to perform a rapid assessment of rainfall data across the region. More specific tests related to extremes such as the ones advocated by Lewis et al. (2021) are needed to provide a definitive analysis of extreme rainfall data quality.

The location of the gauges retained for the analysis is shown in Figure 4 where stations are color-coded based on the duration of their record. The two maps in Figure 4 highlight the increasing density of station from West to East with the highest concentration of stations in the Tweed and Brunswick basins. The high density of climate stations across the border in South-East Queensland is noted, especially close the North-West boundary of the Clarence Basin where this high density contrasts with the sparse network in the Northern Rivers region. The stations located in Queensland are out of the project area and were not considered in the rest of the analysis.

Figure 4 reveals that the duration of the climate station records are satisfactory with few stations having records shorter than 20 years. It is remarkable that several stations possess records of more than 100 years, which is invaluable in studying extreme floods. In contrast, a large majority of flood stations have records shorter than 20 years. This suggests caution in interpreting statistics on extreme rainfall derived from such limited records.

Figure 4.a and Figure 4.b highlight the rain gauges that failed during the 2022 flood with a red circle. The number of failures was significant with 41 failures for the climate network and 8 failures for the flood network. More details are provided in Appendix A and B. Determining the causes for these failures is out of scope for the present report, but recommendations are made to improve the resilience of the network during extreme events.

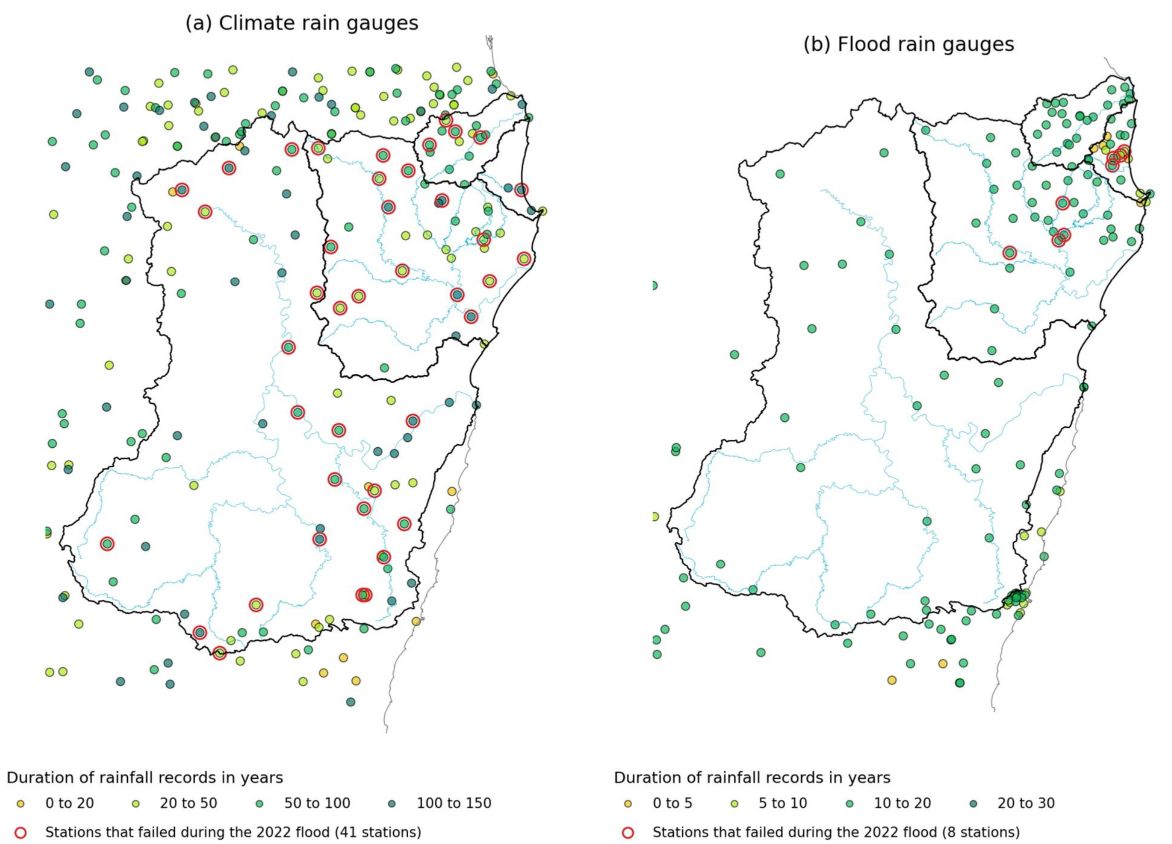

Figure 4 Active climate (daily) and flood (sub-daily) rain gauges across the Northern Rivers region

Data source: Climate Data Online, BoM (2022d) and Australia Rainfall and River Conditions, BoM (2022a)

3.2.2 Australian Gridded Climate Data grids

The Bureau of Meteorology provides a gridded product derived from the climate stations presented in the previous section called the Australian Gridded Climate Data – AGCD (BoM, 2022b; Evans et al., 2020). This product is currently the official historical gridded rainfall product from the Bureau of Meteorology that progressively supersedes the AWAP dataset (Jones et al., 2009). The AGCD data were extracted from the Australian Water Outlook page operated by the Bureau of Meteorology (BoM, 2022c).

The AGCD rainfall grids have the advantage of providing a continuous spatial and temporal coverage from 1911 onwards, at a spatial resolution of 0.05 degrees and daily time resolution. The accuracy of the grids is limited by the underlying station data, the availability of which can be significantly reduced during extreme floods as highlighted in the previous section.

3.2.3 Interpolated hourly rainfall

The rainfall event that triggered the 2022 flood reached its maximum intensity in less than 24 hours and showed a high spatial variability in the Richmond, Tweed and Brunswick basins. In this context, the time and spatial resolution of the AGCD product described in the previous section was found inadequate to get a detailed picture of the event.

Consequently, rainfall data from the flood network were interpolated at a resolution of 0.005 degrees (~ 500 m by 500 m) and hourly time step to complement the analysis derived from the daily AGCD grids. This process is described in Appendix C.

3.2.4 Radar rainfall

Rainfall derived from radars is an important complementary source of information to on-ground observations, which can be sparse in certain parts of the region as described in the previous section. Three radars are included in the analysis:

- Mount Stapylton: the radar is located at 27.72° latitude and 153.240° longitude and described by the Bureau of Meteorology[2] as "located on an isolated hill about 150 m above mean sea level, just east of Beenleigh. This site provides good low-level coverage, ideal for Doppler observations, of the Greater Brisbane area".
- Marburg: the radar is located at 27.61° latitude and 152.54° longitude, and described by the Bureau of Meteorology[2] as "situated at 370 m on the Little Liverpool Range between Marburg and Rosewood and 53 km west of the Brisbane GPO this radar has a good overall view of precipitation in all sectors.
- Grafton: the radar is located at the Grafton NSW Agricultural Research station, at 29.62° latitude and 152.97° longitude. The Bureau of Meteorology[3] describes it as "having a very good view in all directions and (being) the primary weather radar for the North-East of NSW. It should provide useful weather information as far west as Glen Innes, south to Kempsey and north to the Gold Coast".

Radars measure reflectivity from the atmosphere, which is subsequently converted to rainfall using what is referred to as the "Z-R" relationship (Seed et al., 1996). Generally, the raw rainfall surfaces obtained from this process are further corrected to better match on-ground

[2] http://www.bom.gov.au/australia/radar/info/qld_info.shtml

[3] http://www.bom.gov.au/australia/radar/info/nsw_info.shtml

observations. In this analysis, the “rainfields” product generated by the Bureau of Meteorology (Seed et al., 2007) is used. Additional radar data processing described in Appendix E was undertaken to create a single surface by blending the data from the three radars.

3.2.5 Climate averages and monthly statistics

Figure 5 shows the mean-annual rainfall for the region derived from the AGCD grids for the 1991-2020 period. This period is consistent with the computation of climate normal recommended by the World Meteorological Organization (WMO, 2017). Potential Evapotranspiration (PET) data are computed with the Penman equation (Penman, 1948) and obtained from the Australian Water Outlook (BoM, 2022c). These maps highlight the pronounced contrast between the dry climate prevailing in the Western part of the regions with mean annual rainfall below 900 mm/year and the wet conditions characterising the South-East and North-East where mean annual rainfall exceeds 1800 mm/year.

The highest mean annual rainfall in the region is observed in Mount Jerusalem National Park at the intersection between the Richmond, Tweed and Brunswick basins and reaches 2023 mm/year based on AGCD rainfall grids for the period 1991-2020.

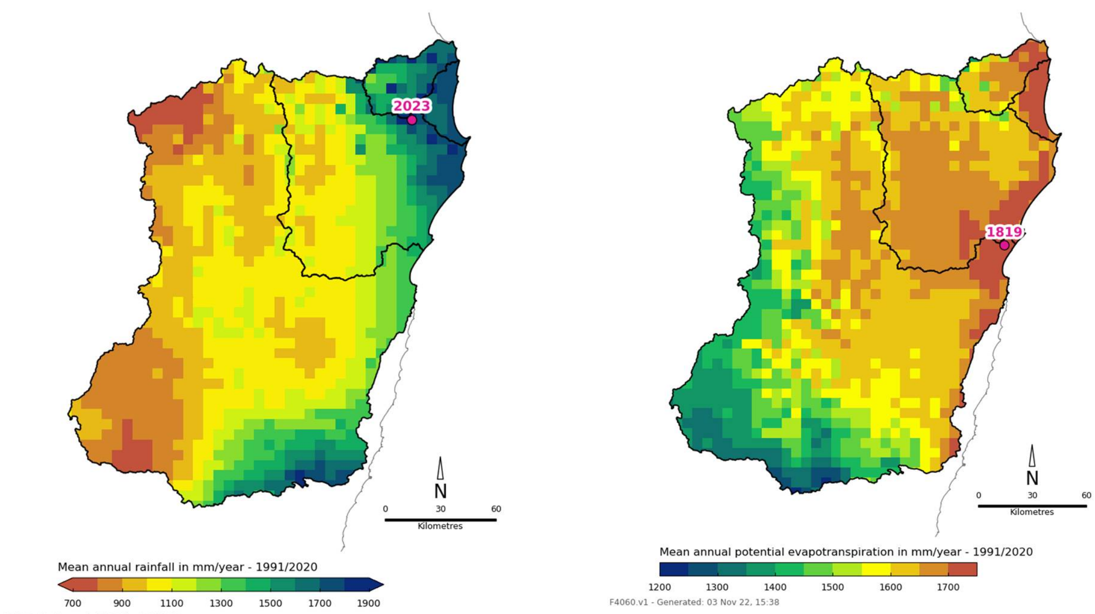

Figure 5 Mean annual rainfall and potential evapotranspiration for the 1991-2020 period. Maximum value in each map is shown as a pink dot.

Data source: Australian Water Outlook, BoM (2022c)

The monthly statistics for rainfall and PET averaged over the four basins in the region are shown in Figure 6. The seasonal distribution of both variables appears comparable in the four basins with the highest values occurring between December and March. The months of August and September correspond to the lowest rainfall and the lowest number of high intensity rainfall days (defined as days where rainfall exceeds 50 mm). Consequently, the water year is defined in this report with a start on the first of September to minimise the risk of splitting a flood event between two consecutive years.

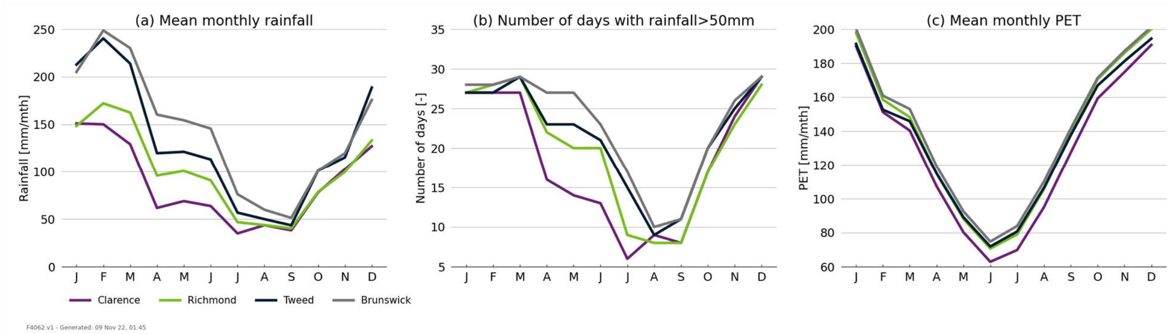

Figure 6 Monthly statistics for rainfall and potential evapotranspiration across the Northern Rivers region

Data source: Australian Water Outlook, BoM (2022c)

3.2.6 Rainfall extremes

Gridded statistics on rainfall extremes were obtained from the Intensity-Frequency-Duration dataset available from the Bureau of Meteorology website (BoM, 2016). Figure 7 shows the design rainfall values for Annual Exceedance Probability (AEP) of 1% and 0.1%, and for durations of 1 to 3 days. These values are used in section 5.3 to estimate the AEP of rainfall values during the 2022 flood.

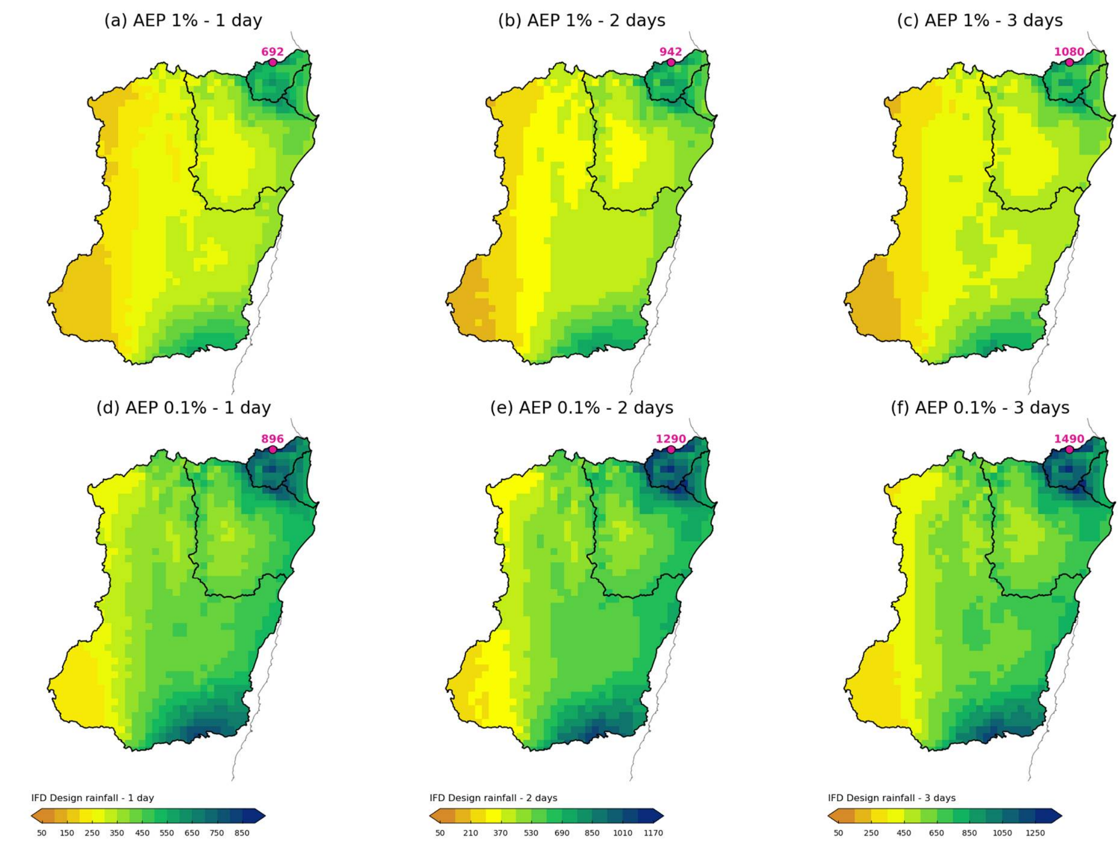

Figure 7 Intensity-Frequency-Duration rainfall data for 1, 2 and 3 days duration, 1% and 0.1% AEP. Maximum value in each plot is shown as a pink dot

Data source: Design Rainfall Data System, BoM (2016)

The rainfall extremes in Figure 7 present a similar spatial pattern to the mean annual rainfall shown in Figure 5 with the highest design rainfall values occurring in the South-East and North-East of the region.

3.3 Surface water in the Northern Rivers region

3.3.1 Surface water data

Surface water data considered in this report consist of water levels measuring the depth of water at a particular point in a river or floodplain, and streamflow data measuring the volume of water passing through a cross-section of a river per unit of time. Many other variables such as water temperature, turbidity or salinity are routinely measured by several data providers such as WaterNSW or Rous County Council to monitor water quality and support the management of environmental assets. Environmental issues associated with the 2022 flood are not covered in this report, consequently the presentation below is restricted to water level and streamflow.

Table 10 provides the list of stations from each data provider along with the number of stations retained and excluded from data analysis per basin. Detailed station lists are provided in appendices A and B.

Table 10 Number of active surface water stations retained for data analysis in this report

BASIN	WATERNSW STREAMFLOW GAUGING STATIONS		BOM WATER LEVEL STATIONS		WATERNSW/ MHL WATER LEVEL STATIONS	
	RETAINED	EXCLUDED	RETAINED	EXCLUDED	RETAINED	EXCLUDED
Clarence	29	3	0	31	13	0
Richmond	17	3	3	33	13	0
Tweed	5	0	0	20	9	0
Brunswick	2	0	0	16	6	0
TOTAL	53	6	3	100	41	0

Data source: Continuous Water Monitoring Network, WaterNSW (2022), Australia Rainfall and River Conditions, BoM (2022a) and Data Collection, Manly Hydraulics Laboratories (2022)

Water level stations

River water levels are measured across the region by WaterNSW as part of its surface water network, BoM in the context of flood warning and MHL for coastal monitoring purposes with stations located in the tidal influence zone. Additional stations are operated by councils to provide complementary flood warning information or support the management of water infrastructures such as dams.

As indicated in Table 10, most of the water level data from BoM are excluded from our data analysis because they are often redundant with stations from WaterNSW and MHL and possess shorter historical records. In addition, the water level data from BoM require significant quality control because they often exhibit spikes and short periods of missing data.

The station of Lismore (Rowing club, H058176) is an exception with no equivalent records available in both WaterNSW and MHL databases.

Four water level stations failed during the 2022 flood: Lismore (H058176), East Gundurimba (203427), Evans River at Fishing co-op (203462) and Rocky mouth Creek (203432). It is recommended to investigate these failures and strengthen the equipment for future flood events.

Streamflow gauging stations

WaterNSW is the only agency in the region providing streamflow data through its website or via direct requests. The process of acquiring streamflow data is a lot more complex than water level because it involves the conversion of water level data to streamflow via what is called a "rating curve". Examples of rating curve for the Wilsons River at Eltham (203014) are presented in Figure 8. A rating curve is built by collecting pairs of water level and streamflow measurements at the site called "gauging points" (green points in Figure 8.b) and fit a curve passing through these points. The process becomes highly uncertain beyond the maximum gauging point where the rating curve relies on extrapolation. Unfortunately, this is the part of the curve determining river flow during floods as can be seen in Figure 8.b with the pink square marking the streamflow corresponding to the 2022 flood at Eltham.

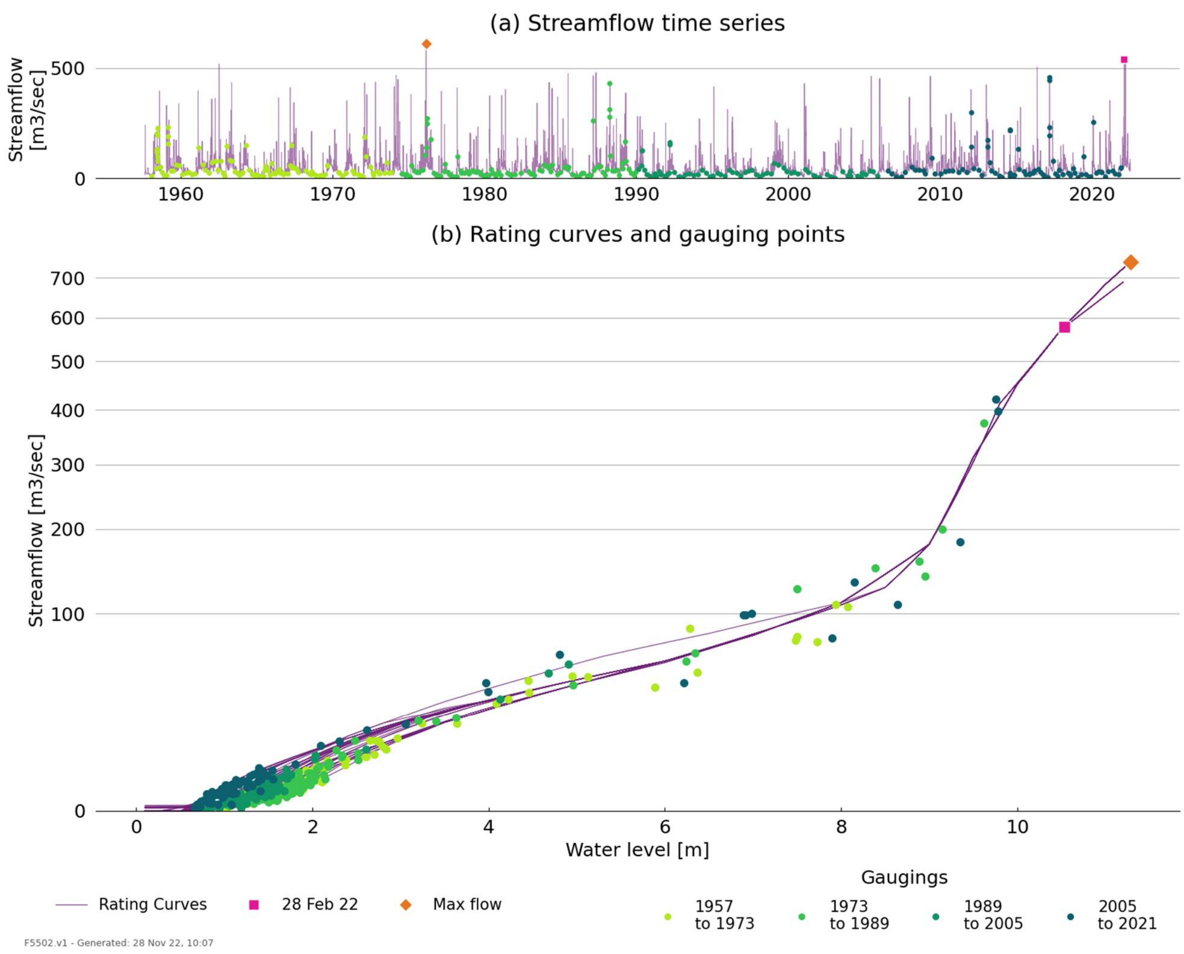

Figure 8 Streamflow data and rating curves for the Wilsons River at Eltham station (203014)

Data source: Continuous Water Monitoring Network, WaterNSW (2022)

The ratio between the maximum gauging and maximum observed streamflow is a simple measure of accuracy where a low ratio reflects a high proportion of rating curve extrapolation at the corresponding station. This ratio is plotted in Figure 9 for the stations in the region. Many stations, mostly in the Western part of the Clarence, have a ratio that is lower than 20%. These values indicate a very high level of extrapolation given that the minimum recommended ratio in the literature is around 50% (Rantz, 1982, p. 334). A more detailed assessment of streamflow extrapolation focused on the 2022 flood is presented in section 5.5.1.

To remediate this problem, it is possible to use a hydrodynamic model that can simulate both water level and streamflow. A modelled rating curve can subsequently be built by combining the model data with existing gaugings. Dore (2018) applied this approach to 12 stations upstream of Lismore using hydrodynamic models covering approximately 1 km of river upstream and downstream of each station. Dore (2018) reports very large discrepancies between current and proposed rating curves at certain stations including Eltham (Dore, 2018, Figure 20 p13). The work undertaken by Dore (2018) is important because it provides an objective review of rating curves for several important stations in the region. Similar work was also conducted for the Brunswick River at Durrumbul (202001) by Sharpe (2016) suggesting a large underestimation of high flows due to a gauge by-pass. However, the large corrections suggested by Dore (2018) and Sharpe (2016) could change streamflow data significantly and calls for more investigation beyond the scope of the present study. The building of a hydrodynamic model for the entire Richmond basin in the second part of this project can be used to complement and extend the work of Dore (2018).

Streamflow data uncertainty is explored in Appendix H using the simpler approach introduced by Kuczera (1996) and recommended by the Australian Rainfall and Runoff guidelines (Kuczera & Francks, 2019). In this approach, streamflow data above a certain threshold (set to the maximum gauged flow in our work) are associated with a fixed but unknown relative error. This error is sampled from a random distribution with a given scale set to 30% following Kuczera (1996).

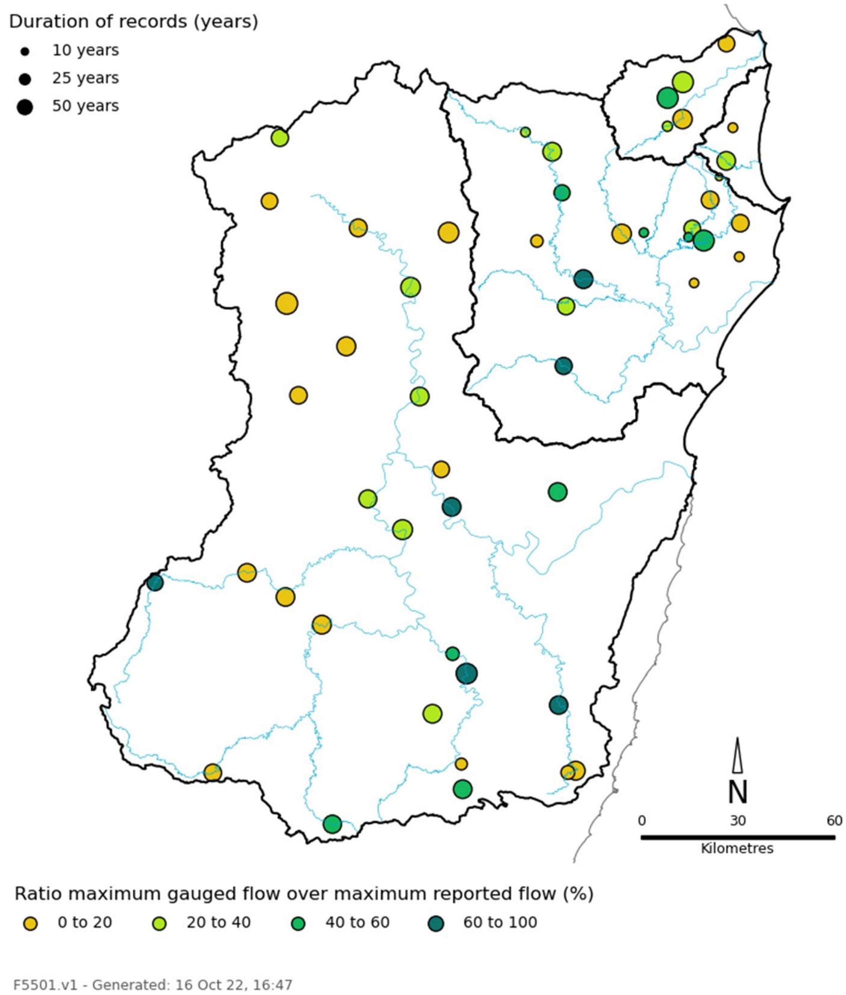

Figure 9 Active streamflow gauging stations in the Northern Rivers region

Data source: Continuous Water Monitoring Network, WaterNSW (2022)

AWRA-L landscape water balance model

The AWRA-L model was developed jointly by CSIRO and the Bureau of Meteorology to underpin several products generated by the Bureau of Meteorology as part of its water program (Hafeez et al., 2015; Vaze et al., 2013). AWRA-L underpins the Australian Water Outlook website (BoM, 2022c) that provides free of charge gridded simulations of surface water variables from 1911 until yesterday, seasonal forecasts (Vogel et al., 2021) and long-term projections at a 5 km grid scale for whole Australia. The model represents the main surface water processes including partitioning of rainfall between interception losses and net rainfall, saturation excess overland flow, infiltration and Hortonian overland flow, saturation, interflow, drainage, and evaporation from soil layers (Frost et al., 2018). It is calibrated against a range of variables at a national scale based on a single set of parameters and local landscape properties (e.g., soil hydraulic properties for different depths). The Bureau of Meteorology recently released version 7 of the model (Frost & Shokri, 2021). This version is still being evaluated by CSIRO. Consequently version 6 (Frost et al., 2018) is used in this report.

In the Northern Rivers region, the AWRA-L model was used by Cui et al. (2016) to compute water balance estimates for the Bioregional Assessment Program that looked at the impacts of coal seam gas and large coal mining developments on water resources and water-dependent assets over six bioregions.

The model has also been used by Bahramian et al. (2021) to initialise event-based hydrological models in the context of flood forecasting, and recently by Wasko et al. (2021) and Ho et al. (2022) to explore the impact of initial conditions on extreme floods.

The average performance of the AWRA-L model against streamflow data is summarised in Table 11 using standard hydrological metrics. Description of the metrics and performance for individual stations is provided in Appendix E. The performance appears satisfactory for a nationally calibrated hydrological model that was not adjusted to local conditions. Performance is best in the Richmond Basin and lowest in the Brunswick Basin, although the low number of stations in this basin may not be representative.

Table 11 Average performance of the AWRA-L model against observed streamflow data across the region

BASIN	NUMBER OF STATIONS	AVERAGE BIAS OF DAILY STREAMFLOW (-)	AVERAGE NSE OF DAILY STREAMFLOW (-)
CLARENCE	29	-0.13	0.6
RICHMOND	17	-0.07	0.64
TWEED	5	0.02	0.55
BRUNSWICK	2	0.42	0.4

Data source: Appendix E.

3.3.2 Surface water regime across the region

Surface water regimes are presented in Figure 10 using AWRA-L simulated runoff and rootzone soil moisture level averaged across the four basins in the Northern Rivers region.

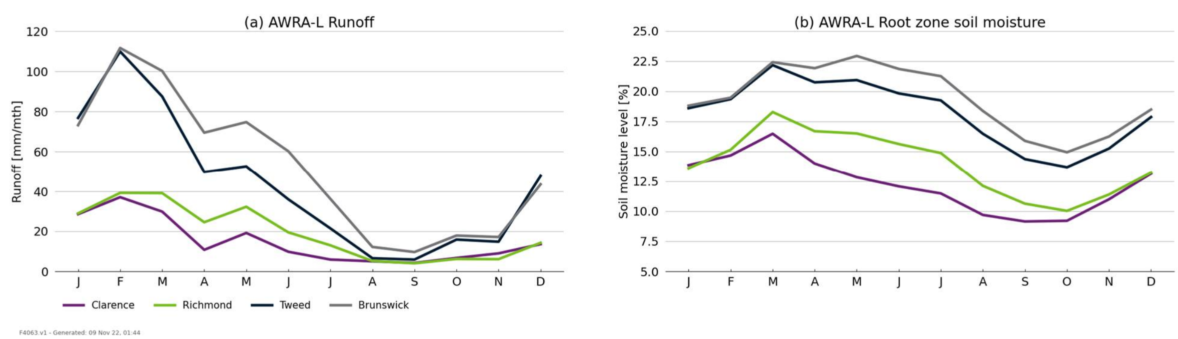

Figure 10 Mean monthly runoff and root zone soil moisture level for the four basins of the region

Data source: AWRA-L simulations, Australian Water Outlook, BoM (2022c)

Both variables broadly follow the seasonal rainfall pattern presented in Figure 6 with a high flow season between December and March.

3.4 Groundwater in the Northern Rivers region

3.4.1 Main groundwater formation

Rassam et al. (2014) describe three aquifer systems in the region: alluvial aquifer systems such as the Tweed and Richmond alluvium constitute one of the main sources of groundwater supply in the region. They present a high degree of connection with nearby rivers and creeks through recharge. Recharge can also occur from bedrock in the headwater areas where alluvial aquifers are incised deep into the Main Range Volcanics.

Bedrock aquifer systems such as the Alstonville Plateau basalt aquifer covering an area of approximately 400 km^2 between Lismore and Ballina are another key source of groundwater in the region.

Finally, the basement aquifer systems are low yield aquifer located in the basement blocks that limit the region. Limited data are available to characterise their hydrogeology.

3.4.2 Groundwater data

The groundwater data used in this report were sourced from the telemetered bores operated by WaterNSW. Four bores listed in Table 11 were chosen because of their location within both the alluvial and Alstonville Plateau basalts and the duration of their historical records.

Table 12 Groundwater bore selected for data analysis

BORE ID	NAME	AQUIFER SYSTEM	LONGITUDE	LATITUDE	RECORD DURATION (YEARS)
GW039117.1.1	Stratheden Road	Alluvial aquifer	152.941	-28.783	9
GW041005.1.1	Duck Creek Site 2	Alstonville Plateau Basalts	153.434	-28.864	16
GW081003.1.1	Astonville Central	Alstonville Plateau Basalts	153.434	-28.864	23
GW081006.1.1	Alstonville North	Alstonville Plateau Basalts	153.441	-28.825	23

Data source: Continuous Water Monitoring Network, WaterNSW (2022)

3.5 Estuaries and coastal data

Manly Hydraulics Laboratory provided data of wave height at one station (Byron Bay Waverider) and tidal data at four gauges detailed in Table 13.

Table 13 Tidal gauges selected for data analysis

STATION ID	NAME	LONGITUDE	LATITUDE	RECORD DURATION (YEARS)
201472	Tweed Entrance	153.55	-28.171	8
202403	Brunswick Heads	153.553	-28.537	36
203425	Ballina Breakwall	153.584	-28.875	14
204454	Yamba	153.362	-29.429	36

Data source: Data Collection, Manly Hydraulics Laboratories (2022)

4 Flooding in the Northern Rivers region

Northern Rivers region has a long history of devastating floods impacting cities such as Grafton and Lismore. Floods are part of the natural hydrological cycle and play a key role in sustaining ecosystems and landscape functions in the region. However, a particular combination of topographical and meteorological factors leads to flood events that are of large magnitude with volumes approaching the largest river flows in Australia, extremely fast where river flow can rise in less than 12 hours and occurring in wide floodplains leading to a significant potential for submerging riverine communities. This chapter provides an overview of the historical flood events in section 4.1 and an overview of flood modelling studies in section 4.2.

4.1 Overview of major historical flood events

Table 14 presents a brief overview of the major floods that affected the region since 1945. A longer list including minor events is provided in Appendix G. Summarising flood history over such a large and diverse area is a complex task, especially when selecting a few representative events. In Table 14, the events were selected based on the flood studies across the region described in the next section and based on the maximum of the daily basin average rainfall during each event derived from AGCD grids (see section 3.2.2). This variable has the advantage of covering the whole area and being available continuously for all recent floods. It has the disadvantage of averaging rainfall across large areas, especially for the Clarence Basin, and may mask localised high rainfall intensity during certain events. To facilitate analysing the data in Table 14, the top 3 events among the longer list of events provided in Appendix F is provided. Finally, the name of tropical cyclones is indicated when relevant.

Rainfall values summarised in Table 14 show that the 2022 flood is the highest on record in terms of maximum basin average rainfall for three out of four basins in the region.

Table 14 List of major flood events in the Northern Rivers region

NAME	START	END	MAXIMUM DAILY BASIN RAINFALL DURING THE EVENT (mm/day)				TROPICAL CYCLONE	COMMENT
			CLARENCE	RICHMOND	TWEED	BRUNSWICK		
Feb-54	16-Feb-54	2-Mar-54	186 *(#1)*	232 *(#2)*	284	253	TC137	Reference flood for all basins. Often cited as the largest flood on record prior to the 2022 event.
Jun-67	10-Jun-67	25-Jun-67	111	89	210	109		Major flood in the Clarence River.
Mar-74	6-Mar-74	25-Mar-74	108	150	223	243	Zoe	Major flood in the Clarence River, Richmond Basin including at Lismore and Tweed Basin.
Feb-76	10-Feb-76	10-Mar-76	130	155	222	202		Largest flood for most parts of the Clarence Basin and for the Wilsons River upstream of Lismore. Significant flood in the Western part of the Richmond Basin. Major flood in Lismore.
Mar-78	12-Mar-78	22-Mar-78	40	95	192	174		Major flood in Lismore, Tweed and Brunswick Basin.
Apr-89	30-Mar-89	10-Apr-89	85	165	327 *(#3)*	195		Major flood in the Clarence River, Lismore and Tweed Basin.
May-96	1-May-96	17-May-96	110	119	164	129		Major flood in the Clarence River and Richmond River.
Feb-01	25-Jan-01	12-Feb-01	104	188	287	314 *(#2)*		Major flood in the Clarence River and Richmond basins including Kyogle and Lismore.
Mar-01	8-Mar-01	25-Mar-01	145 *(#3)*	124	76	92		Major flood on the Clarence
Jan-08	31-Dec-07	20-Jan-08	80	122	191	130		Large flood affecting the Clarence and Richmond basins
May-09	20-May-09	10-Jun-09	142	147	145	166		Major flood in the Clarence River and Richmond basins including at Lismore.
Jan-12	21-Jan-12	31-Jan-12	53	64	174	114		Large flood affecting the Brunswick and Tweed basins
Jan-13	10-Jan-13	15-Feb-13	145 *(#2)*	138	259	226	Oswald	Largest flood on record in the Lower Clarence.
Jun-16	1-Jun-16	15-Jun-16	98	122	162	246		Major flood in the Tweed Basin
Apr-17	25-Mar-17	15-Apr-17	91	210 *(#3)*	368 *(#2)*	300 *(#3)*	Debbie	Significant flood in the Richmond, Tweed and Brunswick basins. Major flood in Lismore. Levee overtopped.
Feb-22	22-Feb-22	15-Mar-22	102	296 *(#1)*	414 *(#1)*	482 *(#1)*		Largest flood on record for most parts of Richmond, Tweed and Brunswick basins. Major flood in Grafton and along the Clarence River downstream.
Apr-22	24-Mar-22	10-Apr-22	77	116	175	165		Major flood in Lismore. Levee overtopped.

Data source: Appendix G, Australian Extreme Weather website (Bath & Deguara, 2022), AGCD rainfall grids, Australian Water Outlook, BoM (2022c)

4.2 Flood modelling studies

The seven LGA covering the region have undertaken targeted studies about major floods and their impact on the communities. Based on the information available in the NSW Flood Data Portal (NSW, 2022) and data provided by the LGA, a series of 77 studies related to flooding were identified in the region and listed in Appendix G. Conducting a detailed review of such a large body of scientific work spanning five decade of investigation is beyond the scope of the present report. This section presents high-level trends observed in the documents listed in Appendix G and a brief overview of modelling activities in the region. Discussions held with the LGA at the beginning of this project indicated that there are several initiatives across the region to update flood models and include the 2022 event. However, no report describing these updates was made available to CSIRO at the time of writing this report. Consequently, this section is based on studies already published and listed in Appendix G.

Table 15 lists the number of studies per basin and decade based on the list of Appendix G. These numbers increase significantly over time from about 10 studies per decade in the 80s to 30 studies in the 2010s. This trend is due in part to progresses with digitisation that see more studies being included in the NSW Data Portal for recent decades. However, it might also reveal an increasing pressure on LGA to address complex flooding issues that require more technical work. In Table 15, the Richmond Basin is the focus of half of the studies in the region, a figure that has not changed over the five decades. This can be explained by the combination of elevated flood hazard in the Basin with the presence of several important population centres along the main rivers such as Kyogle, Lismore, Casino, Coraki, Woodburn and Ballina.

Table 15 Number of studies per basins and decade in the region

BASIN	1980 to 1989	1990 to 1999	2000 to 2009	2010 to 2019	2020 to 2022
Clarence	4	4	8	6	
Richmond	6	3	13	15	1
Tweed	2	1	3	6	
Brunswick			2	3	
Total	12	8	26	30	1

Data source: Appendix G

The large number of studies published indicates that a significant flood modelling expertise exists in the region and covers a wide range of related topics. The reports listed in Appendix G demonstrate a detailed knowledge of hydro-meteorological data including their quality assessment and potential improvement (e.g. rating curves). The development, calibration and validation of event-based hydrological and hydrodynamic models is rigorous with a particular attention to collecting independent data, such as flood marks, to verify the plausibility of model results. Despite these positive aspects, two important limitations of existing studies were noted. First the modelling areas are often disjointed as shown in Figure 11 which maps the extent of hydrodynamic models used as part of published flood studies (not taking into account unpublished work currently on-going). In the Richmond Basin, several area specific models exist, and this makes it difficult to assess the impact of upstream flood mitigation measures on downstream areas.

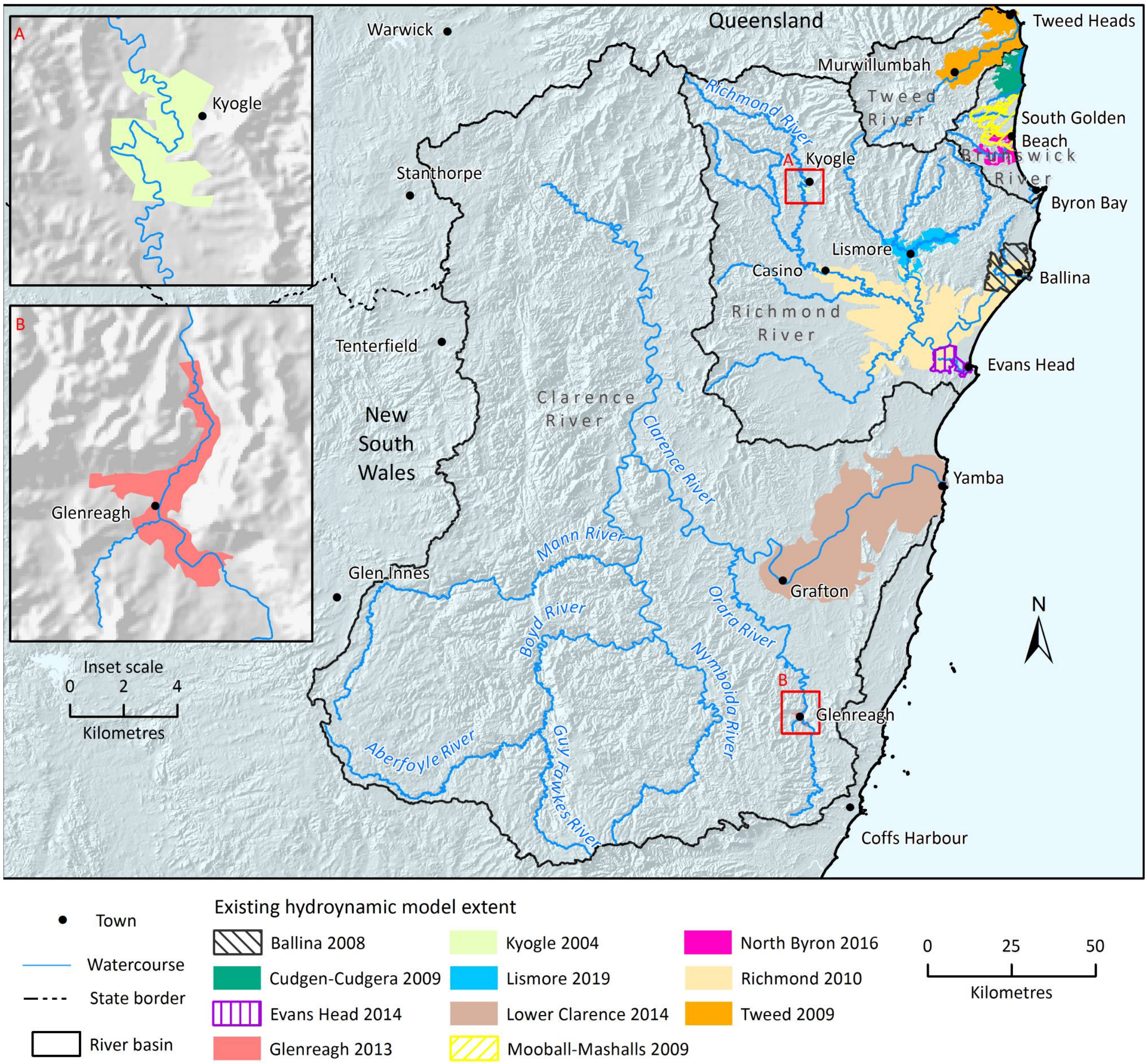

Figure 11 Extent of two-dimensional hydrodynamic models

The second part of the current project intends to improve this situation for the Richmond Basin by developing a single hydrodynamic model covering the floodplains of the Wilsons and Richmond rivers and their main tributaries.

A second point that was noticed in most flood studies in the region is the use of event-based hydrological models that are initialised with a limited (often one) set of initial conditions. Considering the complex effect of initial conditions on flood generation (see section 5.1 later in this report), we recommend including multiple scenarios of initial conditions in line with the recommendation of the ARR (Jordan et al., 2019a, section 3.2.3 and 3.2.4) and NSW Floodplain Management Guide (NSW, 2019, section 3.6.9) or even hybrid event based/continuous modelling (Jordan et al., 2019a, section 3.4) if the data permits. This is particularly important with floods in the Northern Rivers region where the combination of various initial conditions and rainfall pattern can lead to significantly different peak flows.

5 Analysis of the February/March 2022 flood event

This section explores the climatic and hydrologic factors that contributed to the 2022 flood. The event is analysed from different angles based on the data presented in the previous section starting with antecedent catchment conditions across the region before the flood started in section 5.1, then looking at climatic drivers from synoptic situation to hourly rainfall surfaces in section 5.2, and finally river water levels and streamflow in section 5.4. Sections 5.3 and 5.6 put this flood within a historical perspective by providing frequency analysis of rainfall totals and peak flows at key gauges across the region.

5.1 Antecedent conditions

Antecedent conditions encompass all the factors characterising catchment wetness before a flood starts. These conditions have a significant impact on flood generation as they are related to the amount of water that can infiltrate the soil and can be stored in the soil before generating runoff. In the case where catchments are wet, and hence when the soil is close to saturation, rainfall cannot be absorbed and majority of it gets converted to surface runoff, which then becomes river flow and potentially leads to flooding.

The importance of initial conditions in the generation of flood events is illustrated in Figure 12 which uses simulated data from the AWRA-L model to compare soil moisture level at the start of historical floods in the region (see Appendix F) with the runoff coefficient during the flood. The runoff coefficient is the ratio between the total runoff volume generated during the flood and the corresponding rainfall total. It characterises how much rainfall gets converted to runoff during a flood. In the four basins shown in Figure 12, a high degree of correlation can be seen between antecedent soil moisture conditions and runoff coefficients, particularly in the Clarence and Richmond basins highlighting the importance of these conditions in understanding a flood event.

Antecedent condition is not a well-defined hydrological concept because it cannot be directly measured through on-ground or remotely sensed observations. At best, it can be evaluated from different variables starting from the accumulated rainfall prior to the event, soil moisture and groundwater levels. In the following sections, antecedent conditions are analysed prior to the 22nd of February (start of the 2022 flood) as defined in section 1.2.2. Variables analysed in the following sections are compared with their long-term historical distribution to evaluate when they significantly differ from what is often seen in the region.

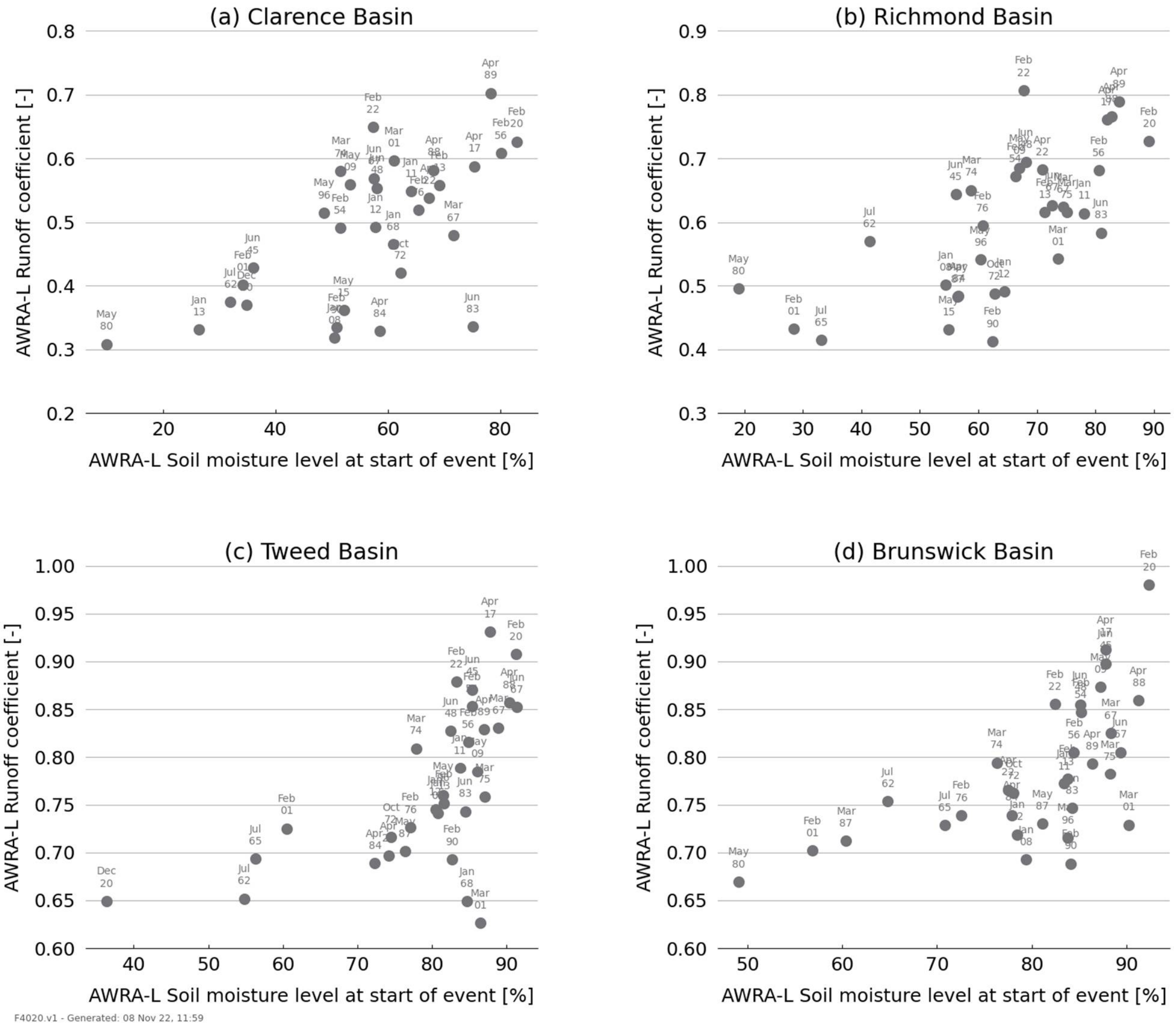

Figure 12 Comparison between initial soil moisture level and runoff coefficient for historical flood events in the region

Data source: AWRA-L simulations, Australian Water Outlook, BoM (2022c)

5.1.1 Rainfall

Using AGCD data (see section 3.2.2), Figure 13 presents the rainfall accumulated over 6, 3 and 1 month before the 2022 flood for the four basins in the region and the Wilsons catchment at Lismore. The figure compares this value shown, as a purple dot, against rainfall totals observed on the same day over the period 1911-2011 shown as grey areas. Figure 13.a and Figure 13.b suggest that 6 and 3 months totals were significantly higher than average prior to the 2022 flood for all basins with values between the 75th and 95th percentiles. The rainfall totals during the month prior to the flood were still wetter than average, but not to the same extend as during the previous months. The one-month totals were mostly between the long-term median and 75th percentile values.

All basins appeared to follow a similar trend. The Richmond basin and Wilsons River catchment at Lismore reached the highest 6-months rainfall totals in comparison to their historical distribution with values approaching the 95th percentile. The rainfall total for the month prior to

2022 flood for the Wilsons River catchment at Lismore is the closest to the 75^{th} percentile among all the other areas presented in the figure.

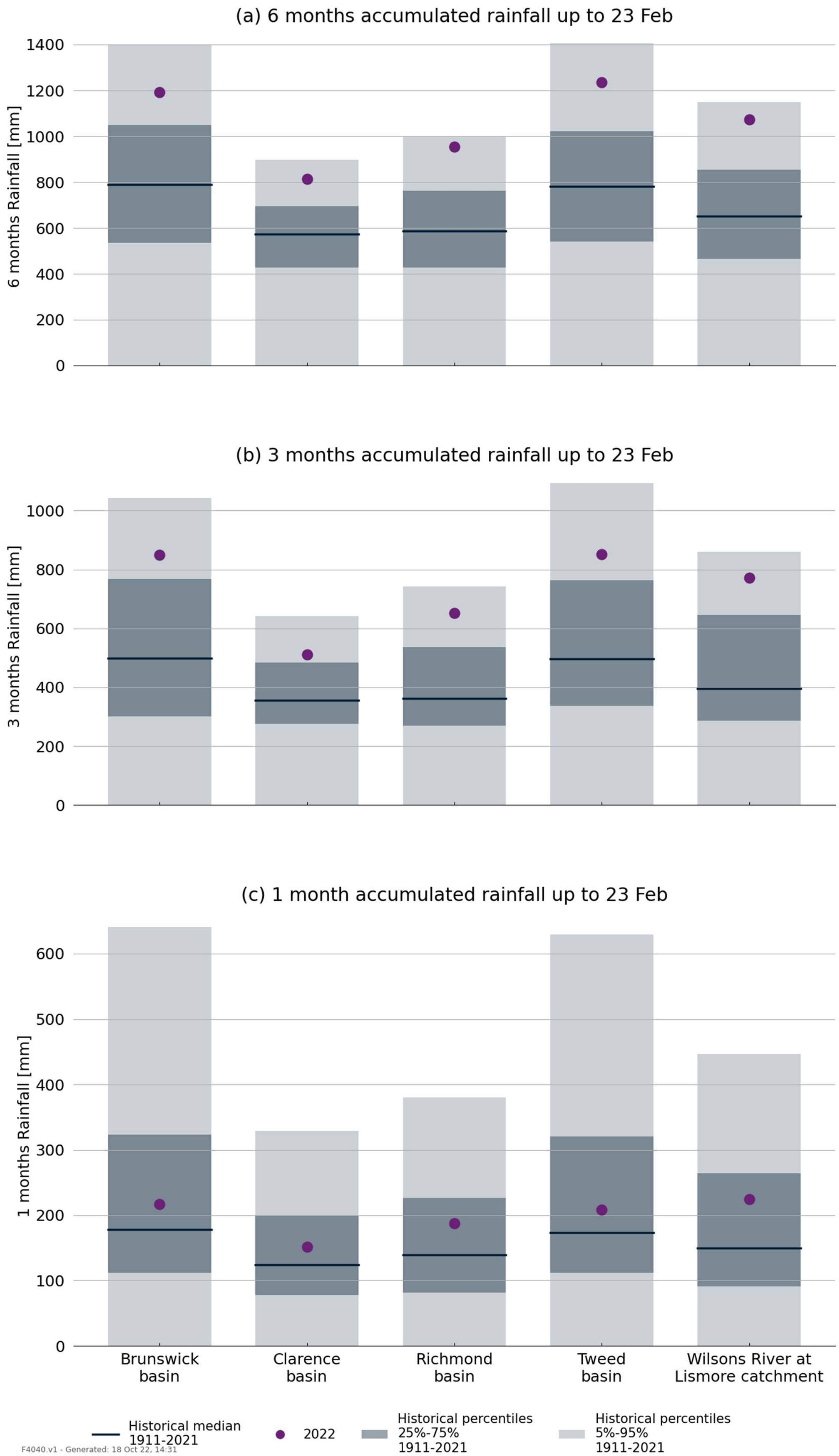

Figure 13 Rainfall totals prior to the 2022 floods across the Northern Rivers region

Data source: AGCD rainfall grids, Australian Water Outlook, BoM (2022c)

5.1.2 Soil moisture

Soil moisture filling level in the top 1 meter of soil (root zone soil layer) computed by the AWRA-L landscape model (see section 3.3.1) is shown in Figure 14. The figure includes soil moisture levels for the four basins in the region and for the Wilsons River catchment at Lismore. The same data is plotted in Figure 14.b for the Wilsons River catchment only against a background showing the its historical distribution for the 1911-2021 period.

In Figure 14.a, root zone soil moisture levels progressively increased from October 2021 to the end of February 2022, to reach values above 60% of soil storage capacity. The Tweed and Brunswick basins along with the Wilsons River catchment at Lismore were the wettest with values above 80% capacity by the 22nd of February. The Clarence Basin was the one with the lowest soil moisture level with values dropping below 60% just before the start of the flood on 22nd Feb 2022. On the contrary, the soil moisture level in the Wilsons River catchment at Lismore remained high from January 2022 onwards with values close to or above the 75th percentile as shown in Figure 14.b.

These data show that the soil moisture levels remained high across the region for several months prior to the 2022 flood. They reached particularly high values just prior to the flood.

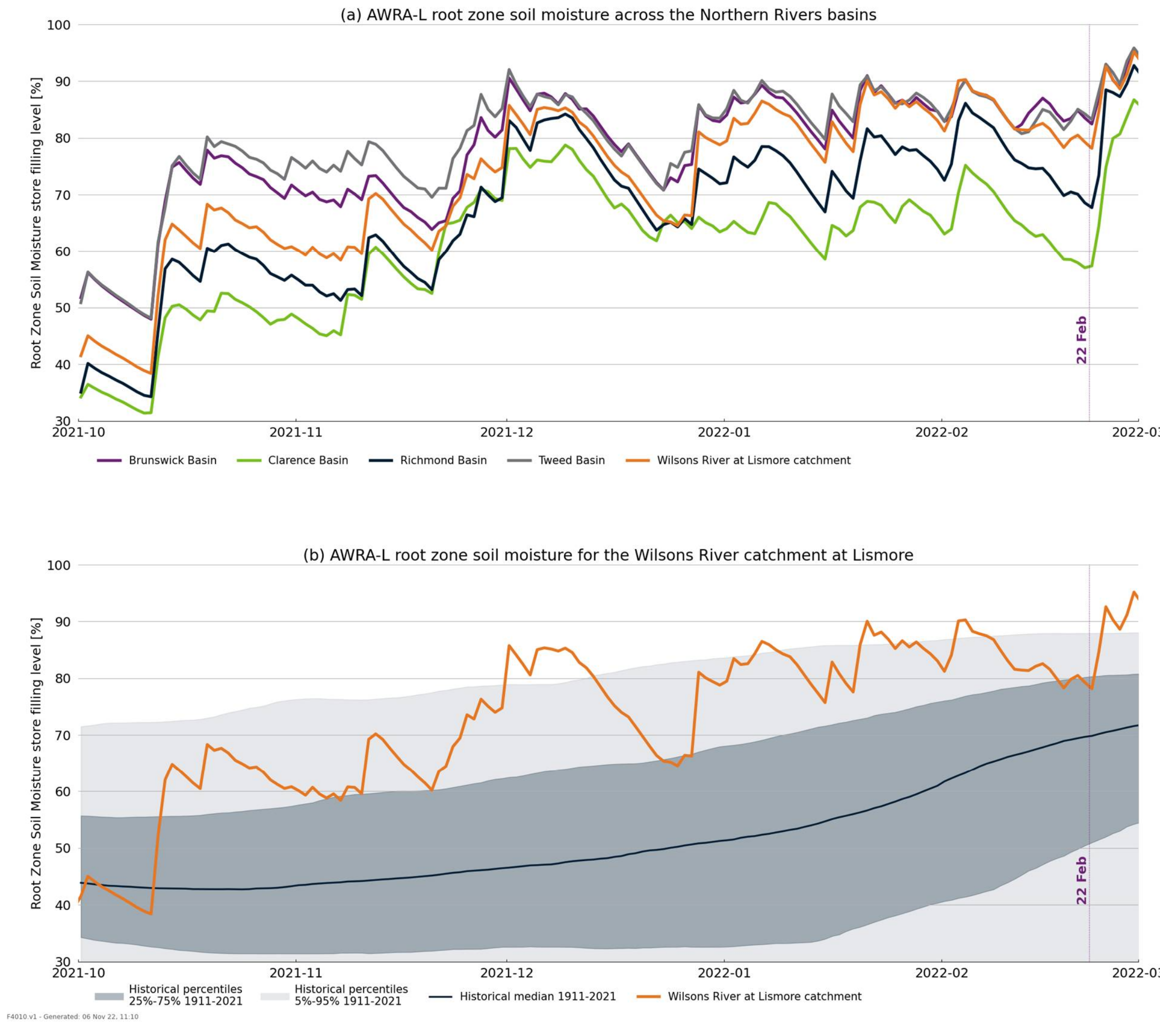

Figure 14 Filling level of the AWRA-L root zone soil moisture layer across the Northern Rivers region

Data source: AWRA-L simulations, Australian Water Outlook, BoM (2022c)

5.1.3 Groundwater

Groundwater level gives important indication on initial conditions affecting flood event, particularly for aquifers that are connected with surface water and generate significant baseflow when the rainfall ceases. Figure 15 shows groundwater level at four telemetered bores located in the Richmond Basin. The bores are selected due to their reasonably long records that allow a comparison between the water levels prior to the 2022 against average conditions (see 3.4.2). It is highlighted that three bores (GW041005.1.1, GW081003.1.1, GW081006.1.1) are screened in the formation of the Alstonville Basalt plateau with less direct connection to surface water than alluvial aquifers such as the one screened by the remaining bore GW039117.1.1. The measurement of water level in alluvial aquifers across the region remains limited and this constitutes a knowledge gap that could be addressed in future investigations.

In spite of these limitations, the groundwater levels shown in Figure 15 present similar patterns with the AWRA-L soil moisture data in Figure 14. Water levels remained higher than average for the two months prior to the 2022 flood with values ranging from the 75^{th} to the 95^{th} percentile.

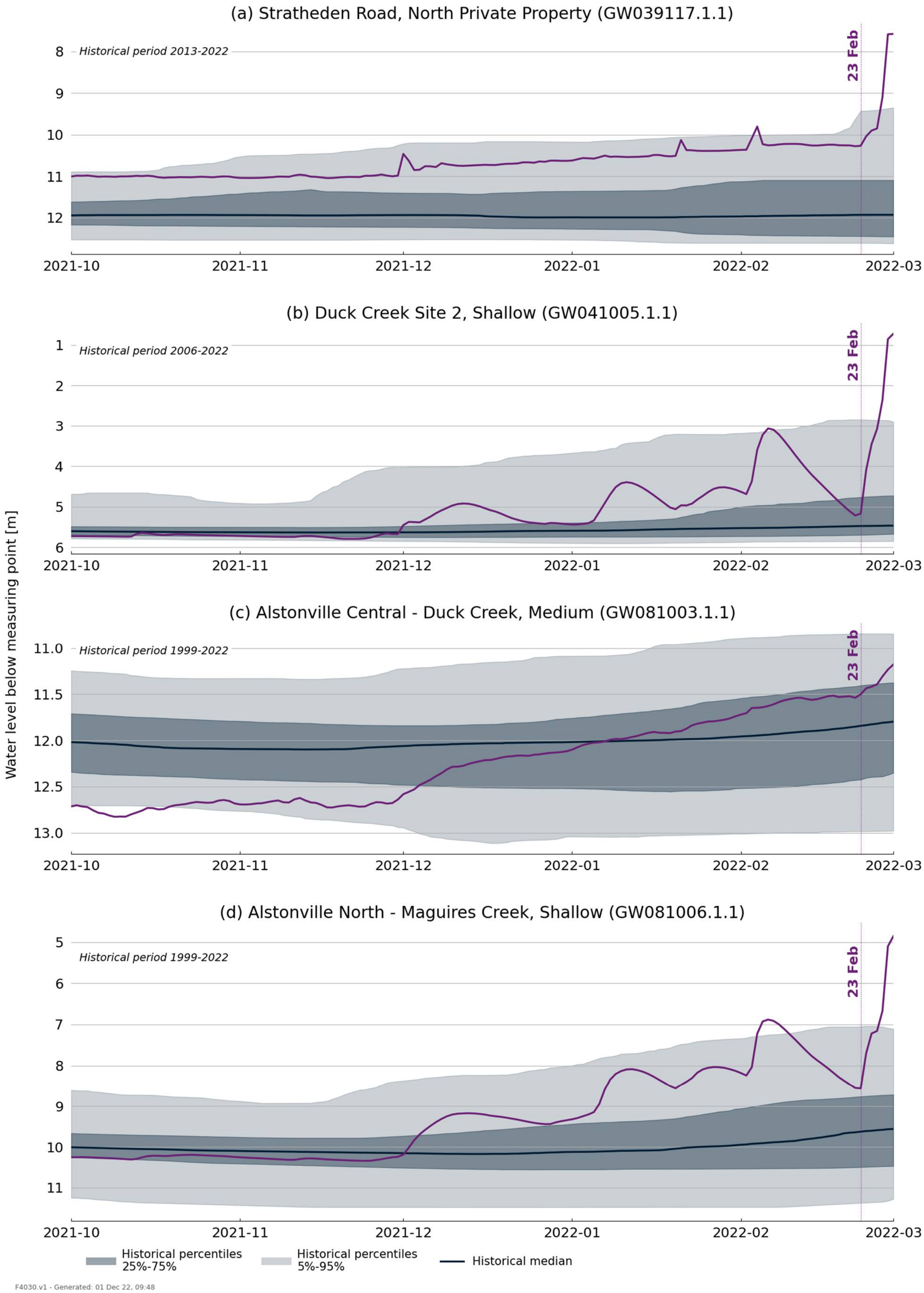

Figure 15 Groundwater levels prior to the 2022 flood events. The plots show the water level below the measuring points for four telemetered bores in the Richmond catchment.

Data source: Continuous Water Monitoring Network, WaterNSW (2022)

5.1.4 Summary of antecedent conditions prior to the 2022 flood

All variables analysed in this section suggest that antecedent conditions were significantly wetter than average across the region prior to the 2022 flood with rainfall totals, soil moisture and groundwater levels often exceeding their 75th historical percentile consistently during the two months preceding the flood.

5.2 Climate conditions during the event

This section analyses the climate conditions that occurred during the 2022 flood between the 22nd February and 15th March as defined in section 1.2.2. The section provides an overview of synoptic atmospheric conditions in section 5.2.1 and review rainfall totals in section 5.2.2.

5.2.1 Synoptic situation

According to the Bureau of Meteorology (BoM, 2022f): "The significant rainfall that affected the coastal regions east of the Great Dividing Range in south-eastern Queensland and eastern New South Wales, between 22nd February and 9th March 2022, resulted from a combination of weather systems. A blocking high pressure system near New Zealand, combined with a series of low-pressure systems, fed a large volume of tropical air over eastern Australia. Heavy rainfall developed in south-eastern Queensland and north-east New South Wales during late February and was drawn southwards at the start of March in response to a deepening east coast low."

Figure 16 shows the synoptic charts at 12 hours interval from the 27th of February until the 1st of March. In these charts, the low-pressure systems mentioned by the Bureau of Meteorology above can be seen in all charts except Figure 16.c. The low pressure moved off the coast on the first of March as can be seen in Figure 16.e and Figure 16.f. The blocking high is visible in all charts and represented as a high-pressure system West of New Zealand.

A more detailed analysis of the synoptic situation is provided by Goodwin (2022) who explains the extreme rainfall observed across the region during the 2022 flood by the blocking high mentioned previously, the warm ocean temperature, the slow moving atmospheric circulation and an inflow of moist air from Western Pacific. Goodwin (2022) also breaks down the event in three parts: first a hybrid tropical dip and subtropical low centred on South East QLD and Northern NSW between the 23rd and 28th of February, then an East Coast low between the 28th of February and 9th of March that made land fall in the mid-North Coast and followed the Eastern Australia coastline towards the South, and finally a second East Coast Low from 28th of March until 2nd of April 2022 that formed in South-East QLD and then moved South along the coastline. Among the three events, only the first and last contributed to the 2022 flood in the region.

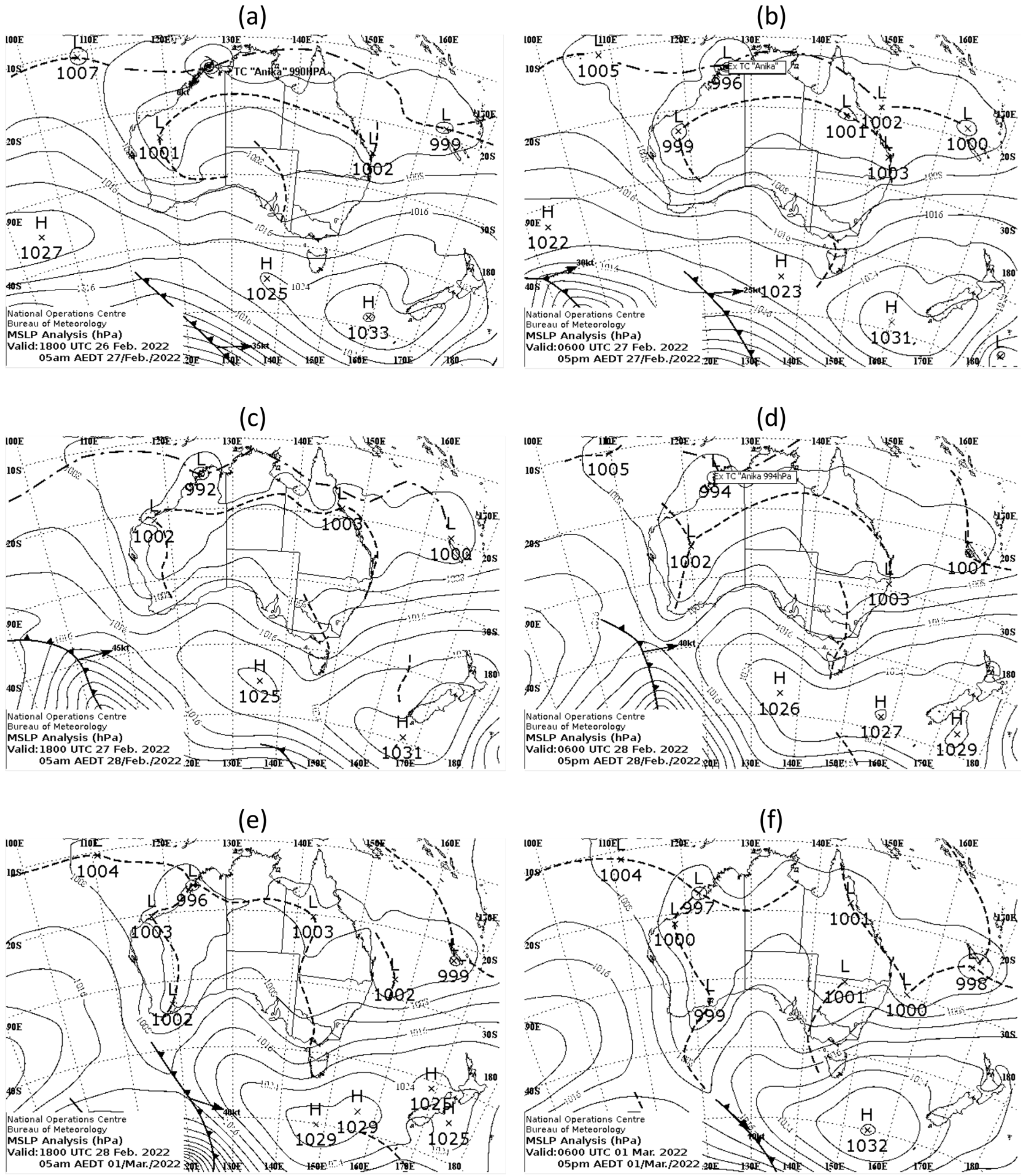

Figure 16 Mean Sea Level pressure charts for the 27, 28 February and 1 March 2022 at 6 AM and 6 PM generated by the Bureau of Meteorology

Data source: Mean Sea-Level Pressure Analysis, BoM (2022e)

5.2.2 Spatial and temporal distribution of rainfall during the 2022 flood

Figure 17 shows the spatial distribution of rainfall totals from the 22nd of February to the 15th of March (Figure 17.a), spatial distribution of maximum daily rainfall for the same period (Figure 17.b) and the dates corresponding to the maximum daily rainfall within the AGCD archive between 1911 and 2022.

Figure 17.a highlights the strong gradient between the extreme West of the Clarence Basin that received less than 100 mm over the whole event and the upper Wilsons catchment, Tweed and

Brunswick basins where rainfall totals exceeded 1700 mm. The highest rainfall total for the climate rain gauge network was observed at Doon Doon gauge (58019) with a value of 1717 mm. The highest value for the flood network was observed at Clarrie Hall dam gauge (H558028) and reached 1875 mm.

A similar West to North-East gradient characterises the maximum daily rainfall as shown in Figure 17.b. In this figure, the spatial gradient appears more pronounced than in Figure 17.a with high daily maximum concentrated in the central and East Richmond, Tweed and Brunswick Basins. The highest rainfall maximum for the climate rain gauge network was observed at Doon Doon gauge (58019) with a value of 758 mm (3rd highest daily rainfall recorded in NSW pending on quality assurance check by the Bureau of Meteorology). The highest value for the flood network was observed at Dunoon gauge (H558031) and reached 774 mm.

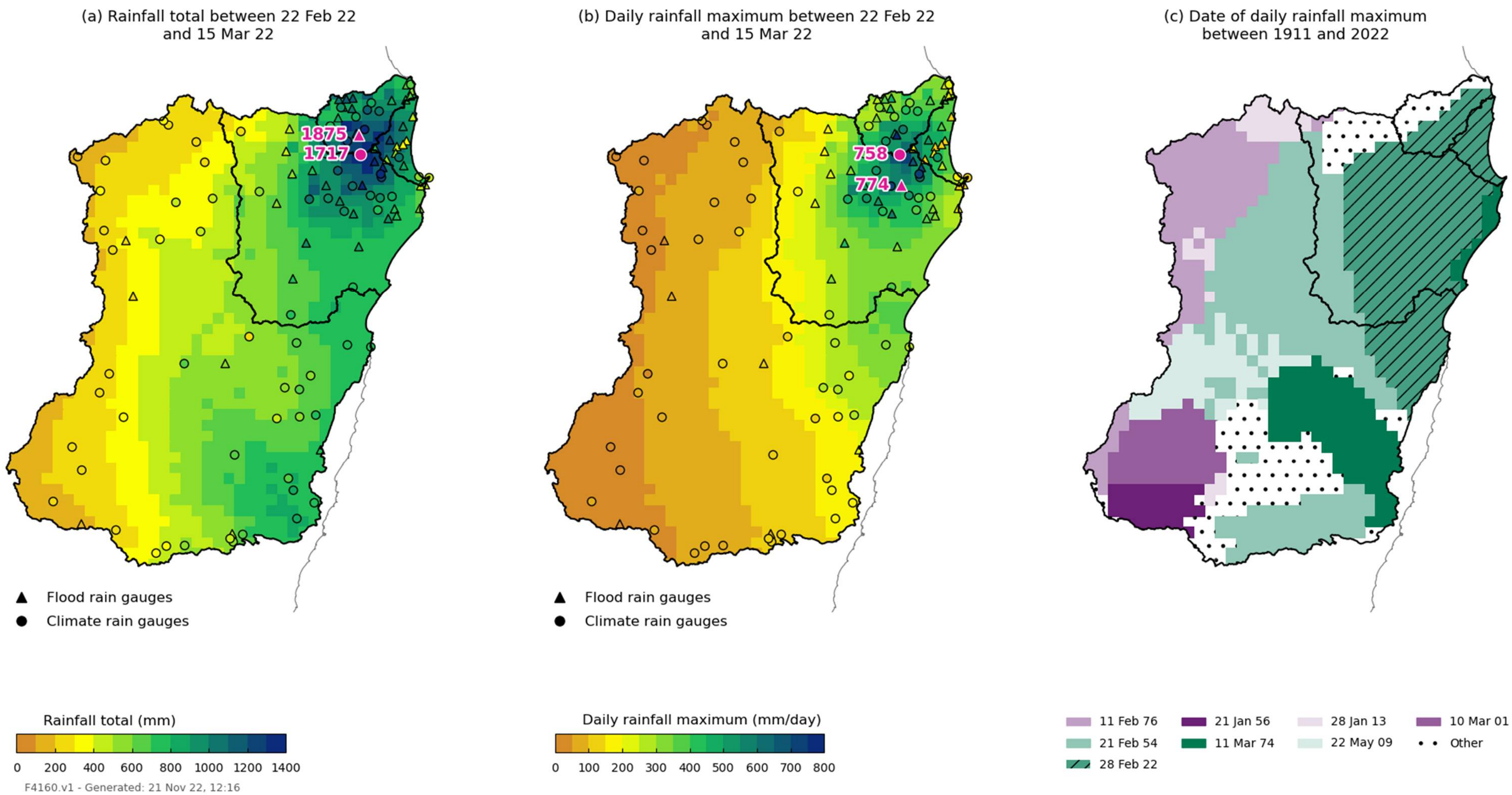

Figure 17 Rainfall total and daily maximum during the 2022 flood along with dates of maximum daily rainfall in the AGCD archive

Data source: AGCD rainfall grids, Australian Water Outlook, BoM (2022c), Climate Data Online, BoM (2022d) and Australia Rainfall and River Conditions, BoM (2022a)

Figure 17.a and Figure 17.b highlight the extreme rainfall values reached during the 2022 flood in the North-East of the region. Figure 17.c shows the spatial extent of this high intensity rainfall phenomenon by displaying the date of the maximum daily rainfall since the beginning of the AGCD archive in 1911. The grid cells where the daily maximum was reached on the 28th February are coloured in green and hatched. The 28th February rainfall was the highest since 1911 for the whole Brunswick Basin, most of the Tweed and Richmond basins and a fraction of the Clarence Basin close the river mouth that includes the towns of Mclean and Yamba.

A more detailed analysis was undertaken at sub-daily time step by developing interpolated hourly rainfall surfaces from the flood rain gauge as described in Section 3.2.3. These surfaces can be compared with radar rainfall from the rainfields product described in section 3.2.4. Figure 18 presents the rainfall surfaces corresponding to three timestamps during the 2022 flood: 24th February at 3 AM, 28th February at 3 AM and 28th February at 10 AM. The figure also shows the average rainfall for the Richmond Basin computed from the radar and interpolated rainfall surfaces.

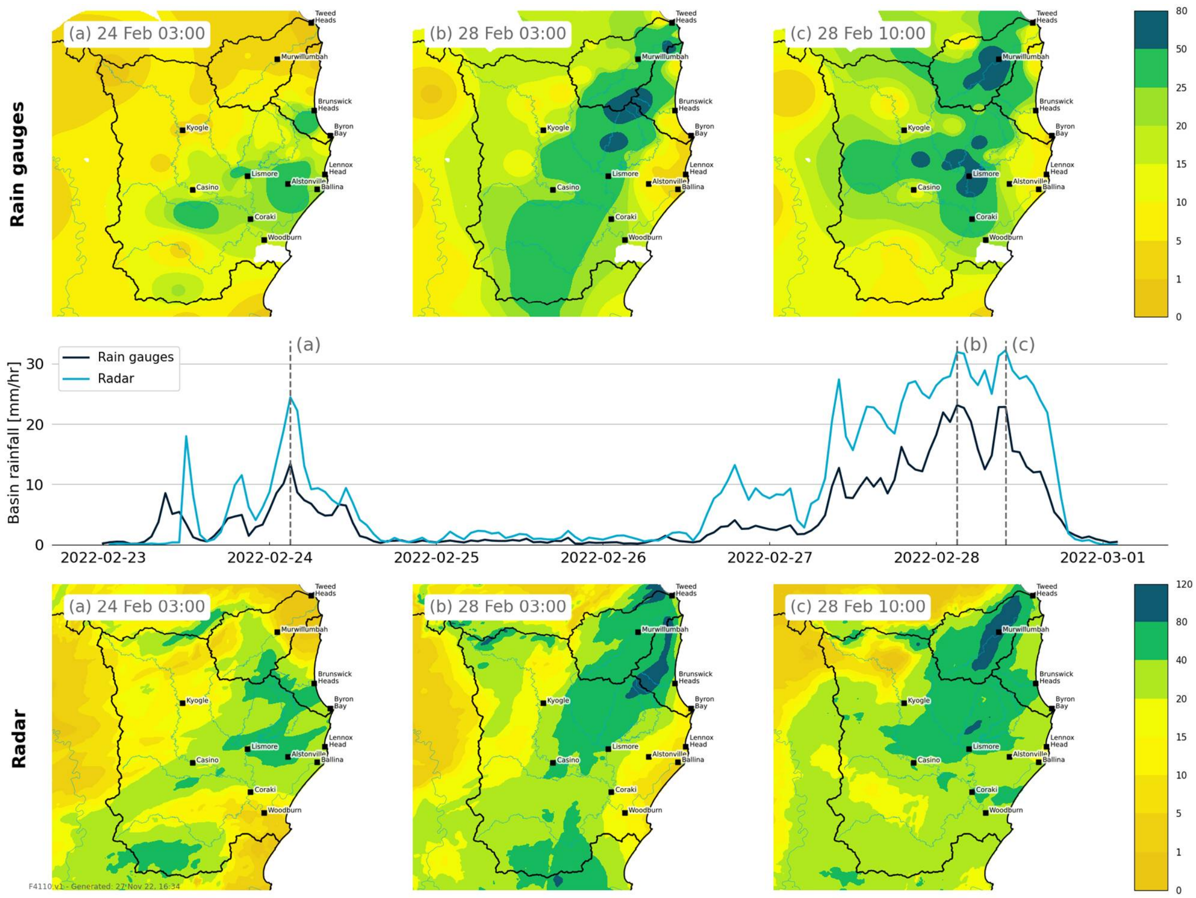

Figure 18 Hourly interpolated and radar rainfall across the Richmond Basin during the 2022 flood event

Data source: Rainfall data interpolation (Appendix C) and regridded radar data (Appendix D)

In the middle row plot of Figure 18, one can distinguish the two rainfall events mentioned by Goodwin (2022) and described in section 5.2.1. The first event started on the 23rd February and ended midday on the 24th February. It affected principally the Wilsons catchment, the lower Richmond Basin and the Southern part of the Brunswick Basin. The location and timing of this first event may have played a critical role in the generation of the 2022 flood as discussed further in section 5.4. The second event started midday on the 26th of February and ended on the morning the 1st of March. This event combined several rainfall bursts as can be seen in the middle row plot of Figure 18 which shows the rainfall surfaces for the largest two bursts that occurred at 3 AM and 10 AM on the 28th of February 2022. These bursts were centred on the upper Wilsons catchment and the Southern part of the Tweed Basin, but also covered most of the Brunswick Basin.

It should be noted that the interpolated rainfall and radar rainfall surfaces differ significantly in terms of their magnitude as can be seen in the middle row plot of Figure 18. However, they remain generally coherent regarding the timing and spatial extent of the rainfall bursts. More work is required to better blend both types of data into a consistent gridded hourly rainfall product as recommended in the conclusions of this report.

5.3 Frequency analysis of 2022 rainfall

This section aims at estimating the Annual Exceedance Probability of rainfall totals during the 2022 flood across the region. The reader is referred to section 1.2.5 for a brief introduction to the concepts underlying frequency analysis.

Frequency analysis for rain gauges in the Richmond, Tweed and Brunswick Basins are provided by Dakin (2022) based on Intensity-Frequency-Duration (IFD, see Figure 7) data published by the Bureau of Meteorology (BoM, 2016). These results are not repeated here. They confirmed the exceptional nature of the 2022 flood event for certain gauges such as the Dunoon gauge (H558031) where 24 hours rainfall is reported with an AEP lower than the 0.05% threshold (Dakin, 2022, p. 119). As indicated in section 3.2.1, these AEP estimates should be treated with caution if the data used at the gauge was limited to the records available from the Bureau of Meteorology which spans less than 16 years only (see Appendix A).

Estimates of AEP for individual rain gauges are important, but not sufficient to characterise a flood event due to the aggregation of point rainfall across catchments during the generation of river flows. The spatial distribution of rainfall frequency for the 2022 flood is analysed based on the gridded IFD data which provide estimates of rainfall AEP at a 0.025 degrees resolution (approximately 2.5 km) across Australia. These gridded data are combined with the AGCD daily rainfall grids to obtain an estimate of the AEP of the 2022 flood for 24- and 72-hours rainfall maximum.

It is important to note that three approximations are used in this process. First, the AGCD and IFD grids do not have the same resolution and a re-gridding process is applied to convert IFD grids to AGCD resolution via a nearest neighbour approach. Second, the AGCD rainfall data are computed from 9:00 am to 9:00 am every day. These data are often referred to as “restricted” compared to “unrestricted” daily maximum computed from a moving window during the day. The difference between the two types of data was mitigated by multiplying AGCD rainfall by a correction factor set to 1.15 following Jakob et al. (2005). A comparison (not shown) against hourly grids generated from flood gauge interpolation presented in section3.2.3 suggested that a value of 1.15 is reasonable for the 2022 event on average, but shows significant spatial variations. Finally, the IFD grids provide design rainfall for predefined AEP values[4] which were interpolated linearly to obtain an AEP for the 2022 event in every grid cell in the region. Note that this approach cannot provide AEP estimates beyond the lowest AEP threshold of the IFD grid (0.05%).

The AEP estimates obtained through this process are useful to assess the spatial distribution of rainfall frequencies as part of a rapid assessment, but cannot be used to support a flood modelling study which would require the characterisation of the associated uncertainty.

Despite these limitations, Figure 19 shows the 24h and 72h rainfall maximum Figure 19.a and Figure 19.b, respectively. The corresponding AEP are shown in Figure 19.c and Figure 19.d. In Figure 19.a and b, the highest rainfall totals occurred in the upper Wilsons River catchment at the boundary between the Wilsons River catchment, the Tweed and Brunswick basins. Figure 19.c and d reveal that the most extreme rainfall in a statistical sense (i.e. lowest AEP) were observed in the centre of the Wilsons River catchment around Lismore, in the mid-Richmond around Casino and in the area close to the Clarence River mouth. This fact suggests that the placement of the 2022 rainfall cell was distinct from most past events with high rainfall occurring at low altitude and close to urban areas.

[4] AEP values available in IFD are 50%, 20%, 10%, 5%, 2%, 1%, 0.5%, 0.2%, 0.1% and 0.05%, see BoM. (2016). *Design Rainfall Data System*. http://www.bom.gov.au/water/designRainfalls/revised-ifd/ .

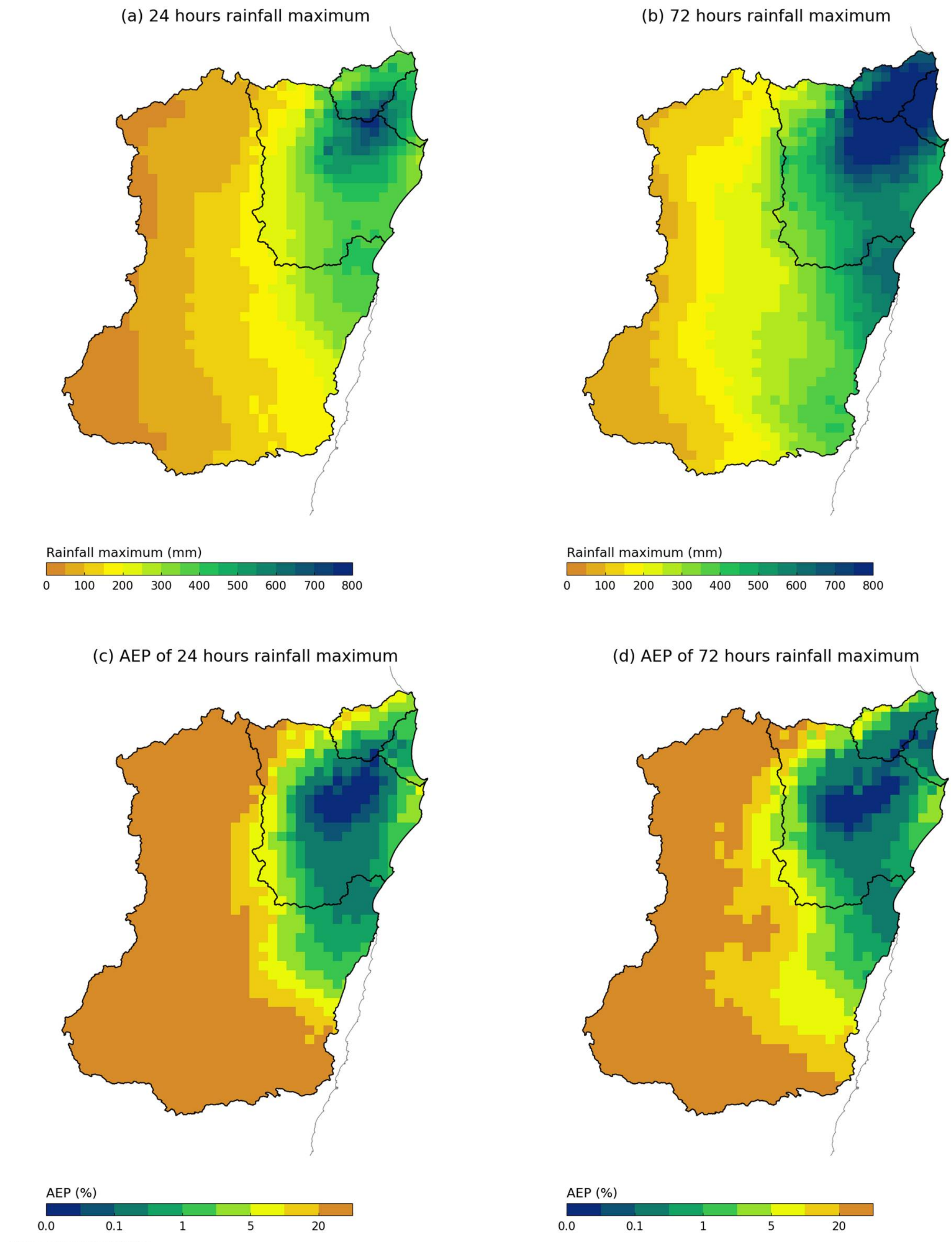

Figure 19 Frequency analysis of 24 hours and 72 hours rainfall maximum for the 2022 flood

Data source: Design Rainfall Data System, BoM (2016), AGCD rainfall grids, Australian Water Outlook, BoM (2022c)

It is useful to compare the previous findings derived from point rainfall with results for catchment average rainfall. AEP of catchment average rainfall can differ significantly from point rainfall for event that affects a small fraction of the catchment. The conversion from point to catchment rainfall AEP is described by Jordan et al. (2019a, Equation 2.4.2 and Table 2.4.2) and involves the calculation of areal correction factors. Estimation of the 2022 catchment average rainfall AEP is presented in Table 16 where correction factors are applied in combination with the factor needed to convert restricted rainfall (9:00 am to 9:00 am) to unrestricted rainfall (maximum sliding window) discussed in the previous paragraph.

Table 16 AEP of catchment rainfall maximums for the 2022 event

BASIN	STATION ID	NAME	24 HOURS			72 HOURS		
			RESTRICTED RAINFALL MAXIMUM (MM)	UNRESTRICTED RAINFALL MAXIMUM (MM)*	AEP (%)**	RESTRICTED RAINFALL MAXIMUM (MM)	UNRESTRICTED RAINFALL MAXIMUM (MM)*	AEP (%)**
Clarence								
	204002	Clarence River At Tabulam	58.3	67	>50	132.9	152.8	28
	204067	Gordon Brook At Fineflower	139.9	160.8	11.5	214.6	246.8	14
	204055	Sportsmans Creek At Gurranang Siding	223.4	256.9	1.9	300.9	346	4.4
Richmond								
	H058176	Lismore	462.4	531.7	<0.05	683.4	785.9	<0.05
	203061	Goolmangar Creek At Mcnamara Bridge Weir	489.9	563.4	<0.05	738.9	849.7	0.1
	H058147	The Channon	563.4	647.9	<0.05	829.8	954.3	<0.05
	203024	Coopers Creek At Ewing Bridge	531.7	611.5	<0.05	776	892.4	0.1
	203010	Leycester River At Rock Valley	434.8	500.1	0.1	669.2	769.6	0.1
	203014	Wilsons River At Eltham	435.7	501	0.2	642	738.3	0.3
	203004	Richmond River At Casino	198.3	228	3.5	345	396.7	1.7
	203041	Shannon Brook At Yorklea	204.4	235.1	2.4	344.1	395.7	1.4
	203030	Myrtle Creek At Rappville	188.1	216.3	3.9	293.8	337.9	4.3
Tweed								
	201900	Tweed River At Uki	516.4	593.9	0.2	853	980.9	0.1
Brunswick								
	202001	Brunswick River At Durrumbul	605.6	696.5	0.1	978.1	1124.9	0.1

Data source: Design Rainfall Data System, BoM (2016), AGCD rainfall grids, Australian Water Outlook, BoM (2022c).
* Correction factor to convert restricted (9:00 am to 9:00 am) to unrestricted data was set to 1.15 following Jakob et al. (2005).
** AEP estimates include an areal correction factor described in Jordan et al. (2019a, Equation 2.4.2).

Table 16 confirms the extreme nature of the 2022 rainfall for the Goolmangar Creek catchment at Mcnamara Bridge (203061), Terania Creek at the Channon (H058176), Coopers Creek at Ewing Bridge (203024) and Wilsons River at the Lismore gauge (H058176) where 24 hours totals exceeded the 0.05% AEP threshold which corresponds to a 1 in 2000 years event. The 24 hours totals remain extreme for the Leycester Creek at Rock Valley (203010), Wilsons River at Eltham

(203014), Tweed River at Uki (201900) and Brunswick River at Durrumbul (202001) with AEP varying between 0.1% and 0.2%.

For 72 hours rainfall aggregation, the Terania Creek catchment at the Channon and the Wilsons River at Lismore shows the most extreme rainfall with a total larger than the 0.05% AEP event. This suggests that the rainfall remained exceptionally intense for a prolonged duration over both catchments.

Overall, the rainfall totals were less extreme in the Clarence basin except in its lower parts represented by the Sportsman Creek catchment at Gurranang Siding (204055) where rainfall totals reached an AEP of 1.9% for 24 hours duration and 4.4% for 72 hours duration.

5.4 Summary of climate conditions

The climate conditions characterising the 2022 flood event can be summarised as follows:

- A rainfall event affected the region between the 23rd of February and the 1st of March and reached the highest daily total in the AGCD archive since 1911 in most parts of the Richmond, Tweed and Brunswick.
- The event was centred on the mid-Richmond and Wilsons River catchment around Lismore where it generated maximum daily rainfall values that were significantly larger than a 1% AEP event.
- The event was split into several bursts with the first between the 23rd and 25th of February. A sequence of bursts followed between the evening of the 27th and the evening of the 28th.

5.5 River levels and flows during the 2022 flood

Water level and river flows in the region reacted strongly to the torrential rains of the 2022 flood described in the previous section. The flood was characterised by a first peak of smaller magnitude between the 24th and 25th of February, followed by a second peak that exceeded historical flood levels in many parts across the region and reached its maximum between the afternoon of the 28th February for upstream areas and the 2nd of March closer to the rivers outlet.

The river levels and flows are presented in section 5.5.1 with streamflow data for stations described in section 3.3.1. Streamflow is the most important variable in describing a flood event because it is not affected by the local topography and can be compared between sites (e.g. to identify losses or gains along a river). However, streamflow measurements are costly and complex, and are generally limited to sites with stable hydraulic characteristics.

When streamflow is not available, water levels provide the best data to understand flood propagation. Consequently, the description of the 2022 flood provided in section 5.5.2 covers water level data for areas with no streamflow measurement, often located below the tidal limit.

Finally, section 5.5.3 concludes by discussing ocean conditions based on wave and tides data.

5.5.1 Streamflow

Figure 20 provides an overview of the maximum streamflow values reached for different gauges during the 2022 flood across the region. Figure 20.a is a map of the ratio between this maximum and the maximum streamflow ever recorded at the same station. This map correlates with the high intensity rainfall areas identified in Figure 19 and centred on the Wilsons River catchment and the mid-Richmond Basins. In these areas, the peak streamflow during the 2022 flood represents the highest streamflow on record for a number of stations (see also Table 23 in Appendix A).

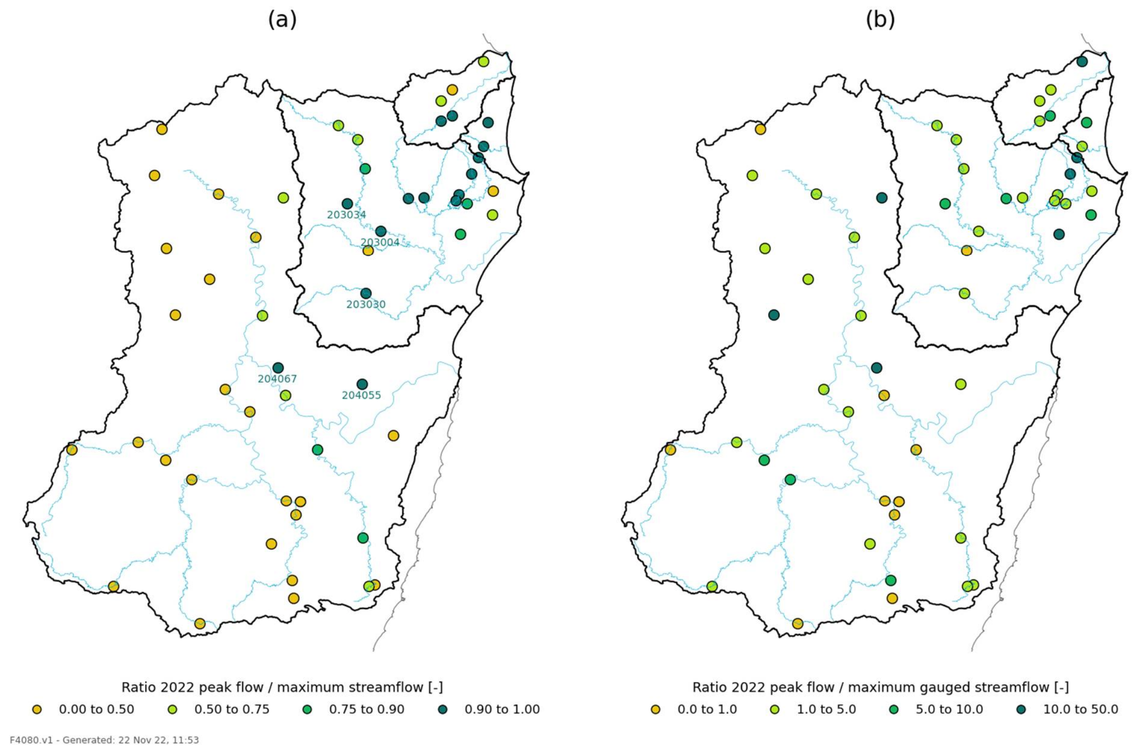

Figure 20 Peak flow of 2022 flood compared to maximum streamflow (figure a) and maximum gauged streamflow (figure b) for streamflow gauging stations across the Northern Rivers region

Data source: Continuous Water Monitoring Network, WaterNSW (2022)

Figure 20.a also suggests that certain catchments such as Eden Creek at Doubtful (203034), Myrtle Creek at Rappville (203030), Gordon Brook at Fineflower (204067) and Sportsman Creek at Gurranang Siding (204055) reached their highest streamflow on record during the 2022 event despite not being close to the centre of the high rainfall intensity areas. Considering the number of stations that failed during the 2022 event as shown in Figure 4, it is likely that the rainfall over these catchments was underestimated.

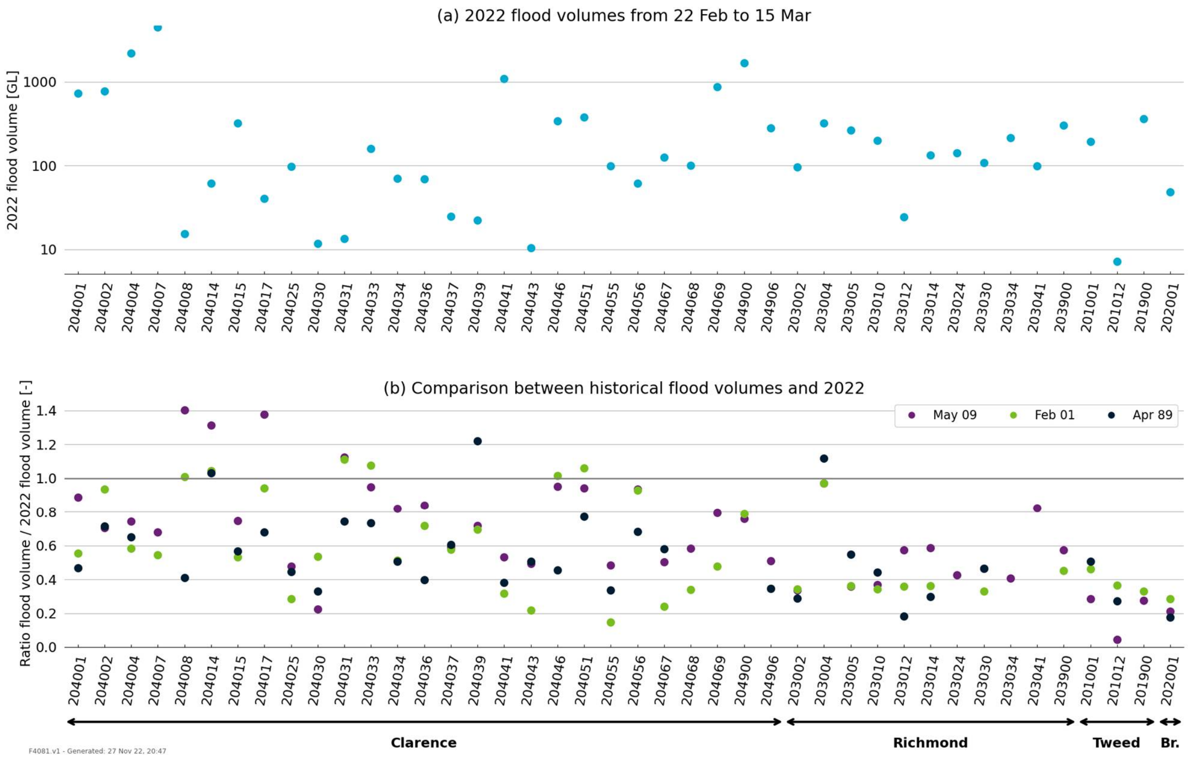

Figure 21 Flood volumes for the 2022 flood at streamflow gauging stations across the Northern Rivers region

Data source: Continuous Water Monitoring Network, WaterNSW (2022)

The high peak flow values discussed in the previous two paragraphs were accompanied by large flood volumes as can be seen in Figure 21.a which presents the total streamflow volumes that passed through the gauging stations in the region between the 22nd February and 15th March 2022. The volumes for other floods are computed as the total streamflow between the dates indicated in Appendix F.

It is remarkable that those volumes are approaching or exceeding 100 GL for many stations, which represents a considerable amount of flow within such a short period of time. However, the region has seen other large floods and it is useful to analyse the ratio between historical flood volumes and the volume of the 2022 event (Figure 21.b). A value of the ratio lower than 1 indicates that the volume of the 2022 event was larger than the one of historical floods, which is the case of most stations in the Richmond, Tweed and Brunswick basins. In these three basins, the ratio is often lower than 0.5, indicating that the volume of the 2022 flood was twice as large as the ones from historical floods. The Richmond River at Casino (203004) and Byron Creek at Binna Burra (203012) appear to be outliers compared to other surrounding stations. Regarding Casino, the station stopped functioning during the peak of the 2022 flood and the exact flood volume cannot be determined precisely at this gauge. It is almost certain that the Casino 2022 flood volume was higher that what is reported in Figure 21.b. No issue was detected related to Binna Burra.

A peculiar fact was identified related to the streamflow time series upstream of Lismore and their peak timing during the 2022 flood. Table 17 reports the peak time differences between the Woodlawn College station (203402) located just upstream of Lismore on the Wilsons River and the stations of Eltham on the Wilsons River (203014), Rock Valley on the Leycester Creek

(203010), Ewing Bridge on the Coopers Creek (203024) and McNamara bridge on the Goolmangar Creek (203061). The peak time differences are computed for the recent floods listed in Appendix F. The Woodlawn College station was chosen to represent the peak time in Lismore. It was preferred to the Rowing club station (H058176) which stopped functioning during the 2022 flood.

Table 17 Peak time difference between the Woodlawn College station on the Wilsons River and upstream gauging stations

FLOOD EVENT	PEAK WATER LEVEL AT WOODLAWN COLLEGE (203402) (m)	PEAK TIME DIFFERENCE ELTHAM (203014) / WOODLAWN COLLEGE (203402) (hours)	PEAK TIME DIFFERENCE ROCK VALLEY (203010) / WOODLAWN COLLEGE (203402) (hours)	PEAK TIME DIFFERENCE EWING BRIDGE (203024) / WOODLAWN COLLEGE (203402) (hours)	PEAK TIME DIFFERENCE MCNAMARA BRIDGE WEIR (203061) / WOODLAWN COLLEGE (203402) (hours)
Jun-83	8.8	14.4	21.5	18.4	-
Apr-84	10.3	17.5	19.7	8.5	-
Mar-87	10.7	13.6	12.3	-	-
May-87	11.0	10.3	13.0	-	-
Apr-88	9.8	12.9	12.9	-	-
Apr-89	11.5	0.5	16.5	-	-
May-96	8.4	3.0	16.8	48.0	-
Feb-01	10.9	15.8	17.2	-	-
Mar-01	8.8	9.2	14.8	-	-
Mar-04	7.9	10.2	20.5	15.5	-
Jun-05	11.0	7.7	8.8	17.8	-
Jan-08	9.6	30.0	11.0	33.5	-
May-09	10.8	11.0	12.8	14.5	-
Jan-11	5.6	10.8	16.0	-7.2	-
Jan-12	8.7	12.5	23.2	20.5	19.2
Jan-13	10.0	16.8	23.0	19.2	8.0
Feb-13	8.6	8.8	15.8	19.0	15.8
May-15	8.1	5.5	16.0	15.2	14.2
Jun-16	9.8	11.2	15.8	13.2	7.0
Apr-17	12.2	2.0	9.5	6.8	14.0
Feb-20	8.3	8.5	13.0	19.8	13.2
Dec-20	7.7	4.8	14.8	13.2	14.2
Feb-22	*15.0*	*-0.8*	*-1.5*	*5.8*	*5.8*
Apr-22	11.9	6.5	27.8	6.0	25.8
Average	**9.8**	**10.1**	**15.5**	**16.0**	**13.7**

Data source: Data Collection, Manly Hydraulics Laboratories (2022)

Table 17 reveals that the 2022 flood is the only event where the peak time difference between Woodlawn College and the two stations of Eltham and Rock Valley is negative. In other words, the 2022 peak at Woodlawn College occurred before the peak at these two upstream stations. The 2022 peak time difference for the McNamara station was the lowest on record and it was the second lowest for the Ewing Bridge station. The lowest on record for this last station was a negative value of -7.2 hours that occurred during the January 2011 flood. However, this flood was a double peak flood at Ewing Bridge which leads to ambiguity in the determination of the peak time difference. Consequently, it can be said that the 2022 flood has the lowest or close to the lowest peak time difference between Woodlawn College and the four upstream stations.

This is a remarkable fact that highlights the unusually fast propagation of the 2022 flood along the Wilsons River and its tributaries upstream of Lismore. One of the plausible explanations for this phenomenon is that the 2022 weather system described in 5.2.1 and 5.2.2 affected lower parts of the Wilsons catchment compared to other floods where rainfall occurred at higher elevation. This did not seem to happen during the 2022 flood where the most extreme rainfall values as per their Annual Exceedance Probability (see section 5.3) were centred around Lismore or immediately upstream. In this case, a significant fraction of the river flow that fed the Wilsons River and its tributaries upstream of Lismore was generated from areas immediately upstream of Lismore with a reduced concentration time compared to other floods.

The NRRI team recently conducted four weeks of stakeholder/community consultations in the Northern Rivers region. In the discussions with the Lismore and surrounding community and there understanding of the 2022 flood event (based on what they observed, and some privately collected rainfall data), The Channon and surrounding areas recorded rainfall totals of around 950mm in 18 to 24 hours. Another hydrologically plausible explanation for this phenomenon is that the extremely high runoff generated by the heavy rainfall in The Channon and surrounding areas drained via the Terania Creek which joins Leycester Creek downstream of the gauge at Rock Valley on the Leycester Creek (203010) (used in this analysis). The streamflow gauge on Terania Creek is not functional and so this flow was not recorded. This may also explain why the recorded flows at Lismore were so much higher in the 2022 event than other historical floods.

Understanding more about this point would require an estimate of the Wilsons River flow at Lismore (currently not measured) to confirm if significant flow gains occurred between Lismore and the upstream gauging stations mentioned above.

5.5.2 Water levels

The water levels during the 2022 flood broke historical records at many locations, especially in Lismore where the water reached 14.37 m at 13:55 on the 28th of February (Bureau of Meteorology station H058176). The station stopped functioning immediately after reaching this value. As a result, it is not known if this value has not been exceeded during the following hours. Comparison with water levels at the Woodlawn College that peaked at 14:45 with a value of 15.02 m suggests that the Lismore water level had reached or was close to its peak at 13:55.

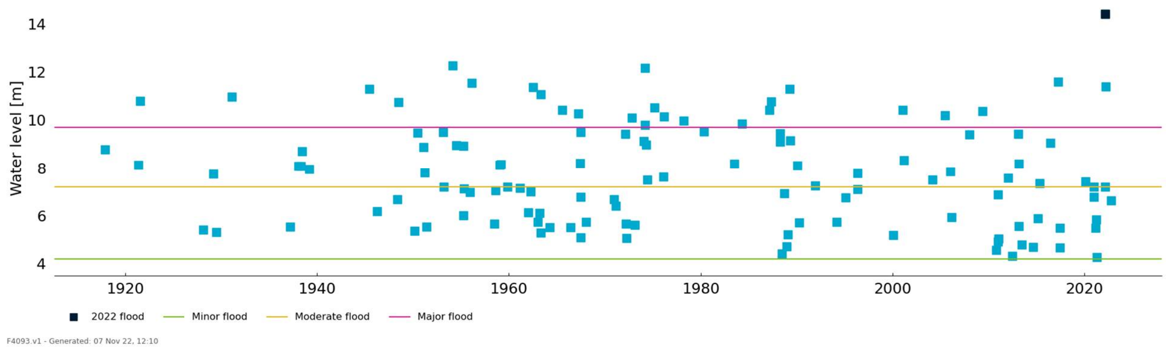

Figure 22 Water levels of historical floods at the Lismore gauge (Rowing Club, H058176)

Data source: Australian Severe Weather website (Bath & Deguara, 2022)

This value is the highest on record by a significant margin for the Lismore gauge where water levels have been measured since the beginning of the 20th Century as shown in Figure 22.

Water levels across the region are shown in Figure 23 with hydrographs above the major flood level highlighted in yellow for the stations where such a classification exists.

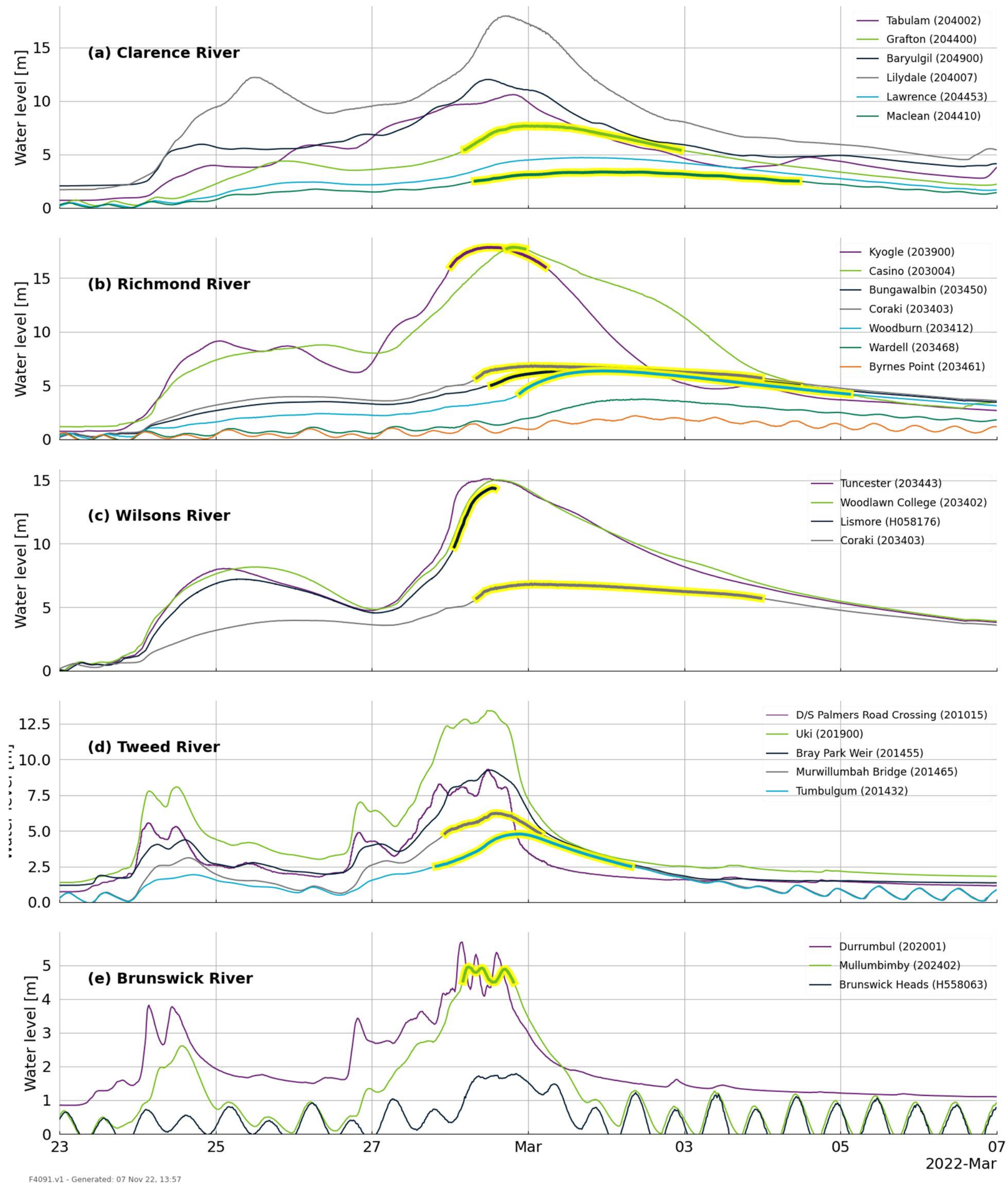

Figure 23 Hydrographs of the 2022 flood across the Northern Rivers region. The highlighted lines correspond to period when the water level was above the major flood level.

Data source: Continuous Water Monitoring Network, WaterNSW (2022), Australia Rainfall and River Conditions, BoM (2022a) and Data Collection, Manly Hydraulics Laboratories (2022)

Figure 23 shows that many stations crossed the major flood level in the four basins for durations varying between 12 hours for the Brunswick River at Mullumbimby (202402) up to more than 48 hours for the Richmond River at Wardell (203468). The major flood threshold was exceeded by more than 2 m at Grafton (7.67 m peak with a threshold of 5.4 m), Lismore (14.37 m peak, 9.7 m threshold), Woodburn (6.36 m peak, 4.2 threshold) and Tumbulgum (4.78 m peak, 2.5 m threshold).

Most hydrographs in Figure 23 include a double peak with a first event of smaller amplitude on the 24th and 25th followed by the second larger event from the 27th until the beginning of March. The first event was triggered by a rainfall event described in section 5.2.2. It had an important role in creating elevated hydraulic conditions in the Wilsons and Richmond floodplains when the second event started.

This point is explored in Figure 24 where the Lismore hydrograph is shown with three timestamps highlighted during the 2017 and 2022 flood (Figure 24.a and Figure 24.b). These timestamps are positioned on the rising limb of the hydrograph and correspond to the instant when the hydrograph crossed the 5m level. For each of these timestamps, Figure 24.c shows a longitudinal river profile along the Wilsons and Richmond Rivers from Lismore to Woodburn. The first two profiles coincide completely, which suggests that the hydraulic state of the floodplain was similar at the beginning of the 2017 event (Profile #1) and at the beginning of the first peak in 2022 (Profile #2). The third profile (Profile #3) coincide with the other two for the Lismore and East Gundurimba stations but diverges significantly downstream with water levels nearly 2m above at Coraki and 1m above in Woodburn. This fact suggests that the water levels in the flood plain at the beginning of the second peak were much higher than for the two other timestamps. In other words, large volumes of water were filling the floodplain downstream of Lismore at the beginning of the second peak, potentially reducing its capacity to propagate the flood and imposing an elevated downstream boundary condition. This may have aggravated the flooding in Lismore at subsequent times.

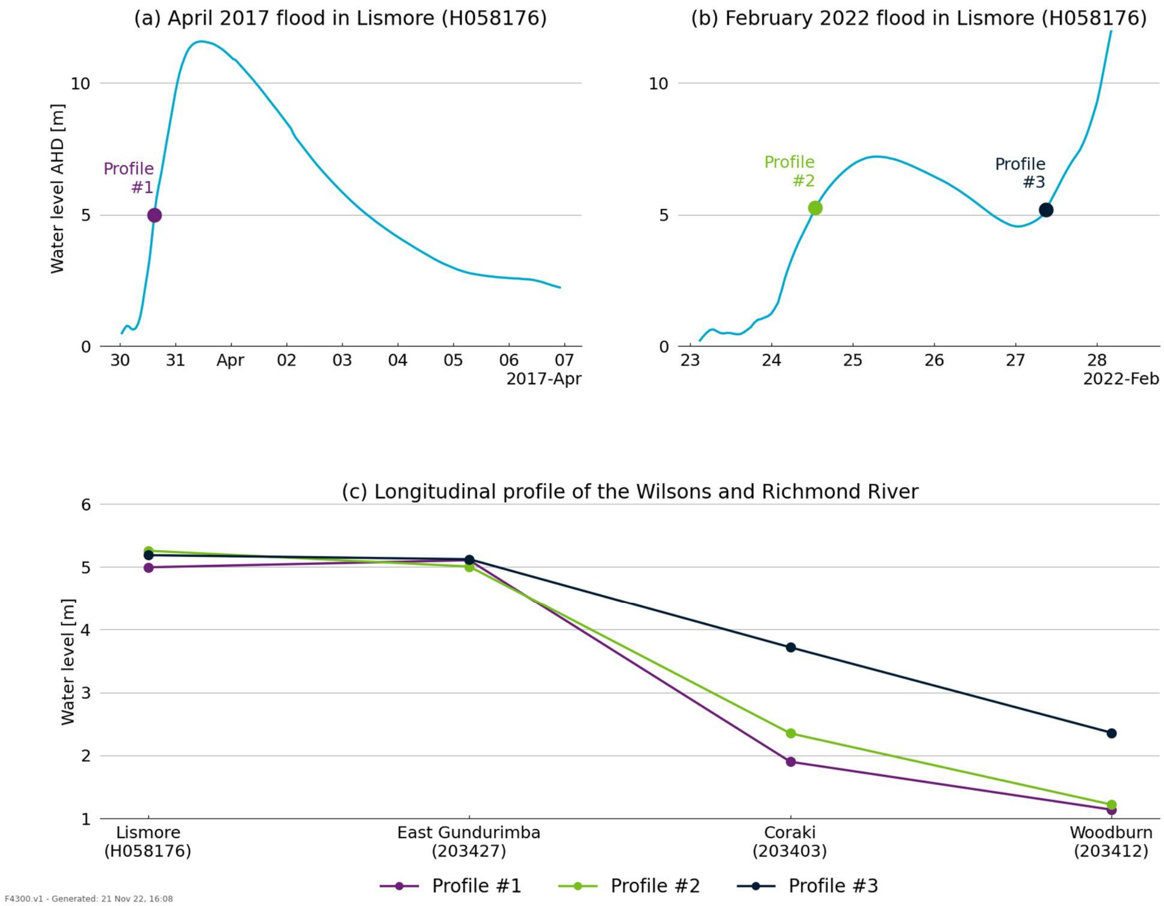

Figure 24 Longitudinal profiles of the Wilsons River during the rising limb of the 2017 and 2022 floods

Data source: Australia Rainfall and River Conditions, BoM (2022a) and Data Collection, Manly Hydraulics Laboratories (2022)

5.5.3 Ocean wave heights and tide data

As indicated in section 3.1, the Northern Rivers region is characterised by large floodplains that are connected to the ocean with significant impact of tidal fluctuations on water levels. During storm surges, elevated ocean conditions impose higher water levels at the rivers outlet which propagates upstream through a backwater effect. Figure 25 shows ocean conditions during the 2022 flood by plotting time series of wave heights at the Byron Bay Waverider buoy and tidal levels at the tidal gauges of Tweed Entrance (201472), Brunswick Head (202403), Ballina Breakwall (203425) and Yamba (204454).

Figure 25.a shows that the wave heights increased significantly in the early morning of the 28th February to reach levels above the 95th percentile of their historical distribution over the period 1976-2022. Fortunately, these levels remained 3m below their historical maximum and receded below the 95th percentile at mid-day on the 28th. At the same time, the level at the four tidal gauges started increasing to reach their maximum on the evening of the 28th of February for Brunswick Head and on 1st of March for the other gauges.

The slight timing offset between wave heights and the rise of tidal levels might have avoided a dangerous situation where storm surge aligns with water level peaks to generate elevated water level at the outlet of the rivers. It is acknowledged that the wave height data used here does not constitute an accurate estimation of storm surge. Additional data about tides and mean sea-level pressure would be required to better characterise the presence of a storm surge or not (Freeman et al., 2020).

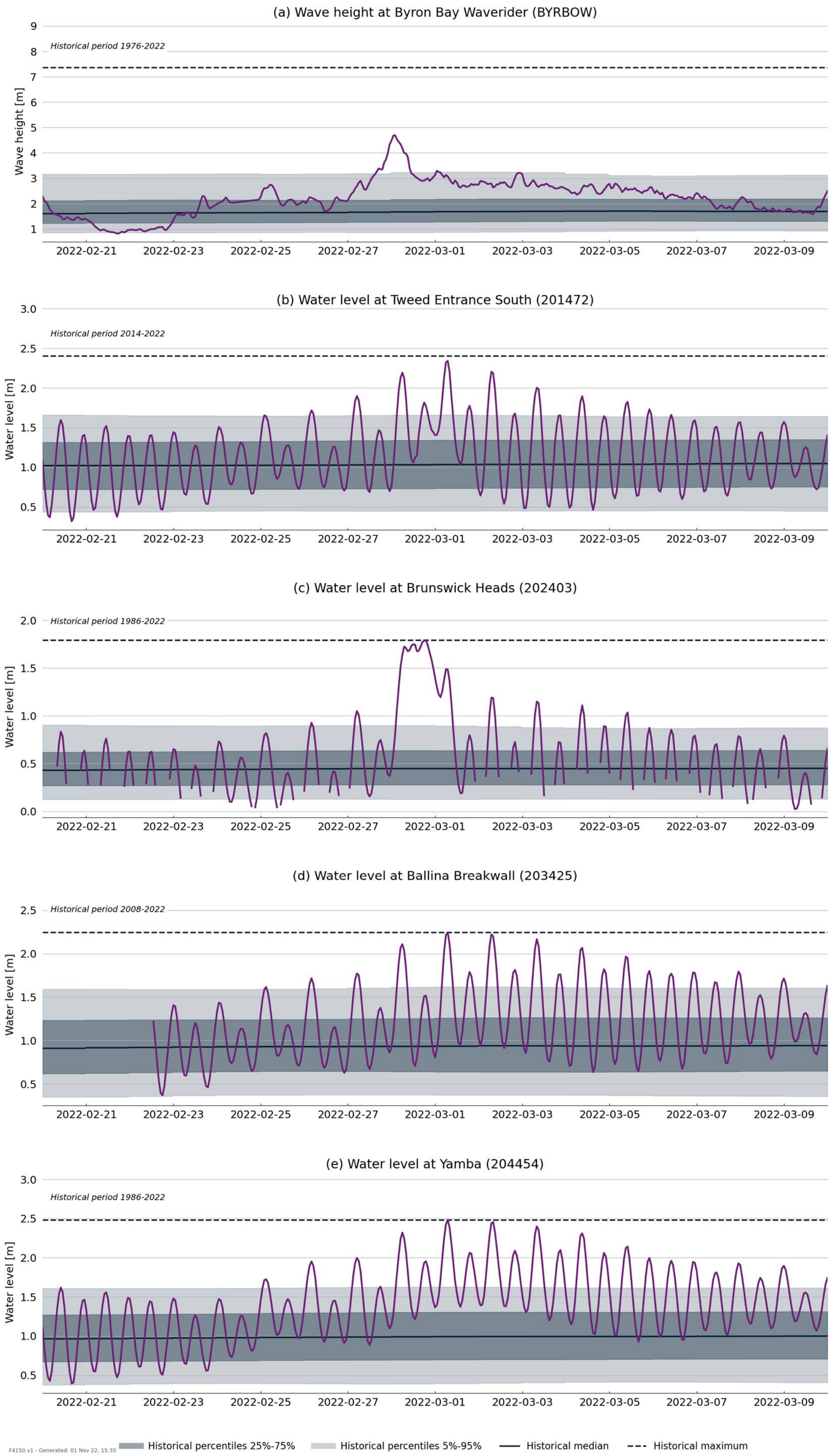

Figure 25 Wave height and tide data from coastal stations in the Northern Rivers region

Data source: Data Collection, Manly Hydraulics Laboratories (2022)

5.6 Frequency analysis of 2022 peak flows

This section presents the estimates of the Annual Exceedance Probability (AEP) of the 2022 peak flows for gauges across the Northern Rivers region. It complements section 5.3 that covered the frequency analysis of rainfall data. The reader is referred to section 1.2.5 for a brief introduction to the concepts underlying a frequency analysis.

5.6.1 Method used to estimate the 2022 flood AEP

In Australia, the approach to be followed for estimating AEP is described in the Australian Rainfall and Runoff guidelines (ARR, Ball et al., 2019), which were recently revised in 2019 and supported by further recommendations for their application in NSW (NSW, 2019). This section follows the guidelines provided in Book 3 that describe the estimation of AEP at a particular site referred to as "At-Site Flood Frequency Analysis". The following paragraphs describe the method briefly with further details provided in Appendix H.

Analysis based on Annual Maxima Series of instantaneous streamflow

The flood frequency analysis presented in this section is based on Annual Maxima Series (AMS) of instantaneous streamflow records at various sites across the region. AMS data were obtained by identifying the maximum streamflow value during each water year for each gauging station described in section 3.3.1. An example of AMS data is presented in Figure 26 for the Wilsons River at Eltham (203014) where the blue line shows the instantaneous streamflow time series, and the dots correspond to the AMS data. The water year is defined with a start on the first of September which is the month with the lowest number of flood events across the region.

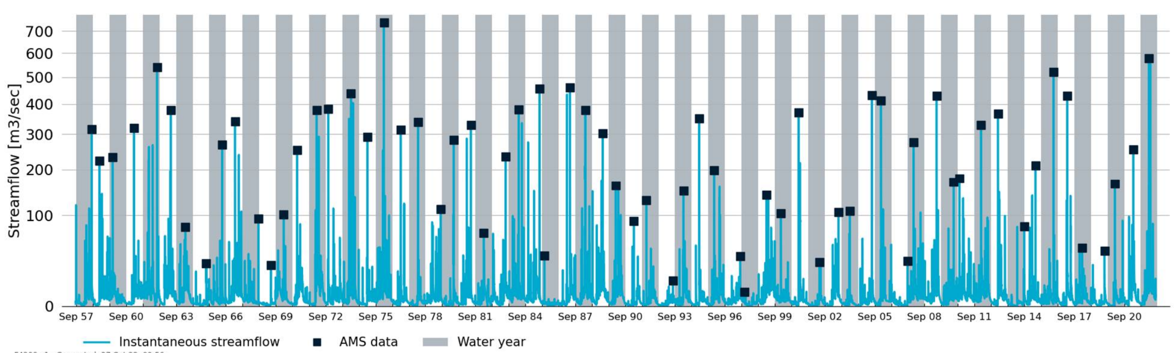

Figure 26 Annual maximum series computed from instantaneous streamflow for the Wilsons River at Eltham (203014)

Data source: Continuous Water Monitoring Network, WaterNSW (2022)

The analysis was applied to 43 streamflow gauging stations listed in Table 29, covering the four basins of the Northern Rivers region. Stations were selected when their record duration exceeded 20 years and when their rating curve was based on a reasonable number of gaugings.

Computation of an Annual Maxima Series for Lismore

The use of streamflow data obviously restricts the analysis to stations where this variable is available. Many sites of interest across the region record water levels but not streamflow such as the Wilsons River at Lismore. To expand the number of sites covered, it is possible to apply flood frequency analysis to water level data. However, Book 3 of the ARR (Kuczera & Francks, 2019, Section 2.2.2) and the NSW Floodplain Risk Management Guidelines (NSW, 2019, section 3.6.1) discourage this practice. Consequently, it was decided to exclude water level data and restrict the analysis performed in this section to streamflow data only.

Despite this restriction and because of its importance during the 2022 flood, an approximation to the streamflow in Lismore is attempted based on several stations located upstream of the Lismore gauge as illustrated in Figure 27. The two stations of Eltham and Rock Valley are selected because of their long records (65 years for Eltham and 55 years for Rock Valley) and similar distance from Lismore. An instantaneous streamflow time series referred to as "Lismore partial inflows" is computed by adding the streamflow from the two stations, which is subsequently used to derive a series of annual maxima. The series is referred to as "partial inflows" because the area drained by the Wilsons River at Eltham and Leycester Creek at Rock Valley covers 402 km^2 (223 km^2 for Eltham and 179 km^2 for Rock Valley), which represents 30% of the 1386 km^2 drained by the Wilsons River at Lismore.

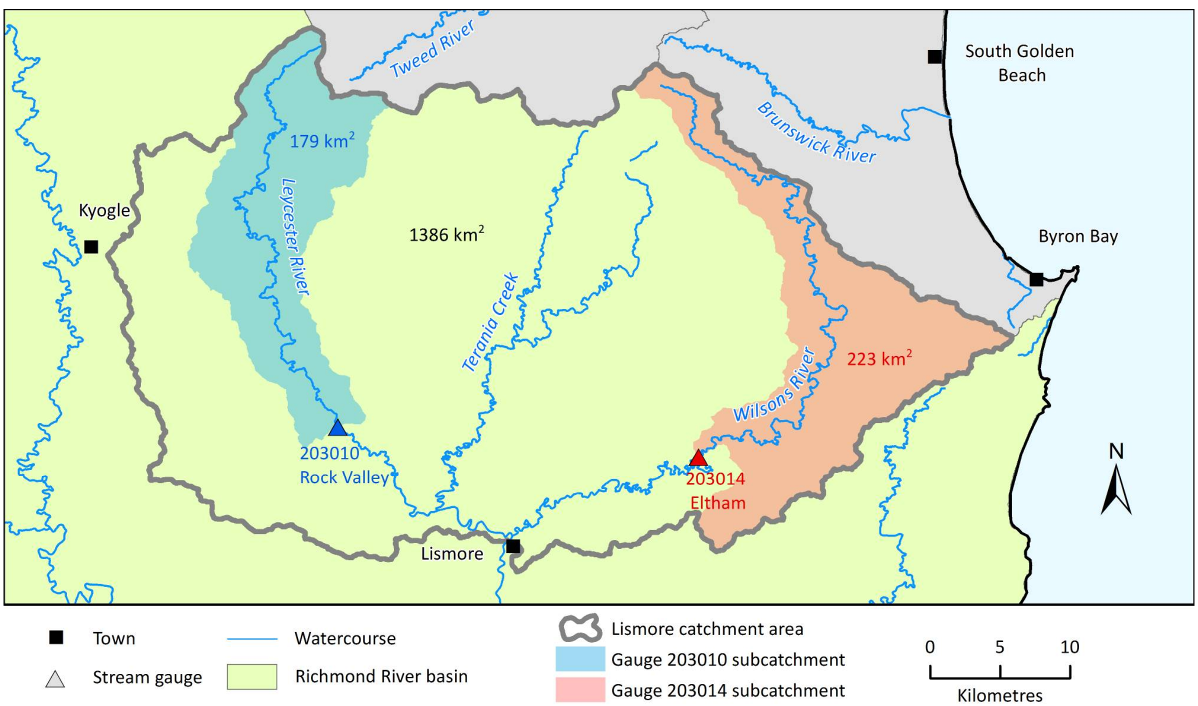

Figure 27 Location of the two stations of Rock Valley (203010) and Eltham (203014) used to compute Lismore partial inflows

Importantly, the partial inflows do not include the contributions from the Back, Terania and Coopers Creek, which join the Leycester Creek and Wilsons River downstream of Rock Valley and Eltham, respectively. Unfortunately, there are no streamflow gauging stations with records that are comparable in length to Eltham and Rock Valley for these creeks. Also note the comment in sections 5.3 about intense rainfall during the 2022 flood in the Terania Creek catchment and in section 5.5.1 about probable major contributions to flow at Lismore from the same catchment. It is also acknowledged that the direct summation of the hydrographs from Rock Valley and Eltham does not consider differences in flood propagation times between the Wilsons River and Leycester Creek upstream of Lismore. However, section 5.5.1 revealed that flood propagation was much faster during the 2022 flood compared to other historical events. Consequently, a simple summation of the upstream hydrograph was preferred over a routing model that could potentially fail to describe the 2022 event. More arguments supporting the computation of the Lismore partial inflows are provided in Appendix H.

Bayesian calibration of the GEV probability distribution

Flood frequency analysis is conducted by fitting the three parameters of the Generalized Extreme Value (GEV) probability distribution to AMS data using a Bayesian calibration approach advocated in the ARR Book 3 (Kuczera & Francks, 2019, Section 2.6.3), in the NSW Floodplain Risk Management Guide (NSW, 2019, section 3.6.1) and described in Appendix H. Once fitted, the distribution is used to estimate the AEP of the February 2022 flood. The GEV distribution was chosen because of its strong theoretical properties (Kuczera & Francks, 2019, section 2.4.2.1), demonstrated flexibility to fit AMS data in Australia (Rahman et al., 1999; Vogel et al., 1993) and use for the recent update of the Lismore Floodplain Risk Management Study (Mundt & Page, 2020, p. 53).

The Bayesian approach applied in this report includes the censoring of low AMS data to reduce the influence of minor floods on the fitting and the use of AWRA-L simulated streamflows as covariate. AWRA-L data are available continuously from 1911 onwards for the whole region, which provides an opportunity to reduce the uncertainty associated with the fitting in a consistent way across the study area.

As indicated in section 1.2.4 and 1.2.5, frequency analysis of a rare floods can lead to significant uncertainty. In this section, uncertainty in AEP is reported as an interval covering 90% of the values (credible interval). The expected AEP representing its average value is also reported following the definition by Kuczera and Francks (2019, see section 2.5.2).

Inclusion or exclusion of the 2022 flood in the fitting of probability distributions

Extreme floods are known to influence the fitting of flood frequency distributions significantly (St. George & Mudelsee, 2019). This fact is due to the sensitivity of most finite sample statistics such as the mean or standard deviation to the addition of a point that exceeds all other values by a large amount. As a result, refitting of the distributions is often required following a major event such as 2022, which prompts the question of including this flood or not while estimating its AEP. On one hand, the 2022 flood has occurred so it cannot be set aside of the fitting. On the other hand, all planning data (e.g. IFD curves) and flood studies in the region have been established prior to the 2022 flood. The ARR and, more broadly, the scientific literature does not provide a clear guidance on this point and both fitting approaches are considered in the following section.

Streamflow data errors

The estimation of high streamflow data is associated with large uncertainty due to the use of rating curves as indicated in section 3.3.1. A sensitivity analysis on streamflow errors is conducted in Appendix H, which led to similar results compared to the original fitting presented below.

5.6.2 Estimation of the 2022 flood Annual Exceedance Probability

Figure 28 presents the fitting of the GEV distribution to observed AMS data for the Lismore partial inflows described in the previous section. The two plots in the figure display the AEP on the x-axis using a Gumbel reduced variable scale[5] and the streamflow in m^3/sec on the y-axis. The observed streamflow data are plotted as blue dots, the 2022 flood is represented as a purple dot, the expected (i.e. average) flood quantiles are materialised by a dotted green line, the associated credible intervals (i.e. uncertainty) are displayed as green areas. Finally, the expected value of the 2022 flood AEP is represented as a pink diamond with an associated credible interval shown as a line of the same colour. The figure distinguishes a fitting that exclude the 2022 flood (Figure 28.a) from a fitting including the event (Figure 28.b).

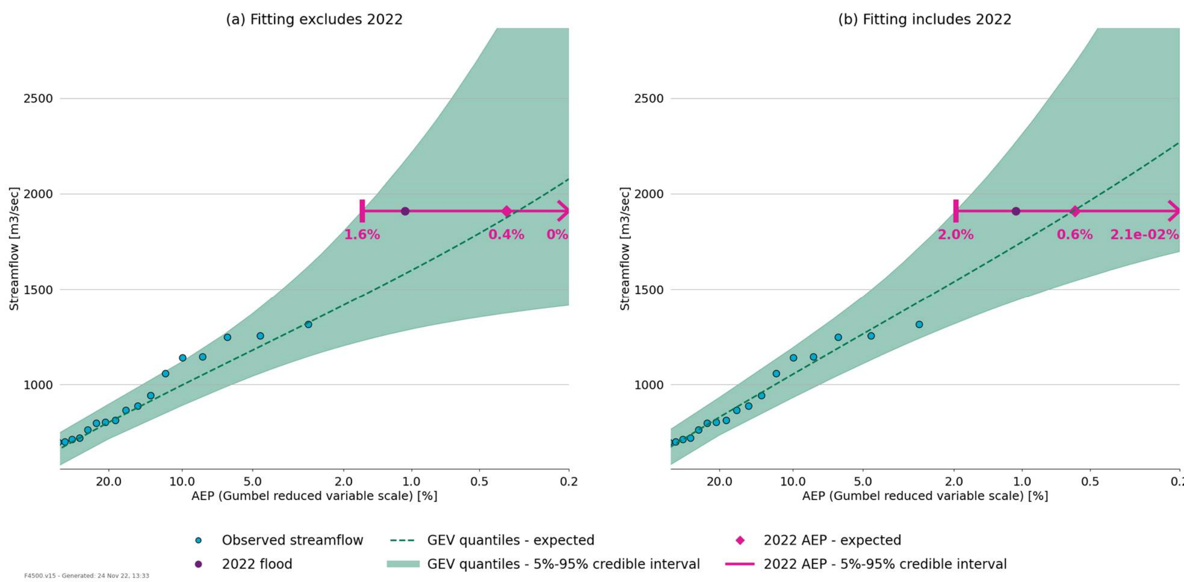

Figure 28 Fitting of the GEV distribution to AMS data from Lismore partial inflows (sum of flow from 203014 and 203010) excluding (figure a) and including (figure b) the 2022 event.

Data source: Continuous Water Monitoring Network, WaterNSW (2022), Appendix H

This figure reveals that the uncertainty of the 2022 AEP for the Lismore partial inflows is significant regardless of the configuration selected. If 2022 flood is included in the fitting (Figure 28.b), the credible interval (i.e. uncertainty range) spans from 0.02%, which corresponds to a 1 in 5000 years event, to 2.0%, which corresponds to a 1 in 50 years event. This level of uncertainty is common in flood frequency analysis, and by extension to flood studies, where a considerable level of uncertainty is unavoidable due to the limited record length (rarely beyond 100 years and often much shorter). The approach advocated by the ARR (Kuczera & Francks, 2019) and followed in this report is to be transparent about this fact and report uncertainty consistently.

[5] The relationship between a reduced Gumbel variable u (dimensionless) and the corresponding AEP α (%) is given by

$$u = -\log\left(-log\left(1 - \frac{\alpha}{100}\right)\right)$$

Despite the large uncertainty reported above, it can be said that the 2022 peak flow of Lismore partial inflows is expected to be well above the 1% AEP threshold. It reaches an expected AEP of 0.4% if the 2022 flood is excluded from the fitting (Figure 28.a) which corresponds to a 1 in 250 years flood, and 0.6% when it is included (Figure 28.b) which corresponds to a 1 in 170 years flood. This result confirms the extreme nature of the 2022 flood, confirming the analysis of rainfall totals mentioned in section 5.3.

In addition, Figure 28 reveals that the inclusion of the 2022 event in the fitting does not affect its estimated frequency significantly with expected AEP increasing from 0.4% when 2022 is excluded to 0.6% when it is included. A similar trend is reported in Appendix H for other stations in the region where the AEP of the 2022 flood events increases (i.e. the severity of the flood decreases) when the 2022 event is included in the fitting. This moderate increase is due to the robust fitting process used in this study and described in Appendix H.

These results obtained for the Lismore partial inflows can be generalised to other stations in the region as can be seen in Figure 29 showing the expected AEP of the 2022 flood for the same two configurations included in Figure 28. The values are also reported in Table 18 along with the associated credible intervals. The AEP for the Richmond River at Casino (203004) was estimated but is not reported here due to the failure of the station during the peak time of the 2022 flood leading to a probable underestimation of the peak and overestimation of the corresponding AEP.

Figure 29 confirms the concentration of extreme peak flows in the Wilsons catchment and mid-Richmond Basin also reported for rainfall values in section 5.3. Seven stations in the region reached a peak flow that was higher than the 1% AEP event: Coopers Creek at Repentance (203002) with an expected AEP of 0.4 %, Leycester Creek at Rock Valley (203010) with 0.8%, Coopers Creek at Ewing Bridge (203024) with 0.5%, Myrtle Creek at Rappville (203030) with 0.7%, Tweed River at Uki (201900) with 0.7%, Brunswick River at Durrumbul (202001) with 0.4% and Lismore partial inflows with 0.6%. In the Clarence, noticeably high peak flows were reached at the stations of Fineflower (204067) and Gurranang Siding (204055) with corresponding AEP of 2.0% and 1.3% respectively.

The high level of uncertainty mentioned previously for Lismore partial inflows is also present for these stations. In Table 18, the four stations in the Richmond basin listed above exhibit a lower bound of the credible intervals that varies between an AEP of 0.01% for Rappville, i.e. 1 in 10, 000 years flood, to 0.04% for Rock Valley, i.e. 1 in 2,500 year flood. The upper bound of the credible interval varies from 1.2% (Repentance, i.e. 83 years flood) to 2.4% (Rock Valley, i.e. 41 years flood).

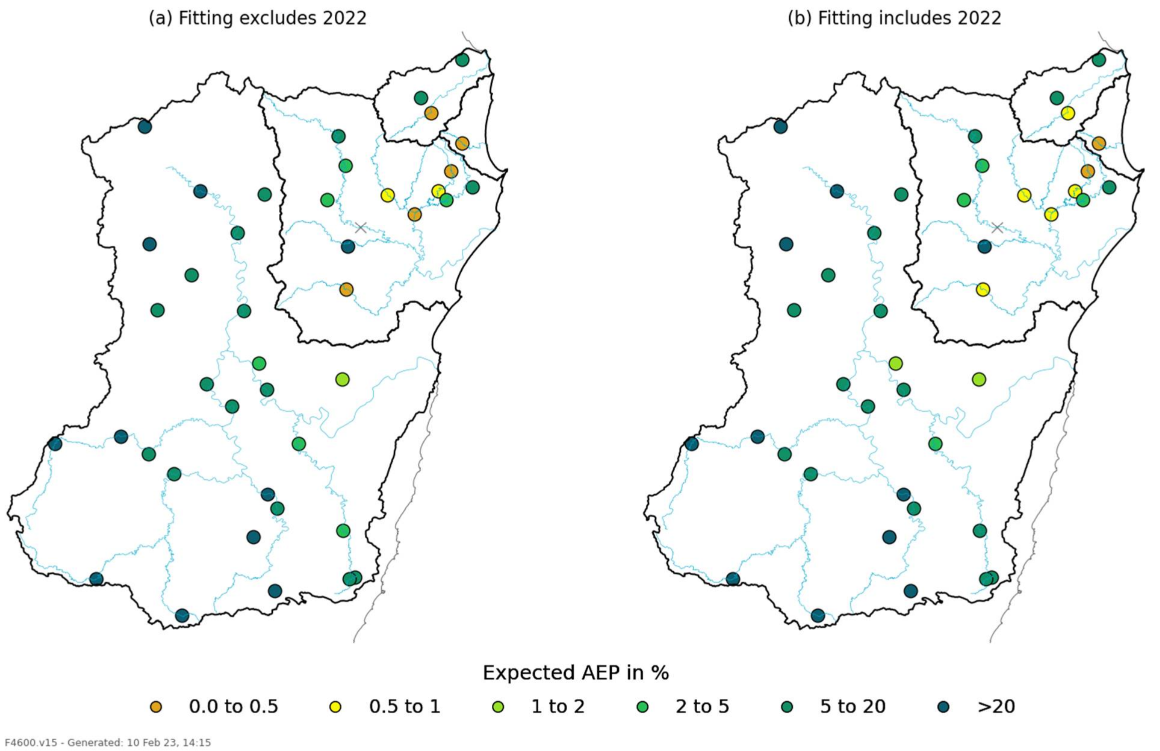

Figure 29 Expected AEP of the 2022 flood for gauging stations across the Northern Rivers region when the event is excluded (figure a) and included (figure b) in the fitting.

Data source: Continuous Water Monitoring Network, WaterNSW (2022), Appendix H. The Casino station (203004) is masked because the 2022 peak flow was not recorded at this station.

Table 18 Expected AEP of the 2022 flood and associated 90% credible interval in brackets for two configurations excluding and including the 2022 event during the fitting

BASIN	STATION ID	NAME	FITTING EXCLUDES THE 2022 EVENT	FITTING INCLUDES THE 2022 EVENT
Clarence				
	204001	Nymboida River at Nymboida	16.5 [11.7, 22.1]	16.9 [11.9, 22.4]
	204002	Clarence River at Tabulam	15.8 [11.0, 21.1]	15.8 [11.0, 21.1]
	204004	Mann River at Jackadgery	14.6 [9.7, 20.4]	14.7 [9.9, 20.4]
	204007	Clarence River at Lilydale	8.0 [4.6, 12.1]	8.0 [4.7, 12.0]
	204008	Guy Fawkes River at Ebor	49.8 [42.1, 57.6]	49.8 [42.1, 57.6]
	204014	Mann River at Mitchell	35.7 [28.3, 43.5]	35.7 [28.3, 43.5]
	204015	Boyd River at Broadmeadows	18.6 [13.0, 24.9]	18.5 [13.0, 24.6]
	204017	Bielsdown Creek at Dorrigo No.2 & No.3	66.0 [54.2, 77.7]	66.0 [54.2, 77.7]
	204025	Orara River at Karangi	19.4 [14.0, 25.3]	19.3 [14.0, 25.2]
	204030	Aberfoyle River at Aberfoyle	32.0 [23.5, 41.1]	31.9 [23.6, 40.9]
	204031	Mann River at Shannon Vale	31.0 [23.0, 39.7]	30.9 [23.1, 39.4]
	204033	Timbarra River at Billyrimba	11.7 [7.2, 17.0]	12.2 [7.7, 17.4]
	204034	Henry River at Newton Boyd	19.7 [13.7, 26.3]	19.7 [13.7, 26.3]
	204036	Cataract Creek at Sandy Hill	30.9 [24.1, 38.0]	30.9 [24.1, 38.0]
	204037	Clouds Creek at Clouds Creek	28.8 [21.1, 36.9]	28.6 [21.0, 36.6]

BASIN	STATION ID	NAME	FITTING EXCLUDES THE 2022 EVENT	FITTING INCLUDES THE 2022 EVENT
	204039	Maryland River D/S Wylie Creek	40.5 [32.3, 48.9]	40.5 [32.3, 48.9]
	204041	Orara River at Bawden Bridge	4.6 [2.2, 7.9]	4.7 [2.2, 7.9]
	204043	Peacock Creek at Bonalbo	5.7 [2.8, 9.5]	5.6 [2.7, 9.3]
	204046	Timbarra River at Drake	12.0 [7.6, 17.3]	12.3 [7.9, 17.5]
	204051	Clarence River at Paddys Flat	33.4 [26.4, 40.7]	33.4 [26.4, 40.7]
	204055	Sportsmans Creek at Gurranang Siding	1.3 [0.05, 3.8]	1.3 [0.15, 3.3]
	204056	Dandahra Creek at Gibraltar Range	15.9 [10.1, 22.5]	15.7 [10.1, 22.3]
	204067	Gordon Brook at Fineflower	2.7 [0.4, 6.1]	2.0 [0.3, 5.0]
	204068	Orara River at Orange Grove	16.2 [10.0, 23.5]	16.0 [10.0, 22.9]
	204069	Nymboida River D/S Nymboida Weir	24.2 [16.3, 33.2]	23.9 [16.3, 32.5]
	204900	Clarence River at Baryulgil	8.1 [4.5, 12.6]	8.2 [4.6, 12.6]
	204906	Orara River at Glenreagh	4.8 [2.1, 8.5]	5.5 [2.6, 9.3]
Richmond				
	203002	Coopers Creek at Repentance	0.2 [0.00, 0.9]	0.4 [0.02, 1.2]
	203004	Richmond River at Casino	-	-
	203005	Richmond River at Wiangaree	11.1 [6.9, 16.1]	11.0 [6.8, 15.9]
	203010	Leycester River at Rock Valley	0.6 [0.00, 2.2]	0.8 [0.04, 2.4]
	203012	Byron Creek at Binna Burra	18.0 [12.0, 24.8]	18.0 [12.0, 24.8]
	203014	Wilsons River at Eltham	3.9 [1.7, 7.1]	4.0 [1.8, 7.1]
	203024	Coopers Creek at Ewing Bridge	0.7 [0.00, 3.5]	0.5 [0.02, 1.7]
	203030	Myrtle Creek at Rappville	0.01 [0.00, 0.00]	0.7 [0.01, 2.1]
	203034	Eden Creek at Doubtful	3.5 [1.1, 7.3]	3.0 [0.8, 6.4]
	203041	Shannon Brook at Yorklea	33.6 [25.1, 42.7]	31.7 [22.1, 42.5]
	203900	Richmond River at Kyogle	3.5 [1.0, 7.3]	3.1 [0.9, 6.5]
	LISPARTINF	Lismore partial inflows. Sum of streamflow from stations 203014 and 203010	0.4 [0.00, 1.6]	0.6 [0.02, 2.0]
Tweed				
	201001	Oxley River at Eungella	7.5 [4.3, 11.4]	7.8 [4.6, 11.8]
	201012	Cobaki Creek at Cobaki	8.8 [4.2, 14.5]	8.0 [3.9, 13.4]
	201900	Tweed River at Uki	0.5 [0.01, 1.6]	0.7 [0.08, 2.1]
Brunswick				
	202001	Brunswick River at Durrumbul	0.20 [0.00, 0.9]	0.4 [0.02, 1.2]

* Results for the Casino station (203004) are not reported because the 2022 peak flow was not recorded at this station.
Data source: Appendix H

5.7 Summary of surface water conditions

The surface water conditions characterising the 2022 flood event can be summarised as follows:

- Extreme rainfalls translated into record high streamflows, volumes and water levels for stations in the mid and lower Richmond, Wilsons catchment, Tweed and Brunswick basins.

- Major flood levels were exceeded by more than 2 m in several locations including in Lismore where the flood reached 14.37 m, a level 4.67 m above the major flood level of 9.7 m.
- The flood propagation upstream of Lismore was the fastest ever recorded on Leycester Creek, Goolmangar Creek, Coopers Creek and Wilsons River where peak time differences with Lismore where the smallest compared to recent historical floods.
- The 2022 flood was a double peak event where the first peak induced elevated water levels in the Wilsons and Richmond rivers floodplains that may have worsened the effect of the second peak.
- The peak flow of the 2022 flood event is estimated to be significantly higher than the 1% AEP at seven stations in the region including Lismore partial inflows. A high degree of uncertainty is associated with these frequency estimates which were found to vary between slightly less than a 1 in 100 year frequency (1% AEP) to 1 in several thousand years (up to 0.01% AEP for one station).
- Damaging impacts of a potential storm surge were avoided in the lower Richmond due to wave height peaking before the flood reached the Richmond River mouth.

6 Conclusion and recommendations

6.1 Key characteristics of the February/March 2022 event

The 2022 flood event was exceptional by many accounts and characterised by the following points:

- Antecedent conditions were significantly wetter than average across the Northern Rivers region with rainfall totals, soil moisture and groundwater levels remaining above their 75th percentile consistently during the two months preceding the flood.
- The 2022 rainfall event affected the region between the 23rd of February and the 1st of March and generated the highest daily rainfall totals in most parts of the Richmond, Tweed and Brunswick.
- The 2022 event was centred on the mid-Richmond and Wilsons River catchment around Lismore where it generated maximum daily rainfall that were significantly higher than the 1% Annual Exceedance Probability event (1 in a 100 years).
- Extreme rainfalls translated into record high streamflows, volumes and water levels for stations in the mid and lower Richmond, Wilsons catchment, Tweed and Brunswick basins. Major flood levels were exceeded by more than 2 m in several locations including in Lismore where the flood reached 14.37 m, a level 4.67 m above the major flood level of 9.7 m.
- The peak flow of the 2022 flood event is estimated to be significantly higher than the 1% AEP at seven stations in the region including Lismore partial inflows. A high degree of uncertainty is associated with these frequency estimates which were found to vary between slightly less than a 1 in 100 year frequency (1% AEP) to 1 in several thousand years (up to 0.01% AEP for one station).

6.2 Recommendations

This study revealed several issues with the data needed to monitor and analyse flood events in the region. The following paragraphs are recommendations to improve the current situation.

6.2.1 R1 - Increasing redundancy and robustness of the rain gauge network

Both climate and flood rain gauge networks suffered from numerous failures during the 2022 flood effectively reducing the number of rain gauges considerably in certain parts of the region. The first recommendation of this report is to increase the redundancy and robustness of the rain gauge network to reduce the risk of failure during extreme weather events. The list of affected gauges that suffered from failures during the 2022 event is provided in Appendix A and B.

6.2.2 R2 – Develop a blended hourly gridded rainfall product

The estimation of rainfall can be done using multiple networks of on-ground observations, remotely sensed data from radar and satellites and data derived from atmospheric models including numerical weather prediction models and re-analysis. Despite this profusion of data source, an authoritative hourly gridded rainfall product remains unavailable which requires that flood studies in the region must perform ad-hoc interpolation of point data like what was undertaken in this analysis. Moreover, the reconciliation of interpolated surface with remotely sensed products such as radar is not a trivial task as both types of data often exhibit significantly different rainfall totals.

Consequently, it is recommended to develop a gridded hourly rainfall product blending on-ground observations with radar and atmospheric models at a resolution equal or lower than 1 km. The blending should also report associated uncertainty in the form of ensembles where uncertainty is expected to increase as we move away from rain gauges.

It is recommended to develop the product in two stages: a first stage should deliver a continuous rainfall re-analysis starting from at least 1990 with periodical updates to include recent data. A second product should provide real-time estimates supporting emergency management.

It is acknowledged that the Bureau of Meteorology has a demonstrated expertise in this field with products such as AGCD (Evans et al., 2020), Rainfields (Seed et al., 2007) and BARRA (Su et al., 2019) that could constitute important building blocks for an new hourly product.

6.2.3 R3 – Improve streamflow measurement across the region

The rating curve at certain streamflow gauging stations in the region (for example Rock Valley, 203010) rely on a limited number of gaugings which reduces the confidence in streamflow data for the estimation of design flood levels. In addition, several stations across the region report water levels but not streamflow which reduces the range of analysis that can be done to support flood modelling.

Consequently, it is recommended to increase the current effort of acquiring streamflow data to:

1. Improve rating curves at existing streamflow gauging stations especially stations with limited gauging data (see Table 23, column "Ratio of max gauge over max flow") along with uncertainty analysis for rating curve extrapolation beyond the maximum gauging,
2. Develop rating curves for additional stations including the Lismore gauge acknowledging that these rating curves might be valid in high flow only due to the tidal influence on low flows,
3. Repair or install a station to measure streamflow on Terania Creek upstream of Lismore (consider re-opening one of the closed stations such as Blakes, 203007, or preferably Keerong, 203022).

Appendix A List of rainfall, water level and streamflow gauging stations retained for data analysis

This appendix lists the rain gauges and surface water stations data collated from the Bureau of Meteorology, WaterNSW and Manly Hydraulics Laboratory for the data analysis performed in this report. It is acknowledged that few additional stations are available from various other data providers including LGAs. However, due to time constraints for this rapid assessment, it was not considered feasible to collect, process, control and analyse all data in the region. It is also acknowledged that the data analysis in this report focused on the 2022 floods and hence retained the active stations only. More historical stations that are now closed are available from Bureau of Meteorology, WaterNSW and Manly Hydraulics Laboratory, but were discarded for the present analysis.

The following tables list the stations used throughout this report.

Table 19 Bureau of Meteorology climate rain gauges

BASIN	STATION ID	NAME	LONGITUDE	LATITUDE	LENGTH OF DATA RECORD COLLECTED (YEARS)	COMMENT
Clarence						
	56022	Legume (New Koreelah)	152.35	-28.46	119.8	Missing daily rainfall data between 2022-02-22 and 2022-03-15
	56023	Old Koreelah (Mcpherson)	152.42	-28.39	110.8	-
	56038	Wylie Creek (Aloomba)	152.16	-28.55	108.8	Missing daily rainfall data between 2022-02-22 and 2022-03-15
	56064	Rivertree (Many Rivers)	152.25	-28.64	20.6	Missing daily rainfall data between 2022-02-22 and 2022-03-15
	56141	Boonoo Boonoo (Currawong)	152.11	-28.89	30.8	-
	56161	Guyra (Gowan Brae)	151.88	-30.16	58.8	-
	56163	Mount Mitchell (Tirranna)	151.85	-30	58.8	Missing daily rainfall data between 2022-02-22 and 2022-03-15
	56164	Legume (Acacia Plateau (Verdant Hills))	152.39	-28.37	19.5	-
	56199	Wylie Creek (Burrenbar)	152.12	-28.56	13.8	-
	56202	Black Swamp (Maxwell)	152.16	-28.98	52.8	-
	56205	Pinkett (Benbookra)	151.96	-29.9	53.8	-
	56207	Maryland	151.99	-28.54	154.8	-
	56239	Wilsons Downfall	152.1	-28.7	29.8	-
	57001	Ebor (Glenowen)	152.23	-30.37	120.8	Missing daily rainfall data between 2022-02-22 and 2022-03-15
	57003	Bonalbo Post Office	152.62	-28.74	109.8	-
	57005	Drake (Village Resource Centre)	152.38	-28.93	131.8	-
	57014	Glen Elgin (Glenbrook)	152.14	-29.56	112.8	-
	57018	Tabulam Post Office	152.57	-28.89	135.8	-
	57020	Urbenville	152.55	-28.47	87.8	-
	57023	Ebor (Wongwibinda)	152.17	-30.29	137.8	-
	57024	Woodenbong (Unumgar St)	152.61	-28.39	89.8	Missing daily rainfall data between 2022-02-22 and 2022-03-15

BASIN	STATION ID	NAME	LONGITUDE	LATITUDE	LENGTH OF DATA RECORD COLLECTED (YEARS)	COMMENT
	57082	Glen Innes (Mt Mitchell Forest)	152.09	-29.65	93.8	-
	57085	Old Bonalbo (Alcheringa)	152.59	-28.57	112.8	-
	57093	Cangai (Smelter Creek)	152.49	-29.51	117.8	-
	57095	Tabulam (Muirne)	152.45	-28.76	52.3	-
	57102	Ebor (Maplewood)	152.31	-30.45	48.8	Missing daily rainfall data between 2022-02-22 and 2022-03-15
	57103	Kookabookra	152.01	-30.01	140.8	-
	57114	Baryulgil (Clarence River)	152.6	-29.2	74.8	Missing daily rainfall data between 2022-02-22 and 2022-03-15
	57121	Mallanganee (Hereford Hills)	152.71	-28.98	35.8	Missing daily rainfall data between 2022-02-22 and 2022-03-15
	57125	Ebor (Pleasant View)	152.36	-30.4	28.4	-
	58006	Brushgrove (Clarence St)	153.08	-29.57	126.8	-
	58012	Yamba Pilot Station	153.36	-29.43	145.8	-
	58027	Harwood Island (Harwood Sugar Mill)	153.25	-29.42	107.8	-
	58028	Coaldale (Bellona)	152.79	-29.38	21.7	-
	58033	Lawrence Post Office	153.1	-29.5	138.8	Missing daily rainfall data between 2022-02-22 and 2022-03-15
	58059	Ulmarra (Newsagency)	153.03	-29.63	131.8	-
	58073	Copmanhurst (Fernglen)	152.8	-29.53	65.8	Missing daily rainfall data between 2022-02-22 and 2022-03-15
	58077	Grafton Research Stn	152.96	-29.62	105.8	-
	58079	Pillar Valley	153.11	-29.75	21.6	-
	58102	Grafton South (South Grafton (Yeerong))	152.79	-29.74	58.8	Missing daily rainfall data between 2022-02-22 and 2022-03-15
	58138	Kangaroo Creek (Hayfield)	152.9	-29.85	85.8	Missing daily rainfall data between 2022-02-22 and 2022-03-15
	58161	Grafton Airport Aws	153.03	-29.76	49.8	-
	58185	Heifer Station (Clarence River)	152.63	-29.46	76.8	Missing daily rainfall data between 2022-02-22 and 2022-03-15
	58189	South Grafton (Divines State Forest)	152.95	-29.78	40.8	Missing daily rainfall data between 2022-02-22 and 2022-03-15

BASIN	STATION ID	NAME	LONGITUDE	LATITUDE	LENGTH OF DATA RECORD COLLECTED (YEARS)	COMMENT
	58231	Grafton South (South Grafton (Clarence	152.92	-29.77	14.8	-
	59006	Lower Bucca	153.1	-30.16	121.8	-
	59009	Coramba (Glenfiddich)	153.02	-30.24	131.8	-
	59019	Ebor (The Racecourse)	152.41	-30.36	94.8	-
	59054	Glenreagh (Coramba Street)	152.98	-30.05	21.7	-
	59092	Halfway Creek (Pacific Hwy)	153.07	-29.92	55.8	Missing daily rainfall data between 2022-02-22 and 2022-03-15
	59105	Lowanna (Grafton St)	152.9	-30.21	50.8	Missing daily rainfall data between 2022-02-22 and 2022-03-15
	59113	Leigh (Rolling Acres)	152.76	-30.31	48.8	-
	59118	Tyringham (Glenferneigh (School House))	152.46	-30.25	45.8	Missing daily rainfall data between 2022-02-22 and 2022-03-15
	59123	Glenreagh Bridge (Orara River)	152.98	-30.05	72.8	Missing daily rainfall data between 2022-02-22 and 2022-03-15
	59124	Nymboida (Nymboida River)	152.72	-29.98	114.8	Missing daily rainfall data between 2022-02-22 and 2022-03-15
	59139	Nana Glen (Cowling Close)	153	-30.1	64.8	-
	59140	Dorrigo (Old Coramba Rd)	152.72	-30.34	25.9	-
	59144	Dorrigo (Elm Street)	152.7	-30.33	15.6	-
	59152	Lowanna (Lowanna Road)	152.91	-30.21	11	Missing daily rainfall data between 2022-02-22 and 2022-03-15
Richmond						
	58004	Mummulgum (Bingeebeebra)	152.77	-28.79	86.8	Missing daily rainfall data between 2022-02-22 and 2022-03-15
	58015	Coraki (Richmond Terrace)	153.29	-28.98	127.8	Missing daily rainfall data between 2022-02-22 and 2022-03-15
	58016	Unumgar (Summerland Way)	152.75	-28.42	22.7	-
	58023	Mcleans Ridges (Lascott Drive)	153.4	-28.79	22.8	-
	58032	Kyogle Post Office	153	-28.62	117.8	Missing daily rainfall data between 2022-02-22 and 2022-03-15

BASIN	STATION ID	NAME	LONGITUDE	LATITUDE	LENGTH OF DATA RECORD COLLECTED (YEARS)	COMMENT
	58044	Nimbin Post Office	153.22	-28.6	119.8	Missing daily rainfall data between 2022-02-22 and 2022-03-15
	58061	Woodburn (Cedar St)	153.34	-29.07	136.8	Missing daily rainfall data between 2022-02-22 and 2022-03-15
	58070	Rosebank (Repentance Creek)	153.41	-28.64	65.8	-
	58097	New Italy (Vineyard Haven)	153.28	-29.15	117.8	-
	58099	Whiporie Post Office	152.99	-29.28	58.8	-
	58113	Green Pigeon (Morning View)	153.09	-28.47	57.8	Missing daily rainfall data between 2022-02-22 and 2022-03-15
	58127	Clunes (Flatley Drive)	153.41	-28.73	60.8	-
	58141	Loadstone (High View)	152.98	-28.41	53.8	Missing daily rainfall data between 2022-02-22 and 2022-03-15
	58147	The Channon	153.28	-28.68	96.8	-
	58148	Lillian Rock (Williams Road)	153.15	-28.53	59.8	-
	58162	Nashua (Wilsons River)	153.46	-28.73	48.8	-
	58165	Rosebank (Upper Coopers Creek)	153.41	-28.62	47.8	-
	58171	Meerschaum Vale (Jenbetdaph)	153.42	-28.93	45.8	Missing daily rainfall data between 2022-02-22 and 2022-03-15
	58180	Nimbin (Goolmangar Creek)	153.21	-28.61	129.8	-
	58192	Upper Mongogarie (Marangaroo)	152.88	-28.99	37.8	Missing daily rainfall data between 2022-02-22 and 2022-03-15
	58194	Dairy Flat	152.72	-28.38	36.8	Missing daily rainfall data between 2022-02-22 and 2022-03-15
	58195	Wiangaree Post Office	152.97	-28.51	36.8	Missing daily rainfall data between 2022-02-22 and 2022-03-15
	58198	Ballina Airport Aws	153.56	-28.84	30	Missing daily rainfall data between 2022-02-22 and 2022-03-15
	58199	Rock Valley (Leycester Creek)	153.16	-28.74	33.8	-
	58200	Eltham (Wilsons Creek)	153.39	-28.76	31.8	Missing daily rainfall data between 2022-02-22 and 2022-03-15
	58201	Tuncester (Leycester Creek)	153.24	-28.8	31.8	-

BASIN	STATION ID	NAME	LONGITUDE	LATITUDE	LENGTH OF DATA RECORD COLLECTED (YEARS)	COMMENT
	58202	Bentley (Back Creek)	153.07	-28.74	31.8	-
	58206	Corndale (Coopers Creek)	153.36	-28.72	31.8	-
	58207	Busbys Flat	152.81	-29.04	29.4	Missing daily rainfall data between 2022-02-22 and 2022-03-15
	58208	Casino Airport Aws	153.06	-28.88	27.9	Missing daily rainfall data between 2022-02-22 and 2022-03-15
	58214	Lismore Airport Aws	153.26	-28.83	20.8	Hourly rainfall station failed from 02:40 28 February 2022.
	58220	Woolners Arm	152.84	-28.7	95.8	-
Tweed						
	40717	Coolangatta	153.51	-28.17	40.8	-
	58005	Brays Creek (Misty Mountain)	153.17	-28.4	72.8	-
	58011	Chillingham	153.28	-28.31	72.8	Missing daily rainfall data between 2022-02-22 and 2022-03-15
	58019	Doon Doon (Mccabes Road)	153.32	-28.53	70.8	-
	58020	Murwillumbah (Dungay (Taleswood))	153.37	-28.29	72.8	-
	58036	Chillingham (Limpinwood)	153.22	-28.31	94.8	-
	58056	Tweed Heads Golf Club	153.55	-28.2	136.8	-
	58109	Tyalgum (Kerrs Lane)	153.17	-28.37	57.8	Missing daily rainfall data between 2022-02-22 and 2022-03-15
	58129	Kunghur (The Junction)	153.25	-28.47	56.8	-
	58158	Murwillumbah (Bray Park)	153.38	-28.34	50.8	Missing daily rainfall data between 2022-02-22 and 2022-03-15
	58167	Uki (Tweed River)	153.33	-28.41	71.8	-
	58186	North Murwillumbah (Tweed River)	153.4	-28.33	94.8	-
	58193	Eungella (Oxley River)	153.29	-28.35	38.8	-
	58197	Mount Numinbah	153.24	-28.27	32.8	Missing daily rainfall data between 2022-02-22 and 2022-03-15
Brunswick						
	58007	Byron Bay (Jacaranda Drive)	153.59	-28.64	130.8	-
	58040	Mullumbimby (Fairview Farm)	153.49	-28.55	124.8	-

BASIN	STATION ID	NAME	LONGITUDE	LATITUDE	LENGTH OF DATA RECORD COLLECTED (YEARS)	COMMENT
	58103	Brunswick Heads Bowling Club	153.55	-28.55	132.8	Missing daily rainfall data between 2022-02-22 and 2022-03-15
	58216	Byron Bay (Cape Byron Aws)	153.64	-28.64	28.8	-

Data source: Climate Data Online, BoM (2022d)

Table 20 Bureau of Meteorology flood rain gauges

BASIN	STATION ID	NAME	LONGITUDE	LATITUDE	LENGTH OF DATA RECORD COLLECTED (YEARS)	COMMENT
Clarence						
	H056161	Guyra (Gowan Brae)	151.88	-30.16	15.8	-
	H056199	Wylie Creek (Burrenbar)	152.12	-28.56	13.5	-
	H057005	Drake (Village Resource Centre)	152.38	-28.93	15.8	-
	H057014	Glen Elgin (Glenbrook)	152.14	-29.56	15.8	-
	H057020	Urbenville	152.55	-28.47	15.8	-
	H057114	Baryulgil (Clarence River)	152.6	-29.2	16.9	-
	H057123	Newton Boyd (Abbey Green)	152.21	-29.76	15.8	-
	H058012	Yamba Pilot Station	153.36	-29.43	15.1	-
	H058028	Coaldale (Bellona)	152.79	-29.38	15.8	-
	H058068	Lawrence Road (Pringles Way)	153.02	-29.41	15.8	-
	H058077	Grafton Research Stn	152.96	-29.62	15.8	-
	H058079	Pillar Valley	153.11	-29.75	15.8	Missing rainfall data points between 2022-02-22 and 2022-03-15
	H058231	South Grafton (Clarence Regional Landfill)	152.92	-29.77	14.8	-
	H059045	Meldrum (Coolawarrah)	152.49	-30.36	15.8	-

BASIN	STATION ID	NAME	LONGITUDE	LATITUDE	LENGTH OF DATA RECORD COLLECTED (YEARS)	COMMENT
	H059054	Glenreagh (Coramba Street)	152.98	-30.05	14.6	-
	H059140	Dorrigo (Old Coramba Rd)	152.72	-30.34	15.4	Missing rainfall data points between 2022-02-22 and 2022-03-15
	H556024	Sandy Hill (Cataract River)	152.22	-28.93	16.9	-
	H557005	Lilydale (Clarence River)	152.68	-29.51	16.9	-
	H557011	Aberfoyle (Aberfoyle River)	152.01	-30.26	16.9	-
	H558068	Wooli (Browns Knob)	153.13	-29.91	14.9	-
	H559025	Dorrigo No 2 & 3 (Bielsdown Creek)	152.71	-30.31	16.9	-
	H560032	Billyrimbah (Timbarra River)	152.25	-29.19	16.9	-
Richmond						
	H058099	Whiporie Post Office	152.99	-29.28	15.8	-
	H058113	Green Pigeon (Morning View)	153.09	-28.47	14.7	-
	H058141	Loadstone (High View)	152.98	-28.41	15.8	-
	H058162	Nashua (Wilsons River)	153.46	-28.73	16.9	-
	H058180	Nimbin (Goolmangar Creek)	153.21	-28.61	16.9	-
	H058194	Dairy Flat	152.72	-28.38	15.8	Missing rainfall data points between 2022-02-22 and 2022-03-15
	H058198	Ballina Airport Aws	153.56	-28.84	15.8	-
	H058199	Rock Valley (Leycester Creek)	153.16	-28.74	16.9	-
	H058201	Tuncester (Leycester Creek)	153.24	-28.8	16.9	-
	H058202	Bentley (Back Creek)	153.07	-28.74	16.9	Short duration rainfall impacted by possible radio transfer interruptions.
	H058206	Corndale (Coopers Creek)	153.36	-28.72	16.9	-
	H058208	Casino Airport Aws	153.06	-28.88	15.8	Rain gauge has a partial blockage of the catch from 29 March 2022 onwards.
	H058212	Evans Head Raaf Bombing Range Aws	153.4	-29.18	15.8	Suspicious rainfall. Gauge discarded.
	H058214	Lismore Airport Aws	153.26	-28.83	15.8	Hourly rainfall station failed from 02:40 28 February 2022.
	H558000	Repentance (Coopers Creek)	153.41	-28.64	52.8	-

BASIN	STATION ID	NAME	LONGITUDE	LATITUDE	LENGTH OF DATA RECORD COLLECTED (YEARS)	COMMENT
	H558001	Wiangaree Bridge (Richmond River)	152.97	-28.52	16.9	-
	H558002	Kyogle (Richmond River)	152.99	-28.62	16.9	-
	H558015	Rappville Tm (Myrtle Creek)	153	-29.11	16.9	-
	H558024	Cawongla	153.09	-28.61	15.8	-
	H558031	Dunoon	153.32	-28.68	15.8	-
	H558037	Eden Ck At Doubtful	152.92	-28.76	16.8	-
	H558038	Shannon Brook At Yorklea	153.06	-28.94	16.9	-
	H558052	Lake Ainsworth	153.59	-28.78	16.9	-
	H558069	Houghlahan'S Creek	153.47	-28.79	14.8	-
	H558071	Tuckombil	153.48	-28.82	14.8	-
	H558072	Alstonville Stp	153.44	-28.83	14.8	-
	H558075	Goolmangar (Goolmangar Creek)	153.22	-28.75	12.9	-
	H558086	Jiggi (Gwynne Rd)	153.15	-28.68	11.3	-
	H558087	Lismore (Dawson Street)	153.28	-28.81	11.3	Rainfall station failed from 27 February 2022 onwards.
	H558098	Byron Bay (Tallow Ck Bridge)	153.62	-28.67	5.5	-
Tweed						
	H058005	Brays Creek (Misty Mountain)	153.17	-28.4	15.8	-
	H058011	Chillingham	153.27	-28.31	12.3	-
	H058019	Doon Doon (Mccabes Road)	153.32	-28.53	15.8	-
	H058129	Kunghur (The Junction)	153.25	-28.47	15.8	-
	H058167	Uki (Tweed River)	153.33	-28.41	16.9	-
	H058186	North Murwillumbah (Tweed River)	153.4	-28.33	16.9	-
	H058193	Eungella (Oxley River)	153.29	-28.35	16.9	-
	H058204	Boat Harbour (Rous River)	153.35	-28.32	16.9	-
	H558010	Chinderah (Tweed River)	153.55	-28.23	16.9	-

BASIN	STATION ID	NAME	LONGITUDE	LATITUDE	LENGTH OF DATA RECORD COLLECTED (YEARS)	COMMENT
	H558011	Tweed Heads (Duranbah)	153.53	-28.27	15.5	-
	H558014	Tumbulgum (Tweed River)	153.46	-28.28	16.9	-
	H558018	Palmers Road	153.29	-28.43	13.6	-
	H558028	Clarrie Hall Dam (Doon Doon Creek)	153.3	-28.44	16.9	-
	H558032	Limpinwood (Bald Mountain)	153.23	-28.31	15.8	-
	H558079	Couchy Creek	153.28	-28.27	12.3	-
	H558080	Upper Rous River (Hopkins Creek)	153.21	-28.27	12.3	-
	H558081	Numinbah	153.25	-28.27	12.3	-
	H558089	Banora (Sewerage Treatmant Plant)	153.53	-28.2	11.2	-
	H558090	Kingscliff (Sewerage Treatment Plant)	153.55	-28.26	11.2	-
	H558092	Bray Park (Water Treatment Plant)	153.38	-28.34	11.2	-
	H558093	Murwillumbah (Sewerage Treatment Plant)	153.35	-28.32	11.2	-
Brunswick						
	H058216	Cape Byron Aws	153.64	-28.64	15.8	-
	H558005	Lacks Creek (Middle Pocket)	153.48	-28.49	16.9	Suspicious constant rainfall reported between 27/2/22 20:00 and 1/3/22 14:00
	H558025	Mullumbimby (Chincogan)	153.48	-28.52	15.8	Suspicious constant rainfall reported between 27/2/22 19:00 and 1/3/22 03:00
	H558034	Mullumbimby (Upper Main Arm)	153.38	-28.5	15.8	-
	H558036	Myocum	153.52	-28.58	15.8	-
	H558091	Hastings (Sewerage Treatment Plant)	153.56	-28.35	11.2	-
	H558095	Wooyung Rd (Crabbes Creek)	153.53	-28.47	9.6	Suspicious constant rainfall reported between 27/2/22 18:00 and 1/3/22 15:00
	H558096	Yelgun (Yelgun Creek)	153.51	-28.49	9.6	Suspicious constant rainfall reported between 27/2/22 19:00 and 1/3/22 14:00

BASIN	STATION ID	NAME	LONGITUDE	LATITUDE	LENGTH OF DATA RECORD COLLECTED (YEARS)	COMMENT
	H558106	Burringbar Rd (Burringbar Creek)	153.44	-28.44	3.3	Missing rainfall data points between 2022-02-22 and 2022-03-15
	H558107	Upper Burringbar Rd	153.41	-28.45	3.3	Missing rainfall data points between 2022-02-22 and 2022-03-15
	H558109	Coopers Shoot Repeater	153.6	-28.68	3.2	-
	H558112	Yelgun Creek (Helen St Bridge)	153.54	-28.5	1.7	Missing rainfall data points between 2022-02-22 and 2022-03-15

Data source: Australia Rainfall and River Conditions, BoM (2022a)

Table 21 BoM flood water level stations

BASIN	STATION ID	NAME	LONGITUDE	LATITUDE	LENGTH OF DATA RECORD COLLECTED (YEARS)	COMMENT
Richmond						
	H058162	Nashua (Wilsons River)	153.46	-28.73	16.9	-
	H058176	Lismore (Wilson River)	153.27	-28.81	16.9	Station failed on 2022-02-28 at 13.55 reaching 14.37 AHD
	H558101	Bungawalbin Creek At Neileys Lagoon Rd	153.17	-29.14	5.5	-

Data source: Australia Rainfall and River Conditions, BoM (2022a)

Table 22 Manly Hydraulics Laboratories water level stations

BASIN	STATION ID	NAME	LONGITUDE	LATITUDE	LENGTH OF DATA RECORD COLLECTED (YEARS)	COMMENT
Clarence						
	204406	Brushgrove	153.08	-29.57	32.8	-
	204400	Grafton	152.93	-29.69	35	-
	204453	Lawrence	153.11	-29.5	19.9	-
	204410	Maclean	153.2	-29.46	31.9	-
	204451	Oyster Channel	153.31	-29.43	19.9	-
	204426	Palmers Island Bridge	153.27	-29.43	20.9	-
	204414	Rogans Bridge	152.88	-29.62	29.3	-
	204476	The Avenue Downstream	153.07	-29.7	19.9	-
	204475	The Avenue Upstream	153.07	-29.7	19.9	-
	204465	Tyndale	153.13	-29.57	19.9	-
	204480	Ulmarra	153.03	-29.63	20.1	-
	2044124	Wilcox Bridge	152.99	-29.67	8.9	-
Richmond						
	203450	Bungawalbin	153.28	-29.03	20.1	-
	203461	Byrnes Point	153.53	-28.87	31.9	-
	203403	Coraki	153.29	-28.98	34.9	-
	203427	East Gundurimba	153.27	-28.85	42.6	Station inundated by flood waters and failed from 07:45 28 February 2022.
	203462	Evans River Fishing Co-op	153.43	-29.12	25.6	Station inundated by flood waters and failed at 06:12 1 March 2022. Equipment was reinstated at 09:45 25 March 2022.
	203475	Iron Gates	153.41	-29.12	29.8	-
	203465	Missingham Bridge	153.58	-28.87	18.9	-
	203432	Rocky Mouth Creek	153.33	-29.1	28.1	Station inundated by flood waters and failed from 21:15 28 February 2022 onwards.
	203480	Tucombil Highway Bridge	153.34	-29.08	32.9	-

BASIN	STATION ID	NAME	LONGITUDE	LATITUDE	LENGTH OF DATA RECORD COLLECTED (YEARS)	COMMENT
	203443	Tuncester	153.24	-28.8	42.6	-
	203468	Wardell	153.46	-28.95	19.9	-
	203412	Woodburn	153.34	-29.07	37.1	-
	203402	Woodlawn College	153.3	-28.79	42.6	-
Tweed						
	201426	Barneys Point	153.55	-28.23	35.6	-
	201455	Bray Park Weir	153.37	-28.35	20	-
	201448	Cobaki	153.5	-28.18	34.9	-
	201428	Dry Dock	153.52	-28.19	34.8	-
	201422	Kynnumboon	153.39	-28.31	32.2	-
	201429	Letitia 2A	153.55	-28.18	34.9	-
	201465	Murwillumbah Bridge	153.4	-28.33	20	-
	201447	Terranora	153.5	-28.2	34.9	-
	201432	Tumbulgum	153.46	-28.28	37.3	-
Brunswick						
	202400	Billinudgel	153.53	-28.5	36.7	-
	202416	Bogangar	153.56	-28.33	36.8	-
	202434	Kingscliff Upstream	153.58	-28.27	8.4	-
	202435	Mooball Creek @ Tweed Coast Road	153.57	-28.39	1.6	-
	202402	Mullumbimby	153.5	-28.55	38.3	-
	202475	Orana Bridge	153.55	-28.52	20	-

Data source: Data Collection, Manly Hydraulics Laboratories (2022)

Table 23 WaterNSW streamflow gauging stations

BASIN	STATION ID	NAME	LONGITUDE	LATITUDE	LENGTH OF DATA RECORD COLLECTED (YEARS)	COMMENT	CATCHMENT AREA (KM2)	MAXIMUM GAUGED FLOW (M3/S)	MAXIMUM REPORTED FLOW (M3/S)	RATIO MAX GAUGE OVER MAX FLOW (-)	FLOOD PEAK, FEB 2022 (M3/S)	RATIO FEB 2022 PEAK OVER MAX FLOW (-)
Clarence												
	204001	Nymboida River At Nymboida	152.73	-29.98	66.4	-	1660	3454.7	5076.1	0.68	2301	0.45
	204002	Clarence River At Tabulam	152.57	-28.89	57.3	-	4550	2665.4	10916.7	0.24	2834.2	0.26
	204004	Mann River At Jackadgery	152.54	-29.57	59	-	7800	3973.4	12776.5	0.31	5821.3	0.46
	204006	Bookookoorara River At Undercliffe	152.17	-28.64	10.9**	Flow data before 2011 was discarded.	127	10.4	175.6	0.06	48.2	0.27
	204007	Clarence River At Lilydale (Newbold Crossing)	152.68	-29.51	51.2	-	16690	14789.9	18648.8	0.79	13150.7	0.71
	204008	Guy Fawkes River At Ebor	152.35	-30.4	49	-	31	95	185.5	0.51	32	0.17
	204014	Mann River At Mitchell	152.11	-29.69	50.5	-	881	129	1904.4	0.07	142.7	0.07
	204015	Boyd River At Broadmeadows	152.32	-29.84	52.4	-	2670	85	1633.6	0.05	771.5	0.47
	204017	Bielsdown Creek At Dorrigo No.2 & No.3	152.71	-30.3	51.2	Significant changes in rating curve over time.	76	316	749.2	0.42	98.7	0.13
	204025	Orara River At Karangi	153.03	-30.25	53	Significant changes in rating curve over time.	135	158.6	960	0.17	404.3	0.42
	204030	Aberfoyle River At Aberfoyle	152.01	-30.26	45.2	-	200	11.2	117.7	0.1	41.1	0.35
	204031	Mann River At Shannon Vale	151.85	-29.72	38.5	-	348	387.9	619.2	0.63	97.3	0.16
	204033	Timbarra River At Billyrimba	152.25	-29.19	44.6	-	985	56.2	1751.4	0.03	568.2	0.32
	204034	Henry River At Newton Boyd	152.21	-29.76	51.2	-	389	24.7	801.9	0.03	168.9	0.21
	204036	Cataract Creek At Sandy Hill(Below Snake Creek)	152.22	-28.93	70.6	-	236	53.2	1066.1	0.05	156.6	0.15
	204037	Clouds Creek At Clouds Creek	152.63	-30.09	51.7	-	62	56.8	225.6	0.25	88.9	0.39

BASIN	STATION ID	NAME	LONGITUDE	LATITUDE	LENGTH OF DATA RECORD COLLECTED (YEARS)	COMMENT	CATCHMENT AREA (KM2)	MAXIMUM GAUGED FLOW (M3/S)	MAXIMUM REPORTED FLOW (M3/S)	RATIO MAX GAUGE OVER MAX FLOW (-)	FLOOD PEAK, FEB 2022 (M3/S)	RATIO FEB 2022 PEAK OVER MAX FLOW (-)
	204039	Maryland River D/S Wylie Creek	152.2	-28.47	43.6	Significant changes in rating curve over time.	373	297.5	1381	0.22	72.3	0.05
	204041	Orara River At Bawden Bridge	152.81	-29.72	62.3	Very high gauging of 2800 m3/sec in March 1974 that exceeds maximum flow reported.	1790	2831.7	2365.5	1.2	2125.3	0.9
	204043	Peacock Creek At Bonalbo	152.67	-28.73	62.6	-	47	8.2	251.2	0.03	155	0.62
	204046	Timbarra River At Drake	152.39	-29.05	53.3	-	1720	430.4	2940.8	0.15	1098.5	0.37
	204051	Clarence River At Paddys Flat	152.42	-28.72	46.6	-	2230	897	5728.1	0.16	989.4	0.17
	204055	Sportsmans Creek At Gurranang Siding	152.98	-29.47	40.3**	Flow data before 1982 was discarded.	202	354.2	615.6	0.58	615.6	1
	204056	Dandahra Creek At Gibraltar Range	152.45	-29.48	47.4	-	104	136.6	655.6	0.21	271.5	0.41
	204067	Gordon Brook At Fineflower	152.65	-29.4	39.5	Significant changes in rating curve over time.	315	39.2	825	0.05	825	1
	204068	Orara River At Orange Grove	153.01	-30.26	27.2	Significant changes in rating curve in 2000.	126	136	688.8	0.2	468.6	0.68
	204069	Nymboida River D/S Nymboida Weir	152.69	-29.92	25.1	-	1732	2453.7	4943.2	0.5	2285	0.46
	204071	Bielsdown River At Charlestead	152.71	-30.23	19.4	-	131	18.9	542.9	0.03	172.7	0.32
	204900	Clarence River At Baryulgil	152.59	-29.2	51.3	-	7490	3324	9526.9	0.35	5969.1	0.63
	204906	Orara River At Glenreagh	152.99	-30.07	49.9	-	446	978	1338.9	0.73	1063.6	0.79
Richmond												
	203002	Coopers Creek At Repentance	153.41	-28.64	46	-	62	127.7	1363.2	0.09	1363.2	1
	203004	Richmond River At Casino	153.06	-28.86	52.6	Significant changes in rating curve over	1790	1806.8	2089.5***	0.86	2089.5***	1

BASIN	STATION ID	NAME	LONGITUDE	LATITUDE	LENGTH OF DATA RECORD COLLECTED (YEARS)	COMMENT	CATCHMENT AREA (KM2)	MAXIMUM GAUGED FLOW (M3/S)	MAXIMUM REPORTED FLOW (M3/S)	RATIO MAX GAUGE OVER MAX FLOW (-)	FLOOD PEAK, FEB 2022 (M3/S)	RATIO FEB 2022 PEAK OVER MAX FLOW (-)
						time. No streamflow data available for the peak of 2022 event between 2022-02-28 11:45 and 2022-03-01 9:45.						
	203005	Richmond River At Wiangaree	152.97	-28.51	51.3	-	702	667	2687.9	0.25	1490.6	0.55
	203010	Leycester River At Rock Valley	153.16	-28.74	55.4	-	179	226.5	1343	0.17	1343	1
	203012	Byron Creek At Binna Burra	153.5	-28.71	45.1	-	39	65.2	459.7	0.14	210.5	0.46
	203014	Wilsons River At Eltham	153.39	-28.76	65.2	-	223	421.3	741.2	0.57	578.4	0.78
	203024	Coopers Creek At Ewing Bridge	153.36	-28.72	21.1**	Flow data before 2001 was discarded.	148	254.6	807.7	0.32	807.7	1
	203030	Myrtle Creek At Rappville	153	-29.11	43.1	-	332	142.4	174.9	0.81	174.9	1
	203034	Eden Creek At Doubtful	152.92	-28.76	21.2	-	581	123.6	873.2	0.14	846	0.97
	203041	Shannon Brook At Yorklea	153.01	-28.94	21.1**	Significant changes in rating curve post 1990.	492	199.1	530.2	0.38	158.8	0.3
	203056	Richmond River At Lavelles Road	152.89	-28.45	12	-	337*	209.8	1016.8	0.21	593.7	0.58
	203057	Houghlahans Creek At Upstream Teven	153.49	-28.8	12	-	8*	4.9	58.1	0.09	35	0.6
	203059	Marom Creek At Graham Road	153.37	-28.87	11.2	-	31*	8.3	206.5	0.04	181.1	0.88
	203060	Coopers Creek At Fairmeadow	153.35	-28.75	11.2	-	191*	210.6	368.5	0.57	368.5	1
	203061	Goolmangar Creek At Mcnamara Bridge Weir	153.23	-28.73	11.2	-	143*	150.9	261.7	0.58	261.7	1
	203062	Wilsons River At Lavertys Gap Weir	153.44	-28.58	6.6	-	25*	7.4	257	0.03	257	1
	203900	Richmond River At Kyogle	152.99	-28.62	37.4	-	899	869.2	1525.3	0.57	1363.2	0.89

BASIN	STATION ID	NAME	LONGITUDE	LATITUDE	LENGTH OF DATA RECORD COLLECTED (YEARS)	COMMENT	CATCHMENT AREA (KM2)	MAXIMUM GAUGED FLOW (M3/S)	MAXIMUM REPORTED FLOW (M3/S)	RATIO MAX GAUGE OVER MAX FLOW (-)	FLOOD PEAK, FEB 2022 (M3/S)	RATIO FEB 2022 PEAK OVER MAX FLOW (-)
Tweed												
	201001	Oxley River At Eungella	153.29	-28.35	65.6	-	213	752.7	1590.6	0.47	1181.4	0.74
	201005	Rous River At Boat Harbour No.3	153.34	-28.31	15.3**	Flow data before 2007 was discarded.	111	197.9	926	0.21	296.7	0.32
	201012	Cobaki Creek At Cobaki	153.46	-28.2	40.4	-	10	5.3	206.8	0.03	120.4	0.58
	201015	Tweed River D/S Palmers Road Crossing	153.29	-28.43	13.5	-	156	230.3	1129.5	0.2	1129.5	1
	201900	Tweed River At Uki	153.33	-28.41	55.4	Station influenced by releases from Clarrie Hall dam.	275	368.1	2557.5	0.14	2557.5	1
Brunswick												
	202001	Brunswick River At Durrumbul (Sherrys Crossing)	153.46	-28.53	51	Significant changes in rating curve over time.	34	220.9	792.1	0.28	792.1	1
	202002	Burringbar Creek At Burringbar	153.48	-28.44	12	-	40*	14.7	122.3	0.12	119.7	0.98

Data source: Continuous Water Monitoring Network, WaterNSW (2022)
* Catchment area computed from SRTM DEM.
** Period of record does not include data prior to record interruption.
*** Maximum flow is likely to be higher at the Casino gauge as it stopped reporting streamflow during the 2022 flood peak.

Appendix B List of rainfall and streamflow gauging stations excluded from data analysis

This appendix presents the list of stations that were collected from BoM and WaterNSW but later discarded due to missing data or suspicions of data errors. It is highlighted that the list of stations identified in this appendix is the result of a rapid quality control of data based on visual inspection. A more definitive analysis would be required to determine the cause of the suspected errors and potential remediations.

In addition, the stations listed in this appendix were excluded as soon as some errors was suspected. It is likely that the data from some of these stations could be used prior to or following the suspicious periods. Such period selection was not undertaken but could result in additional data being available for data analysis.

Table 24 List of rain gauges discarded from data analysis

TYPE	BASIN	STATION ID	NAME	LONGITUDE	LATITUDE	COMMENT
Climate rain gauge						
	Clarence					
		57123	Newton Boyd (Abbey Green)	152.21	-29.76	Non stationarity in rainfall series suspected starting from Jan 2021 by comparing accumulations against 3 neighbours (57082, 57014, 57103).
		58045	Nymboida (Sutton St)	152.73	-29.94	Non stationarity suspected in rainfall series starting from Jan 2009 by comparing accumulations against 3 neighbours (58102, 58231, 59054).
		58068	Lawrence Road (Pringles Way)	153.02	-29.41	Large amount of missing rainfall data between 2017 and 2020.
		59045	Meldrum (Coolawarrah)	152.49	-30.36	Suspicion of non-stationary daily rainfall records starting from 2015
	Richmond					
		58212	Evans Head Raaf Bombing Range Aws	153.4	-29.18	Suspicious rainfall. Gauge discarded.
	Tweed					
		58204	Boat Harbour (Rous River)	153.35	-28.32	Non stationarity in rainfall series suspected starting from Jan 2011 by comparing accumulations against 3 neighbours (58020, 58186, 58193).
Flood rain gauge						
	Clarence					
		H057095	Tabulam (Muirne)	152.45	-28.76	Missing daily rainfall data between 2022-02-22 and 2022-03-15Unreliable hourly rainfall records between 2011 and 2012
		H059124	Nymboida (Nymboida River)	152.72	-29.98	Suspicious hourly rainfall data in 2009
		H557000	Tabulam (Clarence River)	152.57	-28.89	Unreliable hourly rainfall records in 2007 and 2018
		H557009	Ebor (Guy Fawkes River)	152.35	-30.41	Missing daily rainfall data between 2022-02-22 and 2022-03-15Unreliable hourly rainfall records in 2009

TYPE	BASIN	STATION ID	NAME	LONGITUDE	LATITUDE	COMMENT
		H558061	Yamba	153.36	-29.43	Non stationarity in rainfall series suspected between 2009 and 2010, and between 2012 and 2013 by comparing accumulations against 3 neighbouring daily gauges (58012, 58027, 58212).
	Richmond					
		H058147	The Channon	153.28	-28.68	Rainfall station failed from 04:24 28 February 2022 onwards. Station positioned at the confluence between Rocky Creek and Terania Creek.
		H058148	Lillian Rock (Williams Road)	153.15	-28.53	Unreliable hourly rainfall records prior to 2008 and in 2015 and 2017
		H558033	Goonengerry	153.42	-28.59	Unreliable hourly rainfall records prior to 2010
		H558049	Huonbrook	153.38	-28.56	Non stationarity in rainfall series suspected between 2009 and 2010, and between 2012 and 2013 by comparing accumulations against 3 neighbouring daily gauges (58165, 58019, 58070).
		H558076	Tuckurimba (Baxter Lane)	153.31	-28.96	Unreliable hourly rainfall records in 2020 and 2022
		H558078	Terania Creek	153.3	-28.59	Missing daily rainfall data between 2022-02-22 and 2022-03-15Unreliable hourly rainfall records in 2020 and 2022
	Tweed					
		H558085	Bilambil Heights (Marana Reservoir)	153.48	-28.22	Missing daily rainfall data between 2022-02-22 and 2022-03-15No hourly rainfall records
		H558088	Tyalgum Bridge (Tyalgum River)	153.21	-28.36	Unreliable hourly rainfall records prior to 2016
	Brunswick					
		H558046	Cudgera Lake	153.51	-28.4	Non stationarity in rainfall series suspected between 2009 and 2010, and between 2012 and 2013 by comparing accumulations against 3 neighbouring daily gauges (58186, 58158, 58040).
		H558053	Main Arm	153.38	-28.5	Non stationarity in rainfall series suspected between 2009 and 2010, and between 2012 and 2013 by comparing accumulations against 3 neighbouring daily gauges (58019, 58167, 58040).
		H558066	Byron Bay (Belongil Creek)	153.58	-28.64	Missing daily rainfall data between 2022-02-22 and 2022-03-15Non stationarity in rainfall series suspected after 2014 by comparing accumulations against 3 neighbouring daily gauges (58007, 58040, 58162).
		H558082	Clothiers Creek	153.48	-28.34	Missing daily rainfall data between 2022-02-22 and 2022-03-15No hourly rainfall records
		H558083	Burringbar	153.47	-28.44	Missing daily rainfall data between 2022-02-22 and 2022-03-15No hourly rainfall records

TYPE	BASIN	STATION ID	NAME	LONGITUDE	LATITUDE	COMMENT
		H558084	Cudgera Creek (Pottsville Reservoir)	153.53	-28.4	Missing daily rainfall data between 2022-02-22 and 2022-03-15No hourly rainfall records
		H558094	Upper Crabbes Creek (Crabbes Creek Rd)	153.45	-28.46	Unreliable hourly rainfall records in 2018, 2019 and 2021
		H558099	Byron Bay (Belongil Ck Bridge)	153.6	-28.64	Missing daily rainfall data between 2022-02-22 and 2022-03-15No hourly rainfall records
		H558104	Burringbar North Arm (Harwood Rd)	153.46	-28.41	Missing daily rainfall data between 2022-02-22 and 2022-03-15No hourly rainfall records

Data source: Climate Data Online, BoM (2022d) and Australia Rainfall and River Conditions, BoM (2022a)

Table 25 Streamflow gauging stations excluded from data analysis

BASIN	STATION ID	NAME	LONGITUDE	LATITUDE	COMMENT
Clarence					
	204072	Nymboida Tailrace At Power Station Right Bank Flume	152.74	-29.93	Downstream of a power station and very limited streamflow gaugings available.
	204073	Nymboida Tailrace At Power Station Left Bank Flume	152.74	-29.93	Downstream of a power station and very limited streamflow gaugings available.
	204403	Coldstream River At Tucabia	153.11	-29.67	No rating curve.
Richmond					
	203023	Ironpot Creek At Toonumbar	152.8	-28.62	Stations located downstream of Toonumbar dam.
	203042	Ironpot Creek At Toonumbar Dam-Storage Gauge	152.79	-28.62	Stations located downstream of Toonumbar dam.
	203048	Maguires Creek At Alstonville	153.44	-28.82	very few streamflow gaugings available.

Data source: Continuous Water Monitoring Network, WaterNSW (2022), Appendix H

Appendix C Interpolation of hourly point rainfall data

The interpolation of point rainfall data aims at producing an hourly gridded rainfall surface from rainfall data observed at flood rain gauges. Let us assume that a gridded surface is needed at a particular time step where a set of N stations are available and report rainfall values $\{P_1, P_2, \dots, P_N\}$. The interpolation computes rainfall values for each point of the grid using the method referred to as “inverse distance weighting” (Hatono et al., 2022; Woldemeskel et al., 2013) as follows.

$$p(x,y) = \frac{\sum_i \frac{P_i}{\left(\sqrt{(x-x_i)^2 + (y-y_i)^2}\right)^\alpha}}{\sum_i \frac{1}{\left(\sqrt{(x-x_i)^2 + (y-y_i)^2}\right)^\alpha}} \quad \text{Eq. 1}$$

Where x and y are the coordinates of a particular cell in the grid, $p(x,y)$ is the interpolated rainfall to be computed, P_i is rainfall from station i, (x_i, y_i) are the coordinates of station i and α is a parameter controlling the smoothness of the interpolation. In this work a value of $\alpha = 3$ is adopted based on a visual comparison between surfaces generated with different α.

The interpolation was run for each flood event listed in Appendix F and applied to hourly flood stations listed in Appendix A. Finally, the rainfall grids were averaged over selected catchment areas as follows.

$$p_c = \frac{\sum_{x,y} w_c(x,y)\, p(x,y)}{\sum_{x,y} w_c(x,y)} \quad \text{Eq. 2}$$

Where p_c is the catchment average rainfall for catchment c and $w_c(x,y)$ is the fraction of grid cell (x,y) falling into catchment c.

In addition to the previous interpolation configuration, the interpolation algorithm was also run for daily climate stations to offer a point of comparison with AGCD grids.

Figure 30 compares the catchment average rainfall derived from AGCD, interpolated climate stations and interpolated flood stations for four catchments in the region and for the two 2022 events defined in Appendix F. In this plot, the interpolated hourly grids were aggregated to daily to match with the AGCD and climate station interpolation time step. Overall, Figure 30 suggests that there is a good agreement between the three gridded surfaces when aggregated to catchment scale across the region. The largest discrepancy is observed in Figure 30.g between the flood station interpolation and the two other rainfall products for the Clarence River catchment at Baryulgil. This can be explained by the large size of this catchment combined with its small number of flood stations as shown in Figure 4. In these unfavourable conditions, it is expected that flood station interpolation is of poor quality and does not match with AGCD or climate station interpolation.

Despite the satisfactory agreement between the three rainfall surfaces, it is highlighted that the rainfall interpolation undertaken here is intended for use in a data analysis context only. Further work is required to use the interpolated surfaces as inputs to hydrological or hydrodynamic models in order to (1) characterise the uncertainty associated with the interpolation, (2) blend rainfall stations with radar surfaces described in section 3.2.4.

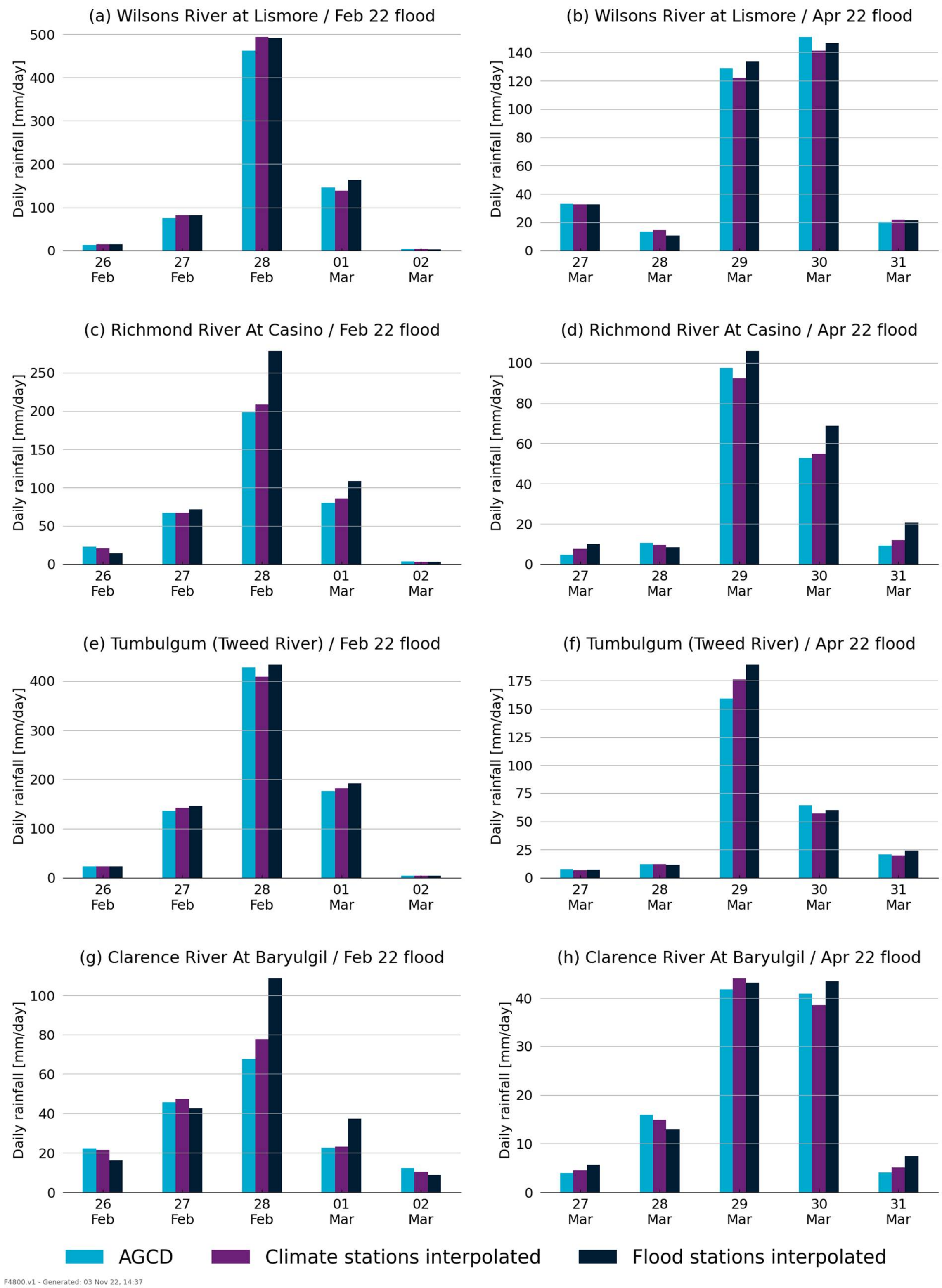

Figure 30 Comparison between catchment average rainfall derived from interpolation and AGCD for four catchments and two flood events

Data source: AGCD rainfall grids, Australian Water Outlook, BoM (2022c)

Appendix D Processing of radar images

Five-minute radar rainfall data were available for three locations: Grafton, Marburg and Mount Stapylton. The radar images needed to be converted from five-minute rainfall intervals, to hourly rainfall intervals. The five-minute radar rainfall data were provided in NetCDF files by the Australian Bureau of Meteorology. Python scripts were used to read the NetCDF files and aggregate rainfall to hourly intervals.

These aggregated images then needed to be re-gridded to have a compatible cell size with the AGCD gridded climate data. The radar data from each location only covered parts of the AGCD gridded region. To provide near complete coverage, the hourly interval rainfall images were blended for Grafton and Marburg, as well as for Grafton, Marburg and Mount Stapylton.

The blending was undertaken by applying an inverse distance weighting as follows:

$$B(x,y) = \frac{\sum_r \frac{P_r(x,y)}{\sqrt{(x-x_r)^2 + (y-y_r)^2}}}{\sum_r \frac{1}{\sqrt{(x-x_r)^2 + (y-y_r)^2}}} \qquad \text{Eq. 3}$$

Where x and y are the coordinates of a particular cell in the grid, $B(x,y)$ is the blended rainfall to be computed, $P_r(x,y)$ is the regridded rainfall from radar r of the 30-minute or three-hourly interval images and (x_r, y_r) are the coordinates of radar r.

The blended images contained minor edge effects at the borders of the original images (Figure 31a). To reduce these effects, a mask was created around the overlapping zones (Figure 31b), and further blending applied based on distance of pixel from the edge of the mask (Figure 31c). The base image in Figure 31b is the Grafton-Marburg blended image (using Equation 1). Area 4 in the overlapping zones (Figure 2b) is the blended image from Marburg-Mount Stapylton (using Equation 1). Area 1 is blended using the following formula:

$$B(x,y) = \frac{G(x,y) * (y - y_{start})}{y_{dist}} + \frac{M(x,y) * (y_{dist} - (y - y_{start}))}{y_{dist}} \qquad \text{Eq. 4}$$

Where *G(x,y)* is the pixel value at *(x,y)* from the Grafton-Marburg blended image, *M(x,y)* is the pixel value at *(x,y)* from the Marburg-Mount Stapylton blended image, y_{start} is the *y* value at the top of Area 1, y_{dist} is the number of pixels from the top of Area 1 to the bottom of Area 1.

Area 2 is blended using:

$$B(x,y) = \frac{M(x,y) * (x - x_{start})}{x_{dist}} + \frac{G(x,y) * (x_{dist} - (x - x_{start}))}{x_{dist}} \qquad \text{Eq. 5}$$

Where *G(x,y)* and *M(x,y)* are from Eq. 4, x_{start} is the *x* value at the left edge of Area 2, x_{dist} is the number of pixels from the left edge to the right edge of Area 2.

Area 3 is blended using:

$$B(x,y) = \frac{G(x,y) * (y - y_{start\_t})}{y_{dist\_t}} + \frac{M(x,y) * (y_{dist_t} - (y - y_{start_t}))}{y_{dist\_t}} \qquad \text{Eq. 6}$$

Where *G(x,y)* and *M(x,y)* are from Eq. 4, y_{start_t} is y value at the top of Area 3 at pixel *x*, y_{dist_t} is the number of pixels from the top of Area 3 to the bottom of Area 3 at pixel *x*.

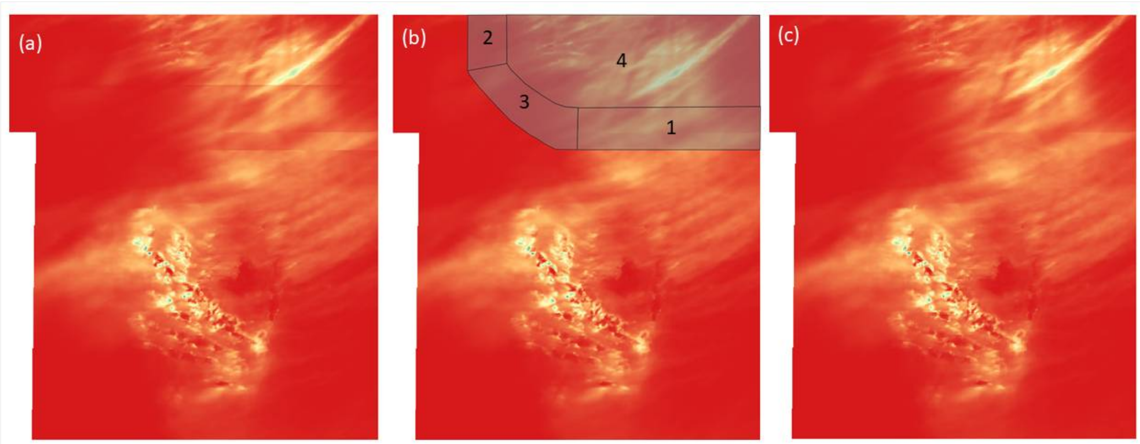

Figure 31 Example of blended images for Grafton, Marburg and Mount Staplton using Equation 1 (figure a), and overlap area (figure b), used to create the image with additional blend (figure c)

The blended radar surfaces are compared with hourly rainfall data from six stations of the flood network in Figure 32. The comparison suggests that both data present similar timings of peak rainfall, but important discrepancies remain in terms of rainfall totals. Generally, the radars generate higher rainfall totals compared to point data except for the Grafton Research station (Figure 32.b) where radar rainfall was not reporting any rainfall during the event. These results require more investigation because Seed et al. (2007) indicate that radar processing undertaken in the Rainfields product includes corrections to nudge the surfaces towards on-ground observations. Consequently, the large discrepancies shown in Figure 32 are unexpected. The first explanation for these discrepancies is that the nudging process of radar data did not incorporate the stations chosen in Figure 32. One could also argue that the discrepancies are introduced during the blending process. However, plots similar to Figure 32 are obtained (not shown) when using data from the three individual radars prior to the blending process. These plots showed the same discrepancies which rules out the blending process for their cause.

Figure 32 Comparison between hourly rainfall from rain gauge and blended radar

The averaging of radar rainfall surfaces over catchment areas was computed based on Eq. 2 from Appendix C.

Appendix E AWRA-L model performance against observed streamflow data

This appendix presents the performance of the nationally calibrated AWRA-L landscape water balance model version 6.0. The model outputs are publicly available from the Bureau of Meteorology website (BoM, 2022c) and the model source code can be downloaded from the associated code repository (BoM, 2019).

This appendix presents the evaluation of the simulated streamflow computed by averaging the grid cell runoff generated by the AWRA-L model to catchment corresponding to each streamflow gauging stations in the Northern Rivers region (see list of stations in Table 23).

Three performance metrics are computed from observed and simulated streamflows. First, the Nash-Sutcliffe efficiency (NSE) is a metric measuring the accuracy of daily streamflow time series as follows:

$$N = 1 - \frac{\sum_t (q_t^* - q_t)^2}{\sum_t (\bar{q} - q_t)^2} \qquad \text{Eq. 7}$$

Where q_t and q_t^* are observed and simulated daily streamflow for day t (m^3/sec), and $\bar{q}$ is the mean daily flow (m^3/sec). The NSE has a maximum value of 1 indicating a perfect match between observed and simulated flows. A value above 0.6 is considered desirable for hydrological simulations, although this threshold varies greatly with the characteristics of the streamflow time series.

Second, the bias measures the accuracy of the mean daily streamflow as follows:

$$B = \frac{\bar{q}^* - \bar{q}}{\bar{q}} \qquad \text{Eq. 8}$$

Where $\bar{q}^*$ is the simulated mean daily streamflow. Bias has an optimal value of 0 indicating a perfect match between observed and simulated mean daily streamflows. A value between -0.1 and 0.1 is considered desirable for hydrological simulations.

Finally, the Spearman rank correlation is computed from observed and simulated annual maximum series (AMS). AMS were derived from instantaneous data for observed streamflow and daily time series for AWRA-L. The Spearman rank correlation was computed as follows:

$$C = \frac{\sum_y (r_y^* - \bar{r}^*)(r_y - \bar{r})}{\sqrt{\sum_y \left(r_y^* - \bar{r}^*\right)^2} \sqrt{\sum_y \left(r_y - \bar{r}\right)^2}} \qquad \text{Eq. 9}$$

Where r_t and r_t^* are the ranks of the observed and simulated AMS value for year y, respectively. This metric has a maximum of 1 denoting a perfect agreement between observed and simulated ranks.

A summary of performance metrics is provided in the main part of this report in Table 11.

Table 26 Performance metrics for AWRA-L simulated streamflow

BASIN	STATION ID	NAME	PERIOD OF EVALUATION	NSE OF DAILY STREAMFLOW (-)	BIAS OF DAILY STREAMFLOW (-)	SPEARMAN RANK CORRELATION OF AMS (-)
Clarence						
	204001	Nymboida River At Nymboida	1956-06-17 to 2022-07-26	0.68	0.15	0.92
	204002	Clarence River At Tabulam	1965-07-09 to 2022-07-31	0.68	-0.15	0.95
	204004	Mann River At Jackadgery	1963-11-02 to 2022-07-26	0.71	0.08	0.9
	204006	Bookookoorara River At Undercliffe	1983-03-01 to 2022-07-31	0.38	-0.41	0.58
	204007	Clarence River At Lilydale (Newbold Crossing)	1971-08-15 to 2022-07-28	0.74	-0.04	0.95
	204008	Guy Fawkes River At Ebor	1973-10-11 to 2022-06-09	0.6	-0.53	0.79
	204014	Mann River At Mitchell	1972-05-12 to 2022-05-02	0.46	-0.18	0.85
	204015	Boyd River At Broadmeadows	1970-05-28 to 2022-06-23	0.72	0.17	0.93
	204017	Bielsdown Creek At Dorrigo No.2 & No.3	1971-08-20 to 2022-07-31	0.55	-0.5	0.82
	204025	Orara River At Karangi	1969-11-02 to 2022-07-04	0.73	0.01	0.88
	204030	Aberfoyle River At Aberfoyle	1977-08-31 to 2022-06-09	0.51	-0.24	0.63
	204031	Mann River At Shannon Vale	1984-04-20 to 2022-06-24	0.44	0.14	0.75
	204033	Timbarra River At Billyrimba	1978-03-09 to 2022-05-06	0.66	-0.1	0.9
	204034	Henry River At Newton Boyd	1971-08-18 to 2022-06-23	0.51	-0.29	0.74
	204036	Cataract Creek At Sandy Hill(Below Snake Creek)	1952-03-16 to 2022-05-05	0.3	-0.43	0.79
	204037	Clouds Creek At Clouds Creek	1971-02-18 to 2022-07-27	0.49	0.54	0.78
	204039	Maryland River D/S Wylie Creek	1979-03-10 to 2022-05-05	0.42	-0.21	0.83
	204041	Orara River At Bawden Bridge	1960-07-01 to 2022-07-28	0.72	-0.07	0.97
	204043	Peacock Creek At Bonalbo	1960-03-27 to 2022-07-31	0.59	0.14	0.8
	204046	Timbarra River At Drake	1969-07-12 to 2022-07-31	0.64	-0.2	0.92
	204051	Clarence River At Paddys Flat	1976-03-28 to 2022-07-31	0.53	-0.36	0.94
	204055	Sportsmans Creek At Gurranang Siding	1972-03-01 to 2022-07-29	0.63	-0.25	0.86
	204056	Dandahra Creek At Gibraltar Range	1975-05-25 to 2022-07-26	0.38	-0.64	0.82
	204067	Gordon Brook At Fineflower	1983-04-23 to 2022-07-28	0.64	-0.19	0.86

BASIN	STATION ID	NAME	PERIOD OF EVALUATION	NSE OF DAILY STREAMFLOW (-)	BIAS OF DAILY STREAMFLOW (-)	SPEARMAN RANK CORRELATION OF AMS (-)
	204068	Orara River At Orange Grove	1995-08-16 to 2022-07-31	0.68	-0.08	0.86
	204069	Nymboida River D/S Nymboida Weir	1997-09-19 to 2022-07-27	0.74	0.21	0.92
	204071	Bielsdown River At Charlestead	2003-05-23 to 2022-07-31	0.75	-0.28	0.82
	204900	Clarence River At Baryulgil	1971-07-16 to 2022-07-27	0.69	-0.25	0.92
	204906	Orara River At Glenreagh	1972-11-17 to 2022-07-31	0.75	0.21	0.91
Richmond						
	203002	Coopers Creek At Repentance	1976-11-06 to 2022-07-29	0.57	-0.28	0.85
	203004	Richmond River At Casino	1970-03-22 to 2022-06-14	0.68	-0.16	0.92
	203005	Richmond River At Wiangaree	1971-07-02 to 2022-07-19	0.65	-0.16	0.93
	203010	Leycester River At Rock Valley	1967-06-19 to 2022-06-15	0.52	-0.19	0.94
	203012	Byron Creek At Binna Burra	1977-10-09 to 2022-07-29	0.55	-0.15	0.85
	203014	Wilsons River At Eltham	1957-08-24 to 2022-07-28	0.72	-0.1	0.87
	203024	Coopers Creek At Ewing Bridge	1982-06-29 to 2022-07-28	0.65	-0.07	0.9
	203030	Myrtle Creek At Rappville	1979-09-29 to 2022-06-14	0.7	0.07	0.92
	203034	Eden Creek At Doubtful	2001-09-01 to 2022-07-20	0.73	-0.05	0.89
	203041	Shannon Brook At Yorklea	1979-03-09 to 2022-07-19	0.47	0.26	0.86
	203056	Richmond River At Lavelles Road	2010-10-29 to 2022-06-15	0.58	0.35	0.82
	203057	Houghlahans Creek At Upstream Teven	2010-11-05 to 2022-07-29	0.54	-0.21	0.76
	203059	Marom Creek At Graham Road	2011-08-04 to 2022-07-25	0.61	-0.22	0.94
	203060	Coopers Creek At Fairmeadow	2011-08-04 to 2022-07-28	0.77	-0.09	0.87
	203061	Goolmangar Creek At Mcnamara Bridge Weir	2011-08-04 to 2022-06-16	0.7	-0.18	0.78
	203062	Wilsons River At Lavertys Gap Weir	2016-03-10 to 2022-07-26	0.75	-0.03	0.94
	203900	Richmond River At Kyogle	1985-06-02 to 2022-07-19	0.72	-0.05	0.93
Tweed						
	201001	Oxley River At Eungella	1957-03-05 to 2022-07-27	0.62	-0.08	0.88
	201005	Rous River At Boat Harbour No.3	1957-04-04 to 2022-07-27	0.52	-0.35	0.88
	201012	Cobaki Creek At Cobaki	1982-06-11 to 2022-07-26	0.56	-0.02	0.75
	201015	Tweed River D/S Palmers Road Crossing	2009-04-29 to 2022-07-26	0.6	0.1	0.94
	201900	Tweed River At Uki	1967-06-30 to 2022-07-26	0.46	0.47	0.84

BASIN	STATION ID	NAME	PERIOD OF EVALUATION	NSE OF DAILY STREAMFLOW (-)	BIAS OF DAILY STREAMFLOW (-)	SPEARMAN RANK CORRELATION OF AMS (-)
Brunswick						
	202001	Brunswick River At Durrumbul (Sherrys Crossing)	1971-10-20 to 2022-07-26	0.59	0.1	0.85
	202002	Burringbar Creek At Burringbar	2010-11-04 to 2022-07-27	0.22	0.75	0.87

Data source: Continuous Water Monitoring Network, WaterNSW (2022), AWRA-L simulations, Australian Water Outlook, BoM (2022c)

Appendix F Major and minor flood events in the Northern Rivers region

This appendix supports section 4.1 and provides a list of significant floods in the Northern Rivers region. Table 27 indicates the start and end date of the event along with the maximum daily basin average rainfall computed from the AGCD grids (see section 3.2.2). The ranking of the event among all the events listed in the table is provided next to the rainfall values for the top 3 events.

Table 27 Major and minor flood events in the Northern Rivers region

NAME	START	END	MAXIMUM DAILY BASIN AVERAGE RAINFALL (mm/day)							
			CLARENCE		RICHMOND		TWEED		BRUNSWICK	
Jun-45	5-Jun-45	21-Jun-45	110		152		224		181	
Jun-48	11-Jun-48	26-Jun-48	104		156		145		142	
Feb-54	16-Feb-54	2-Mar-54	186	*#1*	232	*#2*	284		253	
Feb-56	13-Feb-56	28-Feb-56	72		145		281		218	
Jul-62	6-Jul-62	21-Jul-62	104		145		144		219	
Jul-65	16-Jul-65	31-Jul-65	83		174		253		198	
Mar-67	14-Mar-67	29-Mar-67	44		89		91		115	
Jun-67	10-Jun-67	25-Jun-67	111		89		210		109	
Jan-68	10-Jan-68	20-Jan-68	80		55		71		71	
Oct-72	24-Oct-72	8-Nov-72	77		89		192		185	
Mar-74	6-Mar-74	25-Mar-74	108		150		223		243	
Mar-75	1-Mar-75	10-Mar-75	31		90		107		149	
Feb-76	10-Feb-76	10-Mar-76	130		155		222		202	
Mar-78	12-Mar-78	22-Mar-78	40		95		192		174	
May-80	1-May-80	15-May-80	122		141		189		152	
Jun-83	1-Jun-83	15-Jul-83	28		63		126		106	
Apr-84	30-Mar-84	20-Apr-84	46		126		222		236	
Mar-87	1-Mar-87	16-Mar-87	44		149		170		201	
May-87	6-May-87	21-Jul-87	35		105		208		211	
Apr-88	1-Apr-88	20-Apr-88	74		101		169		150	
Apr-89	30-Mar-89	10-Apr-89	85		165		327	*#3*	195	
Feb-90	1-Feb-90	10-Feb-90	64		115		221		156	
May-96	1-May-96	17-May-96	110		119		164		129	
Feb-01	25-Jan-01	12-Feb-01	104		188		287		314	#2
Mar-01	8-Mar-01	25-Mar-01	145	*#3*	124		76		92	
Mar-04	20-Feb-04	25-Mar-04	63		110		210		164	
Jun-05	25-Jun-05	5-Jul-05	85		149		189		242	
Jan-08	31-Dec-07	20-Jan-08	80		122		191		130	

NAME	START	END	MAXIMUM DAILY BASIN AVERAGE RAINFALL (mm/day)							
			CLARENCE		RICHMOND		TWEED		BRUNSWICK	
May-09	20-May-09	10-Jun-09	142		147		145		166	
Jan-11	1-Jan-11	30-Jan-11	86		44		59		72	
Jan-12	21-Jan-12	31-Jan-12	53		64		174		114	
Jan-13	10-Jan-13	15-Feb-13	145	*#2*	138		259		226	
Feb-13	15-Feb-13	10-Mar-13	116		97		71		84	
May-15	27-Apr-15	12-May-15	97		130		132		137	
Jun-16	1-Jun-16	15-Jun-16	98		122		162		246	
Apr-17	25-Mar-17	15-Apr-17	91		210	*#3*	368	*#2*	300	#3
Feb-20	9-Feb-20	24-Feb-20	74		61		131		134	
Dec-20	10-Dec-20	25-Dec-20	81		103		212		162	
Feb-22	22-Feb-22	15-Mar-22	102		296	*#1*	414	*#1*	482	#1
Apr-22	24-Mar-22	10-Apr-22	77		116		175		165	

Data source: Appendix G, AGCD rainfall grids, Australian Water Outlook, BoM (2022c)

Appendix G Published studies related to flooding in the Northern Rivers region

This appendix summarises the published studies related to flooding in the Northern Rivers region. This list and the associated comments were extracted from the NSW Flood Data portal (NSW, 2022) and from data provided by the LGAs in the region.

Table 28 List of studies related to flooding in the Northern Rivers region

BASIN	LGA	TYPE	TITLE	COMMENT	PUBLICATION DATE	SOURCE	URL
Clarence							
	-	Guidance, Tools and Resources	Woolgoolga to Ballina Pacific Highway Upgrade - Hydrological Mitigation Report - Glenugie to Devils Pulpit	This document forms the hydrological mitigation report for the portion of the Clarence River regional floodplain crossed by the Woolgoolga to Ballina Pacific Highway upgrade.	27/03/2017	Pacific Highway Upgrade project	https://pacifichighway.nsw.gov.au/document-library/hydrological-mitigation-report-summary-glenugie-to-devils-pulpit-clarence
	-	Local Flood Plan	Clarence Valley Flood Emergency Sub Plan	The Clarence Valley Flood Emergency Sub Plan is a sub plan of the Clarence Valley Local Emergency Management Plan (EMPLAN).	3/07/2017	Clarence Valley Council	https://www.clarence.nsw.gov.au/Council/Our-performance/Plans-and-strategies/Clarence-Valley-Flood-Emergency-Sub-Plan
	Clarence	Guidance, Tools and Resources	Clarence River Palmers Island - Bank Erosion Study	Erosion at Palmers Island is studied as the natural outcome of river migration on the valley floodplain.	1/01/1982	NSW Flood Data Portal	https://flooddata.ses.nsw.gov.au/flood-projects/clarence-river-palmers-island-bank-erosion-study
	Clarence	Guidance, Tools and Resources	South Grafton - Levee Local Flooding	This investigation has been carried out to determine the likely level of local flooding in South Grafton for different levee arrangements.	1/06/1984	NSW Flood Data Portal	https://flooddata.ses.nsw.gov.au/flood-projects/south-grafton-levee-local-flooding

BASIN	LGA	TYPE	TITLE	COMMENT	PUBLICATION DATE	SOURCE	URL
	Clarence	Guidance, Tools and Resources	Clarence River - Maximum Probable Flood Estimate at Grafton	The objective of the runoff study was to determine the maximum probable flood hydrograph at Grafton by runoff routing methods, using probable maximum precipitation (PMP) data supplied by Weatherex Pty. Ltd.	1/11/1984	NSW Flood Data Portal	https://flooddata.ses.nsw.gov.au/flood-projects/clarence-river-grafton-maximum-probable-flood-estimate
	Clarence	Guidance, Tools and Resources	Probable Maximum Precipitation Study for the Clarence River Catchment	As part of the investigations relating to the levee bank proposals, the Public Works Department (PWD) commissioned Weatherex Meteorological Services Pty. Ltd. in September, 1983 to estimate the probable maximum precipitation for the Clarence River catchment.	1/11/1984	NSW Flood Data Portal	https://flooddata.ses.nsw.gov.au/flood-projects/clarence-river-catchment-probable-maximum-precipitation-study
	Clarence	Guidance, Tools and Resources	Palmers Island: Bank Erosion Assessment & Management Plan	Patterson Britton & Partners was engaged by Maclean Shire Council to carry out an investigation into the structural and non-structural options available to resolve both the short term and long term community risks associated with progressive and severe riverbank erosion at Palmers Island Village, Clarence River.	1/12/1992	NSW Flood Data Portal	https://flooddata.ses.nsw.gov.au/flood-projects/palmers-island-bank-erosion-assessment-management-plan
	Clarence	Guidance, Tools and Resources	Clarence River - Data Compilation Study	This report was prepared to assist with the assembly and preliminary interpretation of data relevant to estuarine processes and management of the Clarence River.	1/03/1995	NSW Flood Data Portal	https://flooddata.ses.nsw.gov.au/flood-projects/clarence-river-data-compilation-study

BASIN	LGA	TYPE	TITLE	COMMENT	PUBLICATION DATE	SOURCE	URL
	Clarence	Flood study	Alipou Creek Flood Study	In August 1997, Water Studies Ply Ltd was requested by Clarence River County Council (CRCC) to undertake a flood study to investigate flooding behaviour in the Alipou Basin (i.e. areas bounded by Heber Street, Alipou Basin and Clarenza Levees) in South Grafton in general, and determine the impact of the recently constructed Heber Street Levee on flood levels in the above area in particular.	1/02/1998	NSW Flood Data Portal	https://flooddata.ses.nsw.gov.au/flood-projects/alipou-creek-flood-study
	Clarence	Floodplain Risk Management Plan	Lower Clarence River Floodplain Management Plan	The study area comprises the floodplain of the Lower Clarence River within Maclean Shire. This encompasses all of the floodplain of the river downstream of and including Brushgrove. It includes the associated tributaries and branches, as well as the Broadwater and Wooloweyah Lagoon, south of Yamba.	1/09/1999	NSW Flood Data Portal	https://flooddata.ses.nsw.gov.au/flood-projects/lower-clarence-river-floodplain-management-plan
	Clarence	Flood study	Lower Clarence River Flood Study Review (Vol 1)	This study examines and defines the flood behaviour of the Lower Clarence River from Mountain View (approximately 10km upstream of Grafton) to the ocean outlet at Yamba.	1/01/2003	NSW Flood Data Portal	https://flooddata.ses.nsw.gov.au/flood-projects/lower-clarence-river-flood-study-review-vol-1
	Clarence	Geotech Report on levee	Levee Stability & Structural Integrity Investigation at Grafton City Services Bowling & Sporting Club	The Clarence River County Council (CRCe) constructed the levee in North Grafton in 1969, with a crest level equal to a 1% AEP flood or thereabouts. The majority of the levee is situated along the top of the riverbank. The levee comprises of sections of reinforced concrete, concrete block, compacted earth, and in some sections existing building walls were utilised. The investigation comprised the drilling of five vertical boreholes along the alignment of the levee banks and walls.	1/03/2003	NSW Flood Data Portal	https://flooddata.ses.nsw.gov.au/flood-projects/grafton-city-services-bowling-sporting-club-levee-stability-structural-integrity-investigation

BASIN	LGA	TYPE	TITLE	COMMENT	PUBLICATION DATE	SOURCE	URL
	Clarence	Flood study	Lower Clarence River Flood Study Review	This study examines and defines the flood behaviour of the Lower Clarence River from Mountain View (approximately 10km upstream of Grafton) to the ocean outlet at Yamba.	2/04/2004	NSW Flood Data Portal	https://flooddata.ses.nsw.gov.au/flood-projects/lower-clarence-river-flood-study-review
	Clarence	Floodplain Risk Management Plan	Iluka Floodplain Risk Management Plan	The objectives of this Plan are: (1) to review the nature and extent of the flood hazard in light of the recently completed Lower Clarence River Flood Study Review (March 2004), (2) to review the existing management measures aimed at reducing the impact of flooding on both existing and future development, (3) to develop a Plan that addresses the current and future flooding issues for the township of Iluka.	23/03/2007	NSW Flood Data Portal	https://flooddata.ses.nsw.gov.au/flood-projects/iluka-floodplain-risk-management-plan
	Clarence	Flood study	Grafton & Lower Clarence Floodplain Risk Management Plan	The study area essentially covers the Lower Clarence River floodplain downstream of Junction Hill, except those areas that are covered by separate floodplain management studies that are being undertaken by others concurrently.	1/06/2007	NSW Flood Data Portal	https://flooddata.ses.nsw.gov.au/flood-projects/grafton-lower-clarence-floodplain-risk-management-plan
	Clarence	Flood study	Dorrigo Flood Study	The Dorrigo Flood Study has been undertaken to provide flood information for establishment of a floodplain risk management plan for Dorrigo. The end use of this studywill most likely be for the setting of development controls and addressing flood access issues.	1/12/2007	NSW Flood Data Portal	https://flooddata.ses.nsw.gov.au/flood-projects/dorrigo-flood-study

BASIN	LGA	TYPE	TITLE	COMMENT	PUBLICATION DATE	SOURCE	URL
	Clarence	Floodplain Risk Management Study	Yamba Floodplain Risk Management Study	The objectives of this Study are: (1) to review the nature and extent of the flood hazard in light of the recently completed Lower Clarence River Flood Study Review (March 2004), (2) to assess a range of management measures for existing and proposed development, (3) to determine potential impacts of future development and assess options to mitigate these impacts.	13/10/2008	NSW Flood Data Portal	https://flooddata.ses.nsw.gov.au/flood-projects/yamba-floodplain-risk-management-study
	Clarence	Floodplain Risk Management Plan	Yamba Floodplain Risk Management Plan	The objectives of this Plan are: (1) to review the management measures described in the Yamba Floodplain Risk Management Study aimed at reducing the impact of flooding on both existing and future development, (2) to list the agreed measures for addressing the current and future flooding issues for the township of Yamba.	1/02/2009	NSW Flood Data Portal	https://flooddata.ses.nsw.gov.au/flood-projects/yamba-floodplain-risk-management-plan
	Clarence	Flood study	Orara River Flood Study	The primary objective of this study was to define the main-stream flood behaviour under historical conditions and design flood behaviour under existing and future climate conditions in the study area.	18/06/2012	NSW Flood Data Portal	https://flooddata.ses.nsw.gov.au/flood-projects/orara-river-flood-study
	Clarence	Flood study	Glenreagh Flood Study	This study focussed on the village of Glenreagh, located in the Orara River and Bucca Bucca Creek (Bucca Creek) catchments. These catchments lie to the west of Coffs Harbour forming part of the Clarence River catchment.	1/09/2013	NSW Flood Data Portal	https://flooddata.ses.nsw.gov.au/flood-projects/glenreagh-flood-study-extension-of-orara-flood-study
	Clarence	Floodplain Risk Management Plan	Grafton and Lower Clarence Floodplain Risk Management Plan: Review of Brushgrove Section	Clarence Valley Council has decided to reassess the preferred flood mitigation measures recommended in the Grafton and Lower Clarence Floodplain Risk Management Plan for Brushgrove, in the current study.	7/02/2014	NSW Flood Data Portal	https://flooddata.ses.nsw.gov.au/flood-projects/brushgrove-floodplain-risk-management-plan-review

BASIN	LGA	TYPE	TITLE	COMMENT	PUBLICATION DATE	SOURCE	URL
	Kyogle	Floodplain Risk Management Study and Plan	Tabulam Floodplain Risk Management Study and Plan	Final reports, model and spatial data	10/12/2019	NSW Flood Data Portal	https://flooddata.ses.nsw.gov.au/flood-projects/tabulam-floodplain-risk-management-study-and-plan
Richmond							
	-	Floodplain Risk Management Study	Richmond Valley Floodplain Management Study	This study is one of a series of thirteen valley studies completed in the early 1980s to examine flood management measures of the major coastal rivers in NSW.	1/12/1980	NSW Flood Data Portal	https://flooddata.ses.nsw.gov.au/flood-projects/richmond-valley-floodplain-management-study
	-	Flood study	Richmond Valley Floodplain Atlas	This is an atlas of the floodplain of the Richmond River Valley. Includes townships of Kyogle, Casino, Lismore, Coraki, Woodburn, Broadwater, Wardell and Ballina.	1/02/1982	NSW Flood Data Portal	https://flooddata.ses.nsw.gov.au/flood-projects/richmond-valley-floodplain-atlas
	-	Flood study	Lower Richmond River Urban Flood Plain Atlas	Flood maps of urban areas along Richmond River. Flood extents are provided for the 1 in 20 year, 1 in 50 year and 1 in 100 year AEP flood events.	1/05/1983	NSW Flood Data Portal	https://flooddata.ses.nsw.gov.au/flood-projects/lower-richmond-river-urban-flood-plain-atlas
	-	Local Flood Plan	Ballina Shire Flood Emergency Sub Plan	The Ballina Shire Flood Emergency Sub Plan is a sub plan of the Ballina Shire Council Local Emergency Management Plan (EMPLAN).	12/07/2013	Ballina Shire Council	https://www.ses.nsw.gov.au/media/1726/plan-ballina-shire-lfp-july-2013-endorsed.pdf
	-	Local Flood Plan	Kyogle Flood Emergency Sub Plan	The Kyogle Flood Emergency Sub Plan is a sub plan of the Kyogle Local Emergency Management Plan (EMPLAN).	25/07/2013	Kyogle City Council	https://www.ses.nsw.gov.au/media/1728/plan-kyogle-fesp-july-2013-endorsed.pdf
	-	Local Flood Plan	Richmond Valley Flood Emergency Sub Plan	The Richmond Valley Flood Emergency Sub Plan is a sub plan of the Richmond Valley Local Emergency Management Plan (EMPLAN).	26/07/2013	Richmond Valley Council	https://www.ses.nsw.gov.au/media/1730/plan-richmond-valley-fesp-july-2013-endorsed.pdf
	-	Guidance, Tools and Resources	Richmond River Flood Warning and Evacuation Management Review	This review includes an assessment of the adequacy of the current system, as well as identification of gaps and recommendations to improve the system to meet the needs of the community.	20/10/2014	Rous County Council	https://rous.nsw.gov.au/richmond-river-flood-mapping-study

BASIN	LGA	TYPE	TITLE	COMMENT	PUBLICATION DATE	SOURCE	URL
	-	Guidance, Tools and Resources	Woolgoolga to Ballina Pacific Highway Upgrade - Hydrological Mitigation Report - Devils Pulpit to Ballina	This document forms the hydrological mitigation report for the portion of the Clarence River regional floodplain crossed by the Woolgoolga to Ballina Pacific Highway upgrade.	24/04/2017	Pacific Highway Upgrade project	https://www.pacifichighway.nsw.gov.au/document-library/hydrological-mitigation-report-summary-devils-pulpit-to-ballina-richmond-catchment
	-	Local Flood Plan	Lismore City Flood Emergency Sub Plan	The Lismore City Flood Emergency Sub Plan is a sub plan of the Lismore City Local Emergency Management Plan (EMPLAN).	7/03/2018	Lismore City Council	https://www.ses.nsw.gov.au/media/2686/lismore-city-lfp-mar-2018-endorsed.pdf
	Ballina	Flood study	Ballina Flood Study Update	This report is a technical document designed to describe the development and simulation of the flood model and present the simulation results as GIS-based flood mapping.	1/03/2008	NSW Flood Data Portal	https://flooddata.ses.nsw.gov.au/flood-projects/ballina-flood-study-update
	Ballina	Floodplain Risk Management Plan	Cabbage Tree Island - Floodplain Risk Management Plan	his Plan documents the preferred floodplain risk management options for Cabbage Tree Island and incorporates them into a program of works that identifies the likely cost of each measure and their projected benefit to the community.	2/11/2009	NSW Flood Data Portal	https://flooddata.ses.nsw.gov.au/flood-projects/cabbage-tree-island-floodplain-risk-management-plan
	Ballina	Floodplain Risk Management Plan	Wardell Floodplain Risk Management Plan	This document involves the development of a plan of action for reducing existing flood damages, minimising the potential for further problems in the future and providing mechanisms for flood emergency response management.	2/11/2009	NSW Flood Data Portal	https://flooddata.ses.nsw.gov.au/flood-projects/wardell-floodplain-risk-management-plan
	Ballina	Floodplain Risk Management Study	Ballina Floodplain Risk Management Study	This study considers the flooding behaviour of Emigrant Creek, Maguires Creek, North Creek and the lower Richmond River.	12/01/2012	NSW Flood Data Portal	https://flooddata.ses.nsw.gov.au/flood-projects/ballina-floodplain-risk-management-study
	Ballina	Floodplain Risk Management Plan	Ballina Floodplain Risk Management Plan	This Plan aims to mitigate flood risk in the study area and is based on the conclusions and recommendations of the preceding Ballina Floodplain Risk Management Study	14/01/2015	NSW Flood Data Portal	https://flooddata.ses.nsw.gov.au/flood-projects/ballina-floodplain-risk-management-plan

BASIN	LGA	TYPE	TITLE	COMMENT	PUBLICATION DATE	SOURCE	URL
	Kyogle	Guidance, Tools and Resources	Kyogle - Flood Mapping Study	The HEC-2 backwater model developed by the US Corps of Engineers was to be used to predict flood levels. The model was to be calibrated against known flood levels associated with a specific flood and then used to predict flood levels associated with flood events with return periods of 20 years, 50 years and 100 years.	1/08/1983	NSW Flood Data Portal	https://flooddata.ses.nsw.gov.au/flood-projects/kyogle-flood-mapping-study
	Kyogle	Guidance, Tools and Resources	Kyogle - Flood Inundation Map	This map shows on an ortho-photo base, areas within and around the Town of Kyogle which are inundated by floods of various intensities.	1/01/1984	NSW Flood Data Portal	https://flooddata.ses.nsw.gov.au/flood-projects/kyogle-flood-inundation-map
	Kyogle	Flood study	Kyogle Flood Study	This study examines and defines the flood behaviour of the Richmond River and Fawcetts Creek around Kyogle township area including the associated floodplain.	1/02/2004	NSW Flood Data Portal	https://flooddata.ses.nsw.gov.au/flood-projects/kyogle-flood-study-2004
	Kyogle	Floodplain Risk Management Study	Kyogle Floodplain Risk Management Study	The primary objective of the Kyogle Floodplain Management Study is to provide information that will lead to the formulation of a Floodplain Management Plan for the Kyogle area.	20/04/2009	NSW Flood Data Portal	https://flooddata.ses.nsw.gov.au/flood-projects/kyogle-floodplain-risk-management-study

BASIN	LGA	TYPE	TITLE	COMMENT	PUBLICATION DATE	SOURCE	URL
	Kyogle	Floodplain Risk Management Plan	Kyogle Floodplain Risk Management Plan	The objectives of the Kyogle Floodplain Risk Management Plan are: (1) To detail cost effective floodplain management measures for the Kyogle township area; (2) To present a brief economic analysis of the proposed floodplain management scheme, including an overall benefit-cost ratio; To develop an implementation plan for the proposed scheme and present a program to illustrate the proposed actions and annual cost estimates associated with the implementation of the measures; and (3) To take into account the funding from Council and both the State and Commonwealth Governments when estimating the cost for implementation.	20/04/2009	NSW Flood Data Portal	https://flooddata.ses.nsw.gov.au/flood-projects/kyogle-floodplain-risk-management-plan
	Lismore	Flood study	Lismore - Flood Study & Floodplain Management Study	This study determines the 1% and 5% Annual Exceedance Probability (AEP) and Probable Maximum Flood (PMF) flood behaviour for Wilsons River and Leycester Creek adjacent to Lismore.	6/08/1993	NSW Flood Data Portal	https://flooddata.ses.nsw.gov.au/flood-projects/lismore-flood-study-floodplain-management-study
	Lismore	Floodplain Risk Management Study	Lismore Floodplain Management Study	As a precursor to the development of a comprehensive Floodplain Management Plan, the objective of this study is to examine the status of Council's floodplain management measures and to identify policy gaps, inconsistencies and areas which require improvement/expansion.	7/05/2001	NSW Flood Data Portal	https://flooddata.ses.nsw.gov.au/flood-projects/lismore-floodplain-management-study
	Lismore	Guidance, Tools and Resources	Lismore Urban Stormwater Management Plan 2007	The overall aim of urban stormwater management in Lismore is to 'improve and maintain the quality of urban runoff in order to protect the natural, ecological and aesthetic values of Lismore's waterways while enhancing the recreational and economic opportunities for our community'.	1/06/2007	NSW Flood Data Portal	https://flooddata.ses.nsw.gov.au/flood-projects/lismore-stormwater-management-plan

BASIN	LGA	TYPE	TITLE	COMMENT	PUBLICATION DATE	SOURCE	URL
	Lismore	Floodplain Risk Management Plan	Lismore Floodplain Risk Management Plan 2014	This Plan applies to the extent of flood prone land in the urban area of the Lismore local government area. This is defined by the extent of the Probable Maximum Flood (PMF), which includes South, North and Central Lismore.	1/01/2014	NSW Flood Data Portal	https://flooddata.ses.nsw.gov.au/flood-projects/lismore-floodplain-risk-management-plan
	Lismore	Guidance, Tools and Resources	Lismore Flood Model - LiDAR update	In 2013, Council received LiDAR information collected by the NSW Department of Land and Property Information (LPI). Given the increased detail in this dataset, and its consistency across the floodplain, Council commissioned WorleyParsons to update the previous model using the LiDAR dataset.	2/02/2016	Lismore City Council	https://lismore.nsw.gov.au/files/Final-Report-Lismore-Flood-Model-LiDAR-Update-Worley-Parsons.PDF
	Lismore	Guidance, Tools and Resources	Review of Rating Curves in the Wilsons River Catchment	The 12 gauge locations that have been assessed are Bentley – Back Creek, Binna Burra - Byron Creek, Eltham – Wilsons River, Ewing Bridge – Coopers Creek, Fairmeadow – Coopers Creek, Goolmangar - Goolmangar Creek, McNamara Weir - Goolmangar Creek, Nashua – Wilsons River, Nimbin – Goolmangar Creek, Repentance – Coopers Creek, Rock Valley – Leycester Creek, The Channon – Terania Cr	9/05/2018	Lismore City Council	-
	Lismore	Floodplain Risk Management Study	Lismore Floodplain Risk Management Study	The key objectives of the Lismore FRMS were: 1. To develop a detailed understanding of the flood risks using detailed and up to date models. 2. To identify and assess potential management measures to address existing, future and continuing/residual risk and guide the development of the Lismore Floodplain Risk Management Plan	13/04/2021	NSW Flood Data Portal	https://flooddata.ses.nsw.gov.au/flood-projects/lismore-floodplain-risk-management-study

BASIN	LGA	TYPE	TITLE	COMMENT	PUBLICATION DATE	SOURCE	URL
	Lismore	Guidance, Tools and Resources	Gauge Rating Curve Review	As part of the Lismore Floodplain Risk Management Study (Lismore FRMS), Engeny Water Management has undertaken a review of available rating curves for gauges located in the Wilson River catchment upstream or at Lismore.	22/02/2019	Lismore City Council	-
	Richmond	Guidance, Tools and Resources	Richmond River Valley - Flood Problems	Volume 1 of the Richmond River Flood Problem Report contains Part A comprising a general report as well as reports on the set Terms of Reference. It also contains a summary of the recommendations arising from the Committee's investigations into various aspects of the flood problem.	1/01/1985	NSW Flood Data Portal	https://flooddata.ses.nsw.gov.au/flood-projects/richmond-river-valley-flood-problems
	Richmond	Flood study	Casino Flood Study	This study examines and defines the flood behaviour of the Richmond River from the confluence of Richmond River and Eden Creek to the Shannon Brook confluence, including the floodplains on both banks.	16/02/1998	NSW Flood Data Portal	https://flooddata.ses.nsw.gov.au/dataset/casino-flood-study-report
	Richmond	Flood study	Mid Richmond Flood Study	This study examines and defines the flood behaviour of the Richmond River throughout the Mid Richmond region by considering flooding influences from the confluence of the Richmond River and Deep Creek to downstream of Broadwater, including sections of Wilsons River and Bungawalbyn Creek and the floodplains on both banks.	6/11/1998	NSW Flood Data Portal	https://flooddata.ses.nsw.gov.au/flood-projects/mid-richmond-flood-study
	Richmond	Guidance, Tools and Resources	Casino - Floodplain Hazard Categories	Casino Floodplain Hazard Categories Map.	1/11/2001	NSW Flood Data Portal	https://flooddata.ses.nsw.gov.au/flood-projects/casino-floodplain-hazard-categories

BASIN	LGA	TYPE	TITLE	COMMENT	PUBLICATION DATE	SOURCE	URL
	Richmond	Floodplain Risk Management Plan	Casino Floodplain Risk Management Plan	The objectives of the Casino Floodplain Risk Management Plan are: (1) to detail cost effective floodplain management measures for the Casino area; (2) to present a brief economic analysis of the proposed scheme, including an overall benefit-cost ratio; (3) to develop an implementation plan for the proposed scheme and present a program to illustrate the proposed actions and annual cost estimates associated with the implementation of the measures; and (4) to take into account the funding from Council and both the State and Commonwealth Governments when estimating the cost for implementation.	31/05/2002	NSW Flood Data Portal	https://flooddata.ses.nsw.gov.au/flood-projects/casino-floodplain-risk-management-plan
	Richmond	Floodplain Risk Management Study	Casino Floodplain Risk Management Study	The primary objective of the Casino Floodplain Risk Management Study is to provide information that will lead to the formulation of a Floodplain Risk Management Plan for Casino.	7/06/2002	NSW Flood Data Portal	https://flooddata.ses.nsw.gov.au/flood-projects/casino-floodplain-risk-management-study
	Richmond	Floodplain Risk Management Study	Mid-Richmond Floodplain Risk Management Study (Exhibition Copy Vol 1 of 2)	The study focuses on the three urban townships of Coraki, Woodburn and Broadwater. However, it also provides assessments for the surrounding rural areas. The primary objective of the Mid-Richmond Floodplain Risk Management Study is to provide information that will lead to the formulation of a Floodplain Risk Management Plan for the Mid-Richmond area.	25/10/2002	NSW Flood Data Portal	https://flooddata.ses.nsw.gov.au/flood-projects/mid-richmond-floodplain-risk-management-study-exhibition-copy-vol-1-of-2

BASIN	LGA	TYPE	TITLE	COMMENT	PUBLICATION DATE	SOURCE	URL
	Richmond	Floodplain Risk Management Plan	Mid-Richmond Floodplain Risk Management Plan (Exhibition Copy)	The objectives of the Mid-Richmond Floodplain Risk Management Plan are: (1) to detail cost effective floodplain management measures for the Mid-Richmond area; (2) to present a brief economic analysis of the proposed scheme, including an overall benefit-cost ratio; (3) to develop an implementation plan for the proposed scheme and present a program to illustrate the proposed actions and annual cost estimates associated with the implementation of the measures; and (4) to take into account the funding from Council and both the State and Commonwealth Governments when estimating the cost for implementation.	25/10/2002	NSW Flood Data Portal	https://flooddata.ses.nsw.gov.au/flood-projects/mid-richmond-floodplain-risk-management-plan-exhibition-copy
	Richmond	Flood study	Richmond River Flood Mapping Study	The key deliverables from this project are: (1) A calibrated hydrologic model covering the entire Richmond River catchment; (2) A calibrated 1D/2D hydraulic model of the floodplain between Casino, Lismore and Broadwater; (3) A comprehensive understanding of flood behaviour across the study area; and (4) Flood mapping of historical and design flood events, in particular flood levels and hazards.	27/04/2010	NSW Flood Data Portal	https://flooddata.ses.nsw.gov.au/flood-projects/richmond-river-flood-mapping-study

BASIN	LGA	TYPE	TITLE	COMMENT	PUBLICATION DATE	SOURCE	URL
	Richmond	Flood study	Evans River Flood Study	The objectives for this study are to: (1) Develop and calibrate a hydraulic model of the Evans River; (2) Use the hydraulic model to define existing flood risk for design events ranging from a 20 year average recurrence interval (ARI) event to the probable maximum flood (PMF); (3) Identify approximate travel times of the riverine flood along the Evans River; (4) Identify any specific access issues to property during flood events; (5) Identify any drainage infrastructure which may be undersized and cause flooding issues; and (6) Assess the likely implications to flood risk under a future (2100) climate by considering sea level rise.	19/11/2014	NSW Flood Data Portal	https://flooddata.ses.nsw.gov.au/flood-projects/evans-river-flood-study
	Richmond	Flood study	Newrybar Swamp Drainage and Flood Mitigation Study	The five objectives of this study are to: (1) Identify the flooding and drainage problems of the Newrybar Swamp; (2) Integrate the flood modelling of the Newrybar Swamp with Ballina's 'integrated' flood model; (3) Investigate and recommend measures to reduce the flood impacts and improve drainage in the Newrybar Swamp; (4) Consider the consequences of climate change; and (5) Extend Ballina Shire Council's flood planning level policy maps to cover the Newrybar Swamp.	16/06/2015	NSW Flood Data Portal	https://flooddata.ses.nsw.gov.au/flood-projects/newrybar-swamp-drainage-and-flood-mitigation-study
Tweed							
	-	Local Flood Plan	Tweed Shire Emergency Sub Plan	The Tweed Shire Flood Emergency Sub Plan is a sub plan of the Tweed Shire Local Emergency Management Plan (EMPLAN).	28/05/2014	Tweed Shire Council	https://www.ses.nsw.gov.au/media/1731/plan-tweed-shire-lfp-may-2014-endorsed.pdf

BASIN	LGA	TYPE	TITLE	COMMENT	PUBLICATION DATE	SOURCE	URL
	Tweed	Guidance, Tools and Resources	New Barneys Point Bridge With Interim Roadway - Flood Simulations	A mathematical flood model of Chinderah was used to simulate the occurrence of a design 1 in 100 year flood for conditions after the proposed bridge construction.	1/11/1984	NSW Flood Data Portal	https://flooddata.ses.nsw.gov.au/flood-projects/new-barneys-point-bridge-with-interim-roadway-flood-simulations
	Tweed	Guidance, Tools and Resources	The Impact of Storm Setup on Estuary Flooding - The Tweed Experience in 1984	The details of the computer runs and the full summary of maximum and minimum velocities, flows and levels are included in the report.	1/04/1986	NSW Flood Data Portal	https://flooddata.ses.nsw.gov.au/flood-projects/tweed-shire-the-impact-of-storm-setup-on-estuary-flooding
	Tweed	Guidance, Tools and Resources	East Murwillumbah & William/Dorothy Streets, Murwillumbah - Floodplain Management Report	This report has been prepared for Tweed Shire Council and investigates floodplain management options for the East Murwillumbah and William/Dorothy Streets Area of the Murwillumbah township.	1/08/1999	NSW Flood Data Portal	https://flooddata.ses.nsw.gov.au/flood-projects/east-murwillumbah-william-dorothy-streets-floodplain-management-report
	Tweed	Guidance, Tools and Resources	Tweed Valley - Floodplain Risk Management Policy	Aims and objectives of this policy: (1) to alert the community to the extent of flood prone land and the severity of flood risk; (2) to inform the community of Council policy in relation to the development and use of flood prone land, with reference to the Local Environment Plan, Development Control Plan and Floodplain Risk Management Studies and Plans; (3) to reduce flood risk and damage to existing areas of development;	18/12/2007	NSW Flood Data Portal	https://flooddata.ses.nsw.gov.au/flood-projects/tweed-valley-floodplain-risk-management-policy

BASIN	LGA	TYPE	TITLE	COMMENT	PUBLICATION DATE	SOURCE	URL
	Tweed	Flood study	Tweed-Byron Coastal Creeks - Flood Study	This Coastal Creeks Flood Study is the first key stage in the floodplain management process as outlined in the New South Wales Floodplain Development Manual. The key outputs of the study, including a 1D/2D hydrodynamic TUFLOW model, design flood levels, depths, velocities and flows across the floodplains, will form the basis for the subsequent Floodplain Risk Management Studies and Plans for each of the coastal creeks.	24/11/2009	NSW Flood Data Portal	https://flooddata.ses.nsw.gov.au/flood-projects/tweed-byron-coastal-creeks-flood-study
	Tweed	Flood study	Tweed Valley - Flood Study Update	The Tweed Valley Flood Study is the first key stage in the floodplain risk management process as outlined in the New South Wales Floodplain Development Manual. The key outputs of the study, including a 2D hydrodynamic model and design flood levels, depths, velocities and flows across the floodplain, will form the basis for identifying and assessing floodplain management options as part of the subsequent Tweed Valley Floodplain Risk Management Study and Plan.	19/12/2009	NSW Flood Data Portal	https://flooddata.ses.nsw.gov.au/flood-projects/tweed-valley-flood-study-update
	Tweed	Floodplain Risk Management Study	Tweed Valley Floodplain Risk Management Study	This Study draws together a wide range of floodplain management options which have been investigated as part of the Tweed Valley Floodplain Risk Management Study.	13/10/2014	NSW Flood Data Portal	https://flooddata.ses.nsw.gov.au/flood-projects/tweed-valley-floodplain-risk-management-study
	Tweed	Floodplain Risk Management Plan	Tweed Valley Floodplain Risk Management Plan	The Tweed Valley Floodplain Risk Management Plan (FRMP) is the result of detailed investigation and consideration of flood risk across the study area in the Tweed Valley Floodplain Risk Management Study (FRMS).	13/10/2014	NSW Flood Data Portal	https://flooddata.ses.nsw.gov.au/flood-projects/tweed-valley-floodplain-risk-management-plan

BASIN	LGA	TYPE	TITLE	COMMENT	PUBLICATION DATE	SOURCE	URL
	Tweed	Floodplain Risk Management Plan	Tweed Coastal Creeks Floodplain Risk Management Plan	The Plan aims to manage and minimise (where practical and possible) flood risk in the Tweed Coastal Creeks area, based on the outcomes of the broader Floodplain Risk Management Study.	10/12/2015	NSW Flood Data Portal	https://flooddata.ses.nsw.gov.au/flood-projects/tweed-coastal-creeks-floodplain-risk-management-plan
	Tweed	Floodplain Risk Management Study and Plan	Murwillumbah CBD Levee & Drainage Study	A study to better define flooding and drainage behaviour within the CBD associated with local catchment runoff as well as levee overtopping.	22/08/2018	NSW Flood Data Portal	https://flooddata.ses.nsw.gov.au/flood-projects/murwillumbah-cbd-levee-drainage-study
	Tweed	Floodplain Risk Management Study and Plan	South Murwillumbah Floodplain Risk Management Study and Plan	A local Floodplain Risk Management Study and Plan for the South Murwillumbah locality.	21/11/2019	NSW Flood Data Portal	https://flooddata.ses.nsw.gov.au/flood-projects/south-murwillumbah-floodplain-risk-management-study-and-plan
Brunswick							
	-	Local Flood Plan	Byron Shire Flood Emergency Sub Plan	The Byron Shire Flood Emergency Sub Plan is a sub plan of the Byron Shire Council Local Emergency Management Plan (EMPLAN).	19/07/2013	Byron Shire Council	https://www.byron.nsw.gov.au/Community/Community-safety/Emergencies-and-disasters/Local-Emergency-Plans
	Byron	Flood study	Tallow Creek Flood Study	The Tallow Creek catchment is located to the south of Byron Bay in New South Wales.	1/11/2002	NSW Flood Data Portal	https://flooddata.ses.nsw.gov.au/flood-projects/tallow-creek-flood-study
	Byron	Flood study	Belongil Creek Flood Study	Belongil Creek is approximately 3km long and has a catchment of around 30 square kilometres. The township of Byron Bay is situated toward the eastern boundary of the catchment with most of the development on higher ground.	12/11/2009	NSW Flood Data Portal	https://flooddata.ses.nsw.gov.au/flood-projects/belongil-creek-flood-study

BASIN	LGA	TYPE	TITLE	COMMENT	PUBLICATION DATE	SOURCE	URL
	Byron	Floodplain Risk Management Plan	Belongil Creek Floodplain Risk Management Plan	The objectives of the Belongil Creek Floodplain Risk Management Plan are: (1) To detail recommended floodplain management measures for the Byron township area; (2) To present a brief economic analysis of the proposed floodplain management scheme, including an overall benefit-cost ratio; (3) To develop an implementation plan for the proposed scheme and present a program to illustrate the proposed actions and annual cost estimates associated with the implementation of the measures;	13/08/2014	NSW Flood Data Portal	https://flooddata.ses.nsw.gov.au/flood-projects/belongil-creek-floodplain-risk-management-plan
	Byron	Flood study	North Byron Shire Flood Study	The primary objective of the North Byron Shire Flood Study is to examine and define the flood behaviour of the North Byron Shire area, including Brunswick River, Marshalls Creek...	5/04/2016	NSW Flood Data Portal	https://flooddata.ses.nsw.gov.au/flood-projects/north-byron-shire-flood-study

Appendix H Method used in flood frequency analysis for the 2022 event

The flood frequency analysis of peak flow data presented in section 5.6 is based on a Bayesian calibration of the GEV probability distribution following the Book 3 of the ARR guidelines (Kuczera & Francks, 2019, section 2.6.3). This appendix provides additional details and a mathematical description of the method.

H.1 Clarification on flood frequency analysis method

Justification of the use of AMS data versus other approaches

Section 5.6.1 introduced the concept of Annual Maxima Series (AMS) as the main data used in the flood frequency analysis. An important limitation of using AMS data in this context is that only one event per year is retained whereas it is not uncommon to see several floods during a year in the Northern Rivers region such as the February/March and late April flood in 2022. AMS are used in this analysis because of their suitability for representing large floods (Kuczera & Francks, 2019, section 2.3.3), the likely independence between AMS data (a key requirement in flood frequency analysis, see Appendix H), and the fact that AMS data can be computed unambiguously (AMS are simply the maximum streamflow during a given water year). Alternative approaches to AMS such as "Peak-Over-Threshold" are suitable for multi-events during a year, but inferior in terms of all the other criteria listed above. In addition, the difference between results derived from AMS and POT are likely to be negligible when evaluating AEP below 10%.

Justification for the use of the Lismore partial inflows

Section 5.6.1 introduced the estimation of the Lismore partial inflows as the sum of the streamflow observed at the Wilsons River at Eltham (203014) and Leycester Creek at Rock Valley (203010) stations. Figure 33 provides additional justification for this computation by showing the relationship between AMS derived from Lismore partial inflows and the AMS derived from water level at the Lismore Rowing club station (Bath & Deguara, 2022). The two AMS series are highly correlated with a Spearman rank correlation of 0.89. In addition, a polynomial curve is fitted to the data suggesting that the relationship between the two series can be represented with a simple equation for most flood events, including February 2022. However, certain events such as February 2001 deviate from the simple relationship, which can be explained by significant contributions from Back, Terania or Coopers creeks that are not accounted for by the partial inflows.

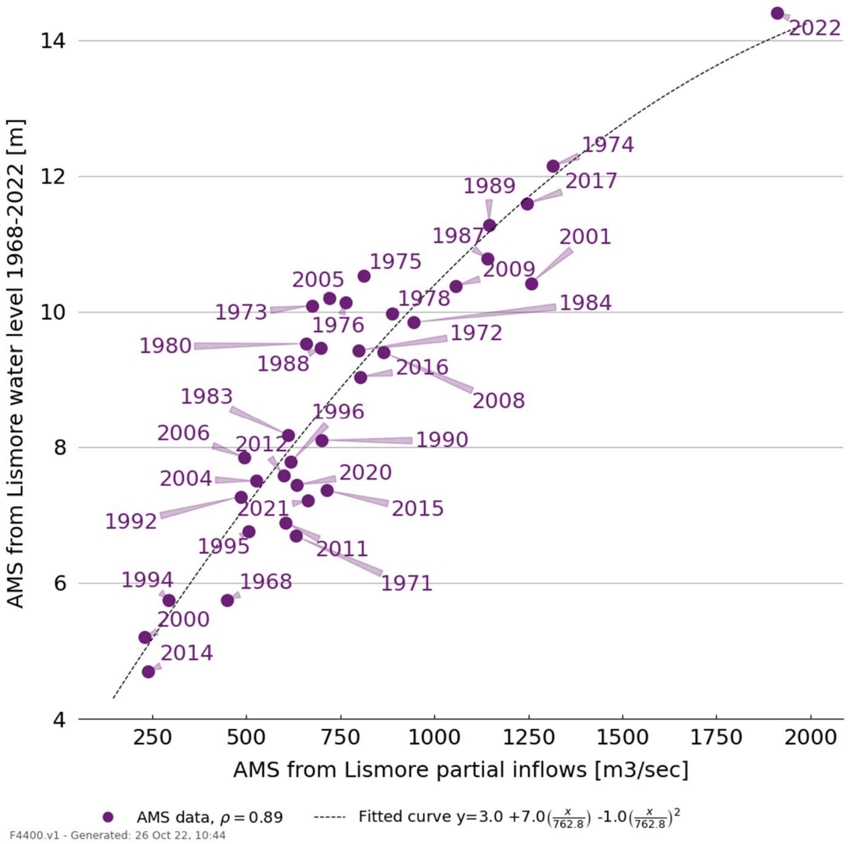

Figure 33 Relationship between AMS data computed from Lismore water levels (H058176) and AMS data computed from Lismore partial inflows (sum of streamflows from Eltham and Rock Valley stations)

Data source: Continuous Water Monitoring Network, WaterNSW (2022), Australian Severe Weather website (Bath & Deguara, 2022)

Use of AWRA-L streamflow covariate to reduce the uncertainty of the fitting

The AWRA-L model presented in section 3.3.1 generates daily estimates of surface water variables across Australia from 1911 until yesterday. Consequently, it offers a valuable insight on extreme floods for periods preceding the start of streamflow records. The value of this information remains limited by the level of accuracy of the AWRA-L model which is explored in section 3.3.1. In addition, the AWRA-L model operates at the daily time step, which is a longer time step than the response time of many catchments (especially in the steep areas) across the Northern Rivers region. The use of AWRA-L data for flood frequency estimation has been done while acknowledging these limitations.

Figure 34 compares AMS data derived from observed and AWRAL-L streamflow for the partial inflows to Lismore described in the section 5.6.1 (sum of flow from the two stations of Eltham and Rock Valley). Figure 34.a and Figure 34.b show the AMS time series for both variables and illustrate the value of AWRA-L in obtaining longer historical records which is known to reduce uncertainty in flood frequency analysis significantly (Viglione et al., 2013).

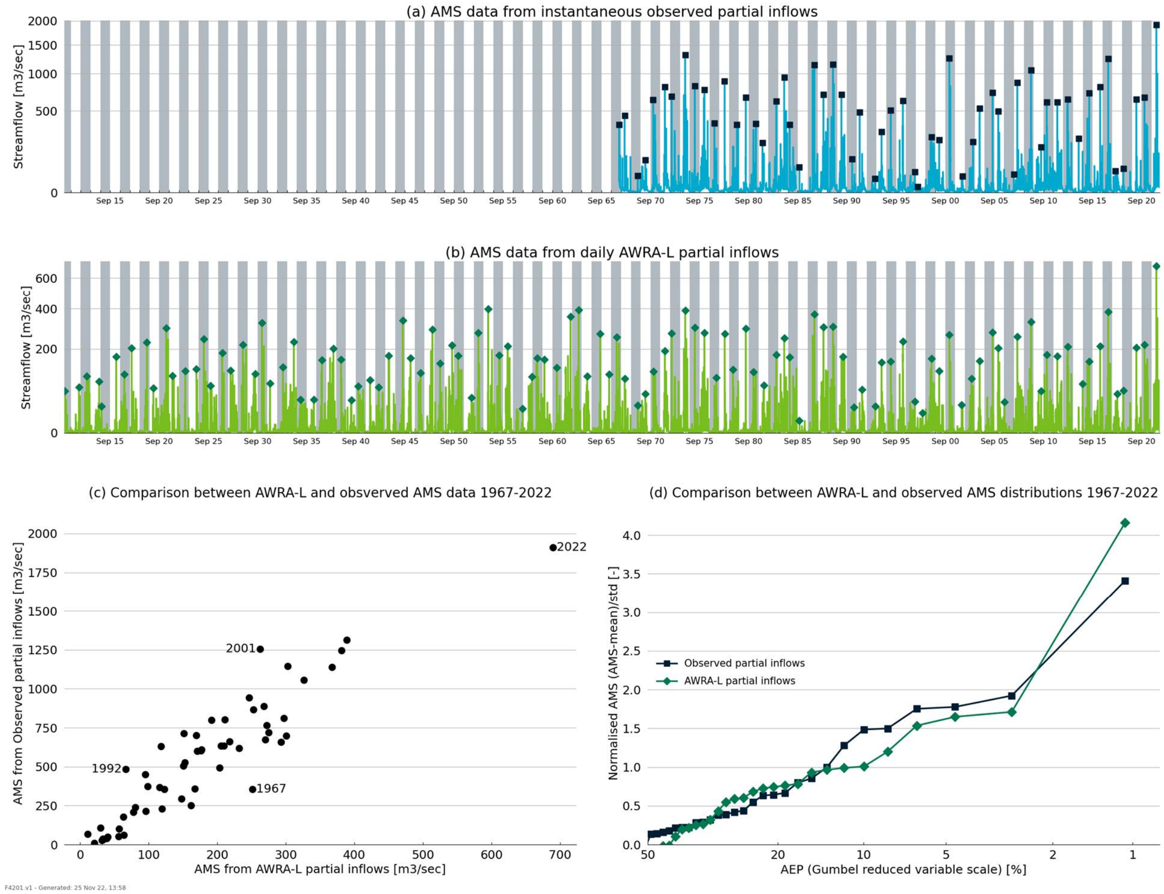

Figure 34 Comparison between AMS data from observed and AWRA-L streamflow for the Lismore partial inflows

Data source: Continuous Water Monitoring Network, WaterNSW (2022), AWRA-L simulations, Australian Water Outlook, BoM (2022c)

Despite the value of the long AWRA-L time series, it can be observed in Figure 34.b that AMS data derived from AWRA-L streamflow exhibit a smaller variability compared to observed AMS (approximately half). This can be explained by the daily time step of AWRA-L which leads to a smoother response and a lower variability compared to the instantaneous time step of observed streamflows. Nonetheless, Figure 34.c compares the two variables in a scatter plot that highlight the high degree of correlation between the two variables except for a few outlier years such as 1967, 1992 and 2001. In Figure 34.d, the distribution of both variables is plotted against AEP using a reduced Gumbel variable scale (see footnote 5 page 60) to highlight rare floods. Note that the variables were standardised by their mean and standard deviation to facilitate the comparison. In this plot, the two distributions appear similar, which supports the idea of fitting them jointly.

All finding from the previous paragraph indicate that AMS data derived from AWRA-L can provide potentially useful information for the flood frequency analysis of observed streamflow, but this additional information cannot be blindly injected in the fitting process. The approach adopted here to perform such transfer was introduced by Wang (2001) and later recommended in the ARR Book 3 (Kuczera & Francks, 2019). The approach introduced by Wang (2001) assumes that AWRA-L and observed AMS data are sampled from two distinct GEV distributions, and that their correlation is governed by a statistical model called a copula. This model allows for the correlation to be high when both variables are in agreement (e.g. for most years shown in

Figure 34.c) and low when they are not. With high correlation, the AWRA-L and observed distribution are jointly fitted and influence each other significantly. Conversely, with low correlation, the fitting of the two distributions remains independent.

The corresponding mathematical model is described in sections H.2 to H.4 of this appendix.

Censoring of low AMS data

AMS data covers a wide range of floods including small events that are well below bank full discharge. These events are of interest for understanding the hydrological regime of a catchment but not for assessing the impact of major floods. Unfortunately, these events can influence the fitting of a probability distribution and distort the frequency analysis of large floods. The Bayesian calibration can reduce the influence of these events by censoring them below a given threshold following the approach described in the ARR Book 3 (Jordan et al., 2019b; Kuczera & Francks, 2019) and NSW Floodplain Management Guide (NSW, 2019, section 3.6.1).

This approach assumes that a censoring threshold is defined and separates the AMS data into uncensored data that are above the threshold and censored data that are below. For the uncensored data, the fitting is identical to the process used prior to censoring. For censored data, the fitting discards the streamflow values and only retain that the data that are below the censor. The mathematical formulation is provided in section H.4 of this appendix.

The censoring thresholds are computed using the Multiple Grubbs-Beck test described by Cohn et al. (2013) and are provided in Table 29 for both observed and AWRA-L simulated streamflows. Note that certain thresholds are adjusted to improve the fit as recommended in Book 3 of the ARR (Kuczera & Francks, 2019). Adjustment consisted in raising the threshold for certain stations where the test led to censoring thresholds of 0. In these cases, and following the recommendation of ARR Book 3, the thresholds were increased while remaining under the upper limit of the median AMS until the fit appeared reasonable.

Table 29 Streamflow gauging stations where flood frequency analysis is performed along with censoring thresholds applied

BASIN	STATION ID	STREAMFLOW MGBT CENSORING THRESHOLD (M3/SEC)	STREAMFLOW FINAL CENSORING THRESHOLD (M3/SEC)	AWRA MGBT CENSORING THRESHOLD (MM/DAY)	AWRA FINAL CENSORING THRESHOLD (MM/DAY)
Clarence					
	204001	858.9	858.9	21.7	21.8
	204002	666.7	666.7	6.4	6.3
	204004	0	1684.9	0	8.5
	204007	0	1907.5	5	7.5
	204008	5.3	5.3	4.4	17
	204014	45.4	45.4	1.6	1
	204015	0	326.5	2.7	2.7
	204017	0	119	6.8	6.8
	204025	58.1	58.1	11.7	42.8
	204030	15.4	15.4	2.3	2.3
	204031	11.9	11.9	2.5	2.1
	204033	0	157	0	3.6

BASIN	STATION ID	STREAMFLOW MGBT CENSORING THRESHOLD (M3/SEC)	STREAMFLOW FINAL CENSORING THRESHOLD (M3/SEC)	AWRA MGBT CENSORING THRESHOLD (MM/DAY)	AWRA FINAL CENSORING THRESHOLD (MM/DAY)
	204034	0	60	0	1.8
	204036	0	83	0	1.9
	204037	33.7	33.7	0	19.7
	204039	0	31.5	0	1.3
	204041	427.5	422.3	19.6	19.6
	204043	9.6	9.6	10.4	10.4
	204046	0	288.2	0	4
	204051	0	376.2	2.7	4.7
	204055	88.1	88.1	8.3	8.3
	204056	0	84.4	0	7.3
	204067	37.9	149.3	11.2	10.9
	204068	227.1	227.1	11.7	42.9
	204069	971.6	971.6	21.2	25.2
	204900	0	1180.5	6.4	6.2
	204906	162.4	162.4	18.1	36.4
Richmond					
	203002	84.2	84.2	39.5	39.5
	203004	152.7	152.7	15.7	1.7
	203005	30.2	251	19.4	19.7
	203010	297.1	297.1	24.5	6.7
	203012	0	92.1	24.1	24.1
	203014	222.4	222.4	21.8	11.1
	203024	124.6	79.6	25	7.3
	203030	76	76	10.8	4.4
	203034	253.4	253.4	12.6	2.8
	203041	33.8	33.8	10	12.8
	203900	286.1	286.1	19.5	19.5
	LISPARTINF	485.3	485.3	28.1	28.1
Tweed					
	201001	450.8	450.8	29.7	29.7
	201012	25.4	25.4	34.2	34.2
	201900	464.5	464.5	34.6	34.6
Brunswick					
	202001	37.7	37.7	28.6	28.6

Sensitivity analysis of streamflow data errors

AMS data are streamflow values that are obtained through rating curves as described in section 3.3.1, which are themselves based on a limited set of point measurements referred to as "gaugings". The use of a rating curve beyond the maximum gauging is hazardous as the relationship between water level and streamflow can change between low and high streamflows. This point is a major concern for flood frequency analysis of extreme floods and has received considerable attention in the scientific literature (Lang et al., 2010; Petersen-Øverleir & Reitan, 2009; Steinbakk et al., 2016). However, no quantitative estimate of streamflow uncertainty is available from data providers for the stations in the Northern Rivers region and it is out of scope to perform such uncertainty estimation within the short duration of the present study.

As a result, the simple streamflow error model presented by Kuczera (1996) and advocated by the ARR Book 3 (Kuczera & Francks, 2019, Section 2.3.7) is implemented where streamflow is assumed to be associated with a multiplicative error above a certain threshold. The error is unknown but has a defined probability distribution (here assumed Gaussian) and a given scale arbitrarily set to 30% as per the recommendations by Kuczera (1996).

This approach remains simplistic and cannot be considered as an accurate estimation of streamflow data uncertainty. Consequently, the impact of streamflow errors on the results needs to be contrasted with results obtained without these errors.

The corresponding mathematical model is presented in section H.4.1 of this appendix.

H.2 Mathematical assumptions underlying the fitting of AMS probability distribution

Let us assume that $\tilde{y} = \{y_1, y_2, \ldots, y_N\}$ and $\tilde{z} = \{z_1, z_2, \ldots z_N\}$ represent Annual Maxima Series (AMS) of N years for the observed streamflow and AWRA-L simulated streamflow at a particular gauging station, respectively. The AWRA-L records starts in 1911, which is earlier than any observed streamflow records in the region. Consequently, we can assume that the first M values in the $\tilde{y}$ series are missing with $M < N$.

The Bayesian calibration assumes that AMS series are independent from one year to the next and that they are sampled from a Generalized Extreme Value (GEV) marginal distribution with a density function given as:

$$f(x|\,\tau,\alpha,\kappa) = \begin{cases} \frac{1}{\alpha}\exp\left(-\left[1-\frac{\kappa}{\alpha}(x-\tau)\right]^{\frac{1}{\kappa}}\right)\left[1-\frac{\kappa}{\alpha}(x-\tau)\right]^{1-\frac{1}{\kappa}} & if\ \kappa \neq 0 \\ \exp\left(-\left[\frac{x-\tau}{\alpha}\right]\right) & otherwise \end{cases} \quad \text{Eq. 10}$$

Where x is either the observed streamflow or the AWRA-L simulated streamflow, and τ, α ($>$ 0), κ are the parameters to be fitted. The parameter set $\{\tau, \alpha, \kappa\}$ is referred to as θ in the rest of this appendix.

The relationship between the observed and simulated streamflow is assumed to follow a Gumbel-Hougaard copula (Joe, 2014) which imposes that their joint cumulative density functions can be written as:

$$F(Y < y, Z < z) = f(y|\theta_y)\ f(z|\theta_z)\ c(F(y|\theta_y), F(z|\theta_z)|m) \quad \text{Eq. 11}$$

Where f and F are the GEV density and cumulative density functions, and θ_y and θ_z the parameters corresponding to observed and AWRA-L streamflow, respectively. The function c is the second derivative of the copula function C:

$$c(u, v|m) = \frac{\partial^2 C}{\partial u \partial v}(u, v|m) \quad \text{Eq. 12}$$

with C defined as

$$C(u, v|m) = exp\left[-((-log(u))^m + (-log(v))^m)^{1/m}\right] \quad \text{Eq. 13}$$

In both c and C, the parameter m controls the degree of correlation between the two variables.

The Bayesian calibration samples the parameters θ_y, θ_z and m from their posterior distribution given the observed and simulated AMS data. Using the Bayes theorem, this distribution can be written as:

$$P(\theta_y, \theta_z, m|\tilde{y}, \tilde{z}) = P(\tilde{y}, \tilde{z}|\theta_y, \theta_z, m)\ P(\theta_y, \theta_z, m) \quad \text{Eq. 14}$$

The first term in the right-hand side of Eq. 14 is the likelihood and defines how observed data constrain the fit. The second term is the prior distribution of the parameters and defines the knowledge available on the parameter prior to any data being available.

H.3 Prior distribution

A weakly informative prior is used in this study with independent priors for each parameter defined as follows:

$$P(\theta_y, \theta_z, m) = P(\tau_y)\ P(\alpha_y)\ P(\kappa_y)\ P(\tau_z)\ P(\alpha_z)\ P(\kappa_z)\ P(m) \quad \text{Eq. 15}$$

A normal prior is applied to m with:

$$m \sim N(2, 6) \quad \text{Eq. 16}$$

Where the notation $N(\mu, \sigma)$ indicate that the variable if sampled from a normal distribution with location and scale parameters set to μ and σ, respectively. Normal priors are also used for other parameters:

$$\tau_y \sim N\left(200 + \frac{A}{3}, 400 + \frac{2A}{3}\right) \quad \text{Eq. 17}$$

$$\log(\alpha_y) \sim N(5, 3) \quad \text{Eq. 18}$$

$$\kappa_y \sim N(0, 4) \quad \text{Eq. 19}$$

$$\tau_z \sim N(17, 50) \quad \text{Eq. 20}$$

$$\log(\alpha_z) \sim N(2, 3) \quad \text{Eq. 21}$$

$$\kappa_z \sim N(0, 4) \quad \text{Eq. 22}$$

Where A (km^2) is the catchment area at the gauging station indicated in Table 23. These priors are weakly informative because their scale parameter is large and do not impose strong constraints on the posterior. The sensitivity to these priors was tested (not reported) but did not lead to significantly different results.

H.4 Likelihood function

The likelihood function mentioned in Eq. 14 can be written as a product of likelihood values for each pair of observed and simulated streamflow $\{y_i, z_i\}$ thanks to the assumed independence of the data points mentioned in section H.2:

$$P(\tilde{y}, \tilde{z}|\theta_y, \theta_z, m) = \prod_i L(y_i, z_i|\theta_y, \theta_z, m) \quad \text{Eq. 23}$$

The point likelihood $L(y_i, z_i|\theta_y, \theta_z, m)$ depends on the fact that observed and AWRA-L simulated streamflow might be missing, censored or above censoring threshold. The corresponding six cases are detailed in Table 30 with point likelihood expressions given in the following sections for each case.

Table 30 Cases considered in the likelihood function related to censored and missing variables

	AWRA-L simulated streamflow is above censoring threshold	AWRA-L simulated streamflow is below censoring threshold
Observed streamflow is above censoring threshold	Case 11	Case 12
Observed streamflow is below censoring threshold	Case 21	Case 22
Observed streamflow is missing	Case 31	Case 32

H.4.1 Case 11 where both observed and simulated streamflow are available

When streamflow error is ignored, the likelihood function for case 11 is given by

$$L_{11}(y, z\,|\theta_y, \theta_z, m) = f(y|\theta_y)\; f(z|\theta_z)\; c\big(F(y|\theta_y), F(z|\theta_z)\big|\, m\big) \quad \text{Eq. 24}$$

If streamflow error is taken into account, it is assumed that the observed streamflow y is related to the true streamflow y^* following Kuczera (1996):

$$y = \begin{cases} y^* & if\ y < y_a \\ y_a + e\,(y^* - y_a) & otherwise \end{cases} \quad \text{Eq. 25}$$

$$e \sim N(1, \sigma_e) \quad \text{Eq. 26}$$

Where y_a (m3/sec) is the anchor threshold above which streamflow error is considered non negligible and e (dimensionless) is the streamflow error. In our study, this anchor is defined as the maximum gauging (i.e. the highest point streamflow measurement at a particular gauging station). Note that the observed censoring threshold y_c was defined so that it always remains below the anchor y_a to ensure that the set of censored observed values remains independent from the streamflow error. This is a reasonable assumption unless the maximum gauging corresponds to a very low streamflow value. However, such gauges were excluded from the flood frequency analysis presented here.

In our study, a normal distribution with location set to 1 and a scale set to 0.3 (σ_e=0.3) is used. This choice remains arbitrary and is not based on a review of the streamflow data in the Northern Rivers region. It is acknowledged that more work is required to precise this error model, but this is out of scope of the present study.

In the case where streamflow error is considered, the likelihood function L_{11} becomes:

$$L_{11}^{*}(y, z\,|\theta_y, \theta_z, m) = \begin{cases} f(y|\theta_y)\; f(z|\theta_z)\; c\big(F(y|\theta_y), F(z|\theta_z)\big|\, m\big) & if\ y < y_a \\ \frac{1}{e}\, f(w|\theta_y)\; f(z|\theta_z)\, c\big(F(w|\theta_y), F(z|\theta_z)\big|\, m\big) & otherwise \end{cases} \quad \text{Eq. 27}$$

Where w is given by

$$w = y_a + \frac{y - y_a}{e} \quad \text{Eq. 28}$$

H.4.2 Case 12 where observed streamflow is available but simulated streamflow is censored

When streamflow error is ignored, the likelihood function for this case is:

$$L_{12}(y, z\,|\theta_y, \theta_z, m) = f(y|\theta_y) \int_{-\infty}^{z_c} f(z|\theta_z)\, c\big(F(y|\theta_y), F(z|\theta_z)\big|\, m\big) dz \quad \text{Eq. 29}$$

$$= f(y|\theta_y) \frac{\partial C}{\partial u} \big(F(y|\theta_y), F(z_c|\theta_z)\big|\, m\big) \quad \text{Eq. 30}$$

Where z_c is the censoring threshold associated with AWRA-L simulated streamflow (threshold values given in Table 29). The expression for the derivative of C against u can be obtained from Eq. 13.

If streamflow error is considered, the likelihood function L_{12} is modified following Eq. 27 and Eq. 28.

H.4.3 Case 21 where observed streamflow is censored and simulated streamflow is available

The likelihood function for case 21 is similar to L_{12} in Eq. 30, except that the variables y and z are interchanged. Streamflow errors do not impact this case because the anchor z_a is assumed to be greater than the censoring threshold z_c.

H.4.4 Case 22 where both observed and simulated streamflows are censored

The likelihood function for case 22 is obtained by integrating both y and z variables in Eq. **24** leading to:

$$L_{22}(y, z \,|\theta_y, \theta_z, m) = C\big(F(y_c|\theta_y), F(z_c|\theta_z)\big|\, m\big) \qquad \text{Eq. 31}$$

H.4.5 Case 31 where observed streamflow is missing and simulated streamflow is available

As the observed streamflow is missing, the likelihood function becomes a univariate likelihood for variable z defined as:

$$L_{31}(y, z \,|\theta_y, \theta_z, m) = f(z|\theta_z) \qquad \text{Eq. 32}$$

In the previous equation, y is missing so it could be dropped from the notation. The equation includes y to remain consistent with likelihood functions defined for previous cases.

H.4.6 Case 32 where observed streamflow is missing and simulated streamflow is censored

As the observed streamflow is assumed missing, the likelihood function becomes a univariate censored likelihood for variable z defined as:

$$L_{32}(y, z \,|\theta_y, \theta_z, m) = F(z_c|\theta_z) \qquad \text{Eq. 33}$$

H.4.7 Likelihood function for univariate fitting

To compare the results with a simpler statistical model, a univariate GEV model was fitted to observed streamflow data. This model is less parameterised because it does not take into account AWRA-L covariate, hence only GEV parameters θ_y need to be estimated.

When fitting a univariate GEV distribution, only two cases need to be considered for the likelihood function that are analogous to cases 31 and 32 discussed above except that variable z is replaced by y. In the first case, the streamflow data is available which leads to the following function:

$$L_1^u(y \,|\theta_y) = f(y|\theta_y) \qquad \text{Eq. 34}$$

In the second case, the streamflow data is censored. This leads to the following function:

$$L_2^u(y\,|\theta_y) = F(y_c|\theta_y) \quad \text{Eq. 35}$$

H.5 Inference and estimation of AEP for the 2022 flood

Sampling from the posterior distribution given in Eq. 14 is not trivial and can only be achieved through numerical sampling that generates a series of K parameter sets $\{\eta_1, \dots, \eta_K\}$ that are expected to be sampled from the posterior distribution. In other words, it is expected that

$$\forall k \quad \eta_k \sim P(\circ\,|\tilde{y}, \tilde{z}) \quad \text{Eq. 36}$$

Where $\eta_k = \{\theta_y^k, \theta_z^k, m^k\}$ is the k^{th} parameter set. A wide range of methods exist to perform such task including the one suggested in the Book 3 of the ARR called "importance sampling" (Kuczera & Francks, 2019, section 2.6.3.6). In this study, a Hamiltonian Monte Carlo sampling scheme introduced by Hoffman and Gelman (2014) is used. This scheme has been well tested for a range of applications and provides fast and robust convergence of the sampled variables.

For each parameter sample η_k, the AEP of the 2022 flood can be computed as

$$\alpha_k = 100\left[1 - F\left(y_{2022}|\theta_y^k\right)\right] \quad \text{Eq. 37}$$

Where y_{2022} (m3/sec) is the peak flow of the 2022 flood. The expected AEP is subsequently computed as:

$$\bar{\alpha} = \frac{1}{K}\sum_k \alpha_k \quad \text{Eq. 38}$$

In addition, a 90% credible interval is computed from the samples as $[\alpha_{5\%}, \alpha_{95\%}]$ where $\alpha_{X\%}$ is the X^{th} quantile computed from the series $\{\alpha_1, \dots, \alpha_K\}$.

The sampling was conducted using the Stan statistical software (Stan Development Team, 2022). This software is one of the most cited statistical computing framework currently available and has been developed by a team of internationally recognised statisticians (Carpenter et al., 2017). Stan was preferred to other specialised software such as FLIKE (Kuczera & Francks, 2019, section 2.6.3.10) or RMC-BestFit (Smith & Doughty, 2020) because the high number of stations covered in this study and the large number of options tested required automation, which is not possible with neither FLIKE nor RMC-BestFit. In addition, the use of covariates such as AWRA-L simulated streamflow is not possible with these tools.

In this work, Stan was configured to generate 40,000 parameter samples from 8 chains (i.e. 8 independent random start points) for each station and each sampling configuration implemented.

H.6 Validation of the copula model

Wang (2001) following Gumbel and Mustafi (1967) suggests a test to verify that the copula model introduced in Eq. 11 and Eq. 12 is coherent with the data. This test first transforms both y and z variables to their reduced form as follows:

$$\tilde{y} = -\frac{1}{\kappa_y} \log\left(1 - \kappa_y \frac{y - \tau_y}{\alpha_y}\right) \quad \text{Eq. 39}$$

Where $\tilde{y}$ is the reduced variable corresponding to y. The same equation is applied to z to obtain a reduced variable $\tilde{z}$. Let us assume that the difference $t_i = \tilde{y}_i - \tilde{z}_i$ is computed for every data point $i = 1..N$. In this case, Gumbel and Mustafi (1967) state that the differences t_i follows a logistic distribution defined as

$$G(t) = \frac{1}{1 - e^{-mt}} \quad \text{Eq. 40}$$

Where m is the copula parameter defined in Eq. 12. This hypothesis is tested within our results as follows:

1. For each parameter sample η_k, the reduced variables $\{\tilde{y}_i, \tilde{z}_i\}$ are computed using Eq. 39.
2. The differences $t_i = \tilde{y}_i - \tilde{z}_i$ is computed for every AMS data pair.
3. A Kolmogorov-Smirnov test (D'Agostino, 2017) is applied to the series $\{t_i\}$ against the cumulative density function of the logistic distribution defined in Eq. 40. This test provides a p-value w_k.
4. An expected p-value is computed as

$$\bar{w} = \frac{1}{K} \sum_k w_k \quad \text{Eq. 41}$$

The copula model cannot be rejected on the basis of this test if the expected p-value $\bar{w}$ is above a certain threshold. In this work, an arbitrary threshold of 0.01 is used.

H.7 Overview of fitting configurations

The statistical model described in section H.2, H.3 and H.4 is fitted to AMS data for the 43 stations listed in Table 29 with 8 configurations obtained by combining the following three sets of options:

- with and without streamflow error model to highlight the impact of streamflow data quality on AEP,
- with and without using 2022 data to understand the impact of the 2022 flood on AEP values.
- With and without using AWRA-L simulated streamflows as covariate.

H.8 Fitting results

GEV and copula parameters

The values of the seven parameters (the three GEV parameters for observed streamflow and AWRA-L covariate, and the copula parameter m) are shown in Figure 35 for the fitting on Lismore partial inflows with no streamflow errors and including the 2022 event. The figure shows the distribution of the parameter on the diagonal and scatter plots of parameter pairs above the diagonal. The parameters all have a marginal distribution with a single mode and moderate left or right skew depending on the parameter. The copula parameter m is greater than 2, which indicates a high level of correlation between the observed streamflow and the AWRA-L covariate. Pairwise parameter correlations are generally low which is an indication that MCMC sampling explores the parameter space homogenously. The strong interaction between α_y and κ_y suggests that the model could be re-parameterised to accelerate sampling. Similar figures (not shown) leading to same comments were analysed for other stations and other fitting configurations.

The expected parameter values are provided in Table 31 for fittings including the 2022 event.

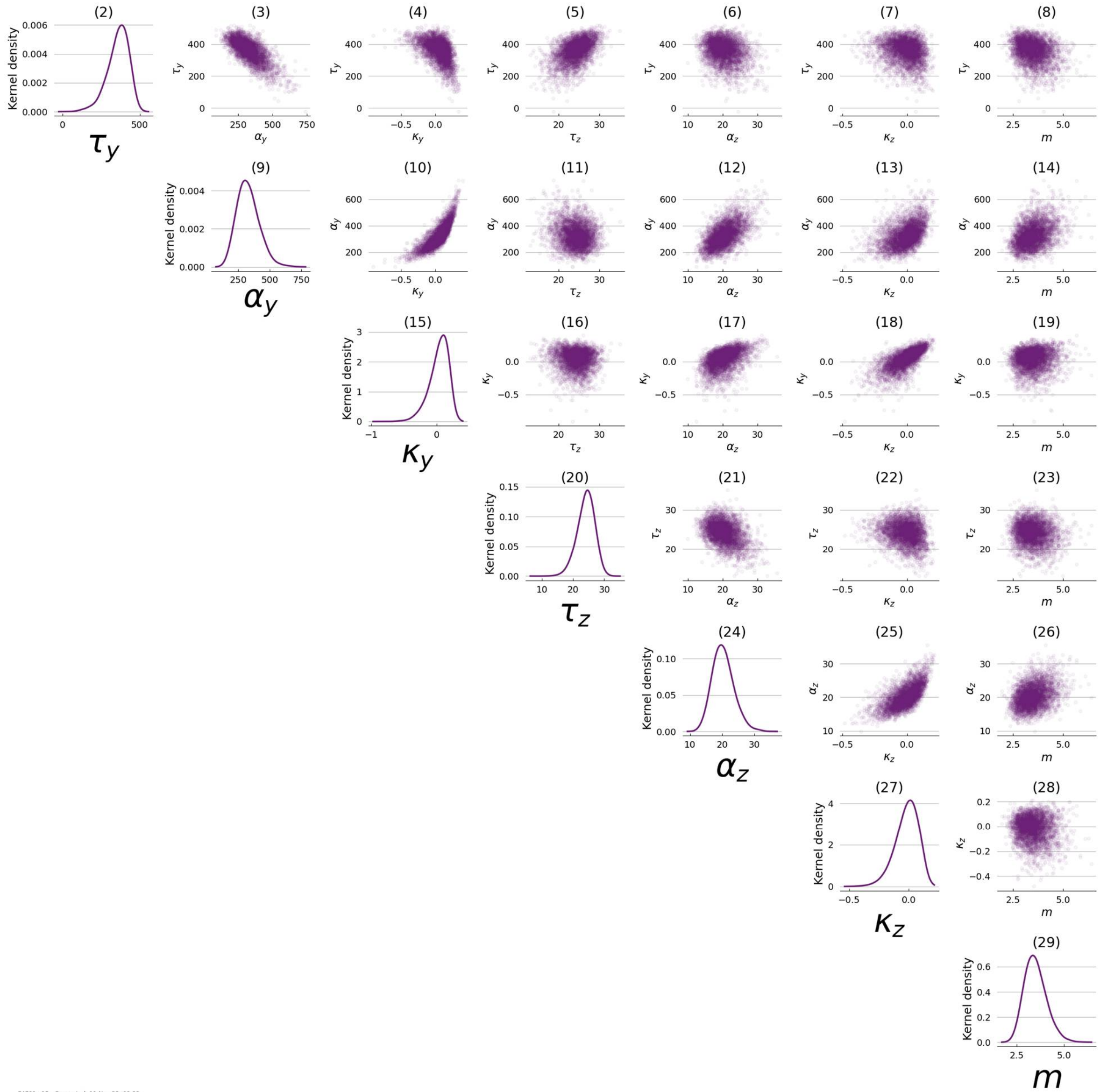

Figure 35 Distribution of GEV and copula parameters for the Lismore partial inflows when fitting ignores streamflow errors and includes the 2022 event

Validity of the copula model

Figure 36 presents the expected p-value of the Kolmogorov-Smirnov test that measures the validity of the copula model for a fitting configuration ignoring streamflow errors and including the 2022 event.

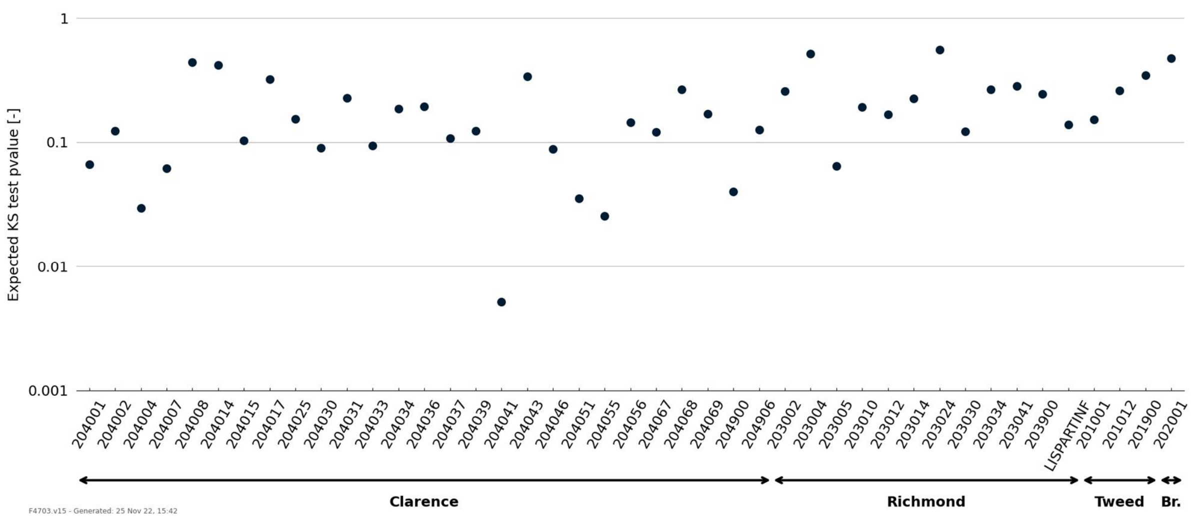

Figure 36 Expected KS test p-value for fitting ignoring streamflow errors and including the 2022 event

The figure suggests that the expected p-value is above the 0.01 threshold for all stations except for the Orara River at Bowden Bridge (204041). In other words, is not possible to reject the hypothesis that the bi-variate distribution of observed and simulated AMS follows the Gumbel copula model for all stations in the region except for the Orara River at Bowden Bridge. Further investigations would be required at this station. Considering that the AEP of the 2022 flood at this station was not extreme (expected value of 4.7% reported in Table 18), these investigations were left for future work.

Value of AWRA-L covariates

The value of the AWRA-L covariate for fitting the GEV distribution is explored in Figure 37 where Figure 37.a shows the AEP of the 2022 peak flow for the 43 stations in the region using the AWRA-L covariates and no streamflow errors. The plain line in this figure corresponds to a configuration including the 2022 event. The dashed line corresponds to a configuration excluding the 2022 event. Figure 37.b is similar but shows the results of the univariate fit (no AWRA-L covariate). When using covariates (Figure 37.a), the AEP estimates appear similar whether the 2022 event is included in the fitting or not, including for stations in the Richmond, Tweed and Brunswick basins where the AEP is low. Conversely, when using univariate fitting (Figure 37.b), AEP values can vary significantly depending on the inclusion of 2022. Several AEP values in this figure are below the 1% threshold when excluding 2022 and above when including 2022. This is a major issue with univariate fitting that tends to be extremely sensitive to the inclusion of an extreme value such as the 2022 peak flow. Conversely, the use of AWRA-L covariates provides a more stable estimation of the AEP, which reinforces the confidence one can have in the AEP estimates.

Figure 37.c provides another argument in favour of using the AWRA-L covariate by plotting the width of the 90% credible intervals for univariate fitting (light blue) and covariate fitting (dark blue). The figure clearly highlights the reduction in the width of the interval (i.e. reduction in uncertainty) when using covariates compared to univariate fitting.

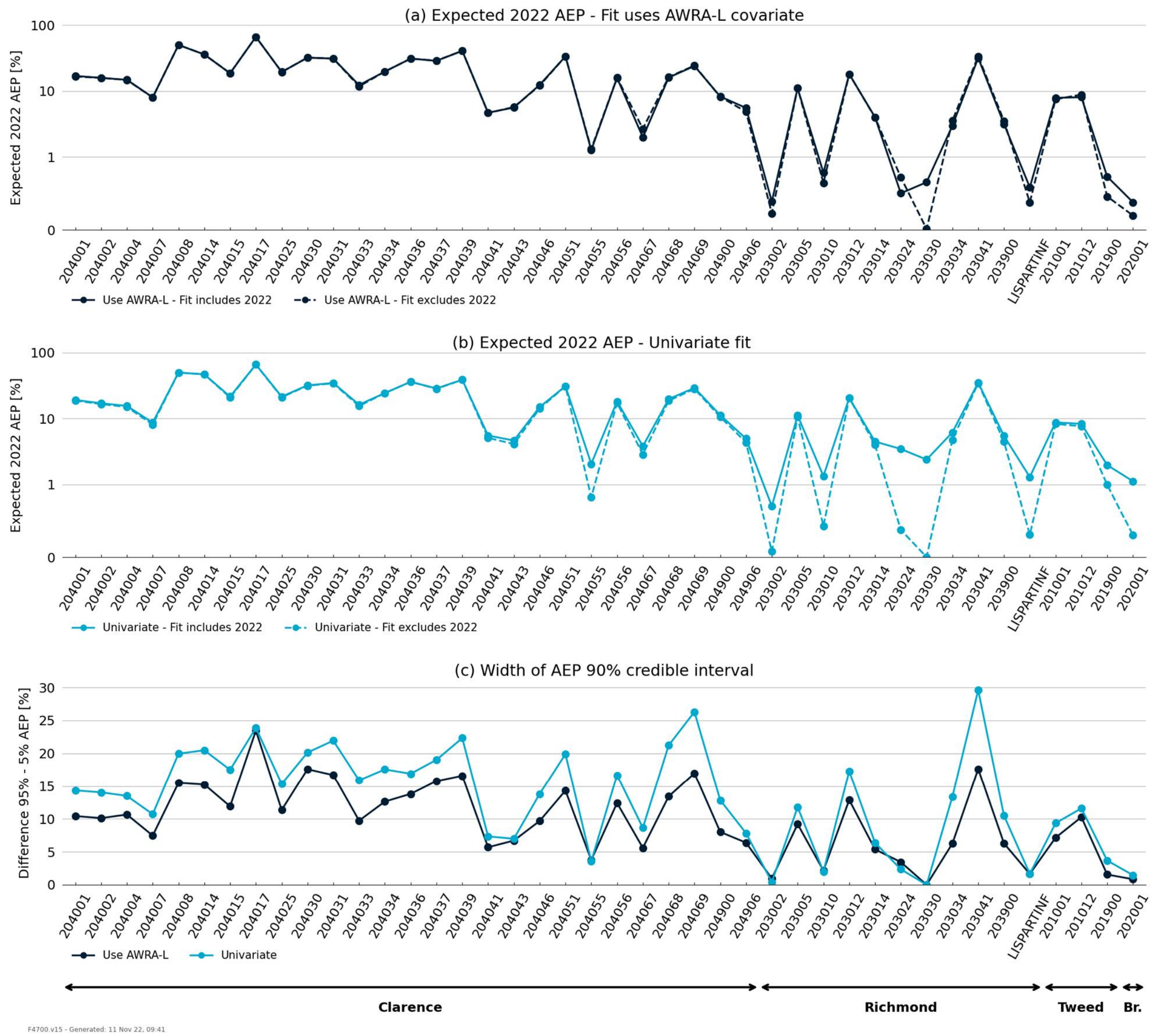

Figure 37 Comparison of AEP values generated with a model including AWRA covariate (dark blue) against values generated from a univariate model (light blue). Streamflow errors are ignored for all configurations shown in this figure. A logarithmic scale is used for the y-axis in figures (a) and (b). Dotted lines in figure (a) and (b) shows fitting results when excluding the 2022 flood. Plain line show results of fitting including 2022 flood.

Impact of streamflow errors

Figure 38 compares the expected AEP of the 2022 peak flows and its associated credible intervals for fitting configurations including streamflow errors (light blue) and no streamflow errors (dark blue).

The figure shows that streamflow errors do not affect the estimation of AEP when AEP is high (i.e. for 2022 peak flows that are not extreme). This can be seen for all stations in the Clarence Basin where expected AEP and credible intervals are very close between configurations including streamflow errors or not. This result is expected because streamflow errors only affect the data that are above the maximum gauged flow (anchor point). As a result, if the 2022 peak flow remains below or close to this maximum as is the case for many stations in the Clarence, it won't be affected by streamflow errors. Conversely, streamflow errors affect the 2022 AEP across many stations in the Richmond, Tweed and Brunswick. Generally, streamflow errors tend to increase the AEP (i.e. decrease the estimated severity of the 2022 flood) as can be seen for the Coopers

Creek at Repentance (203002), the Leycester Creek at Rock Valley (203010), the partial Lismore inflows and the Tweed River at Uki (201900). For all these stations, the 2022 peak flow is higher than the 1% AEP threshold when streamflow errors are ignored but lower than this threshold when streamflow errors are considered. In other words, streamflow errors reduce the severity of the 2022 peak flow. This result is not surprising when using a streamflow error model such as the one advocated in the ARR (Kuczera & Francks, 2019). Streamflow errors reduce the confidence placed on high streamflow data, which in turns, leads to a wider range of streamflow data becoming plausible compared to when errors are ignored. In other words, an extreme flood like 2022 becomes more likely if one has little confidence in the available streamflow measurements. Given that the scale of the streamflow errors was arbitrarily set to 30%, these results should be treated with caution. It is recommended to conduct more investigation on streamflow errors to inform the definition of design flood levels.

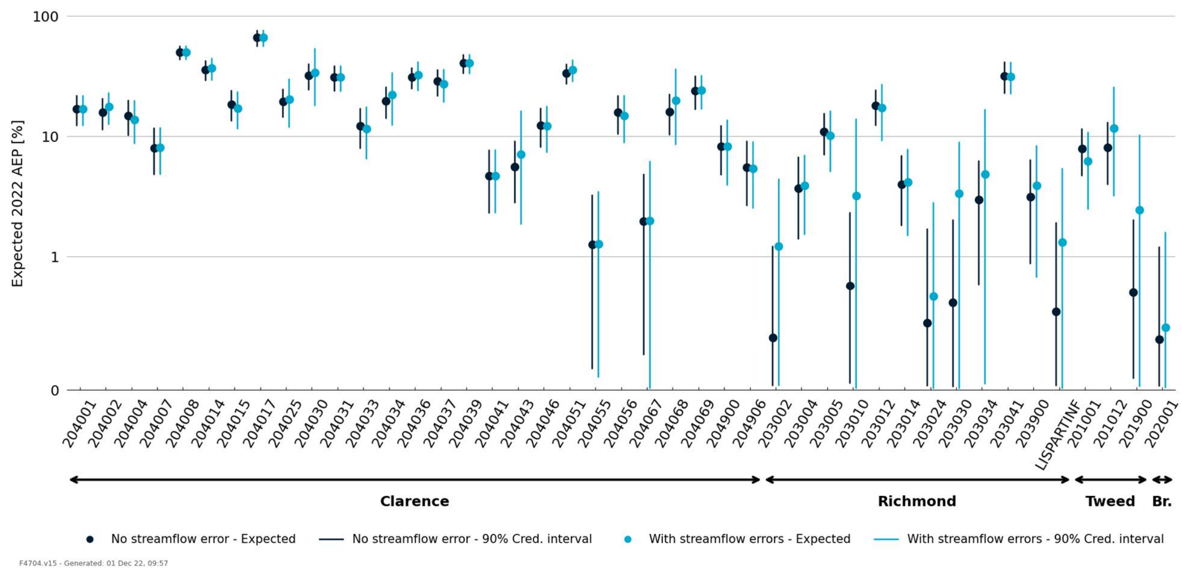

Figure 38 Comparison of AEP of the 2022 peak flow between fittings ignoring (dark blue) and including (light blue) streamflow errors. All fittings include the 2022 event and use AWRA covariates.

Issues with the fitting in certain stations

For certain stations in the region, the fitting of the statistical model described in section H.2 to H.4 did not appear satisfactory for high streamflow values. More specifically, several observed AMS data points are lying outside the 90% credible intervals for the Clarence River at Lilydale (204007, see Figure 45.a to 45.d), the Boyd River at Broadmeadows (204015, see Figure 46.a to 46.d) and the Orara River at (204068, see Figure 51.i to 51.l).

This result suggests that the fitted model should not be used for the estimation of extreme peak flows without further investigations. For the purpose of this report, the 2022 flood did not reach extreme peak flow values at these stations as suggested in Table 18 with peak flow estimated to be significantly below the 1% AEP threshold (i.e. AEP larger than 1%: 8% for 204007, 18.5% for 204015 and 16% for 204068). Consequently, the improvement of the statistical model for these stations was not considered critical and left for future work.

Table 31 Expected GEV and copula parameters when the fitting includes streamflow data from the 2022 flood

BASIN	STATION ID	NO COVARIATE (UNIVARIATE FITTING)						USE AWRA COVARIATE													
		NO STREAMFLOW ERROR			INCLUDING STREAMFLOW ERROR			NO STREAMFLOW ERROR							INCLUDING STREAMFLOW ERROR						
		OBS. TAU τ_y (m³/sec)	OBS. ALPHA α_y (m³/sec)	OBS. KAPPA κ_y (-)	OBS. TAU τ_y (m³/sec)	OBS. ALPHA α_y (m³/sec)	OBS. KAPPA κ_y (-)	OBS. TAU τ_y (m³/sec)	AWRA TAU τ_z (mm/day)	OBS. ALPHA α_y (m³/sec)	AWRA ALPHA α_z (mm/day)	OBS. KAPPA κ_y (-)	AWRA KAPPA κ_z (-)	COPULA M (-)	OBS. TAU τ_y (m³/sec)	AWRA TAU τ_z (mm/day)	OBS. ALPHA α_y (m³/sec)	AWRA ALPHA α_z (mm/day)	OBS. KAPPA κ_y (-)	AWRA KAPPA κ_z (-)	COPULA M (-)
Clarence																					
	204001	606	1126.9	0.02	603.4	1134.8	0.02	623.3	18.1	842.1	21.4	-0.21	0	3.7	620.4	18.1	851.1	21.5	-0.2	0.01	3.7
	204002	462	1083.5	-0.34	476.4	994.7	-0.55	585.2	4.5	795.7	5.9	-0.52	-0.31	4.5	589.7	4.5	724.6	6	-0.73	-0.29	4.5
	204004	610.3	2849.9	-0.07	625.2	2817.7	-0.07	744.2	5.7	2657.1	8.7	-0.07	-0.08	3.3	752.1	5.6	2739.9	8.9	0	-0.06	3.3
	204007	-447.5	6165.8	0.01	-231.8	5775	-0.04	798.6	2	2920.7	13.6	-0.42	0.18	5	792	2	2925	13.6	-0.43	0.19	5
	204008	24.4	19.8	-0.32	24.4	19.7	-0.32	24.1	15.9	20.3	15.8	-0.29	-0.06	3.2	24.1	15.9	20.3	15.8	-0.29	-0.06	3.2
	204014	74.1	141.7	-0.39	74.7	147.6	-0.41	51.2	1.6	91.1	1.7	-0.52	-0.36	2.7	51	1.6	96.6	1.7	-0.55	-0.36	2.8
	204015	119.4	506.3	0.06	131.6	478.9	0.08	98.2	2.6	350.7	3.4	-0.35	-0.39	4.1	101.1	2.6	356	3.4	-0.26	-0.39	4.1
	204017	105.9	134.2	-0.08	106.1	132.7	-0.11	104.1	27	109.8	17.4	-0.29	-0.22	2.6	103.9	27	109.4	17.4	-0.31	-0.22	2.6
	204025	175.9	143.5	-0.16	175.9	143.5	-0.16	160.7	31.6	127.7	28	-0.27	0.1	2.8	163	31.6	132.3	28	-0.29	0.1	2.8
	204030	23.4	17.6	-0.13	24.6	20	-0.13	23.5	0.5	16.9	5.1	-0.21	0.13	1.9	24.6	0.5	19.2	5.1	-0.21	0.13	1.9
	204031	42.2	51.3	-0.57	42.1	51.2	-0.57	37.1	1.7	45.3	4.2	-0.58	0.08	2.1	37.1	1.7	45.3	4.2	-0.58	0.08	2.1
	204033	64	207.5	-0.47	68.7	199.4	-0.42	90.7	0.6	140.7	7.6	-0.5	-0.03	3.2	92.8	0.6	137.6	7.6	-0.48	-0.03	3.2
	204034	20.3	101.9	-0.27	10.3	128.4	-0.27	12.8	0.6	89.8	3	-0.2	-0.21	2.5	-0.6	0.6	115.7	3	-0.2	-0.21	2.5
	204036	40.1	137.2	-0.18	28.1	175.7	-0.18	29.1	1.4	109.5	1.1	-0.34	-0.95	2.6	15.1	1.4	138.7	1.1	-0.34	-0.95	2.6
	204037	17.6	71.6	0.11	17.5	71.8	0.13	9.2	12.6	84.7	19.1	0.21	0.05	2.4	11.4	12.5	79.6	19	0.22	0.05	2.4
	204039	-9.9	100	-0.58	-9.1	98.3	-0.61	13.4	1.4	78	1	-0.47	-0.63	3.3	13.2	1.4	78.1	1	-0.48	-0.63	3.3
	204041	-129	1626.6	0.57	-166.6	1701.9	0.59	-119.8	13.1	1151.1	19.9	0.3	-0.01	5.7	-117.9	13.1	1149.5	19.9	0.3	-0.01	5.7
	204043	19.4	24.3	-0.37	20.7	27.4	-0.37	19	9.1	23.9	13.6	-0.44	-0.02	2.6	20.4	9.1	27.2	13.6	-0.44	-0.02	2.6
	204046	124.5	402.5	-0.39	127.5	394	-0.37	172.1	1.5	250.1	6.3	-0.6	-0.22	3.1	170.8	1.5	251.1	6.3	-0.59	-0.22	3.1
	204051	-2.1	946.5	-0.18	-36.9	1008.8	-0.27	208.9	2	819.1	6.1	-0.15	-0.18	4.3	159.2	2.1	949.8	5.9	-0.23	-0.19	4.4
	204055	88.1	82.4	-0.23	87.8	82.8	-0.22	86.2	0.2	88.8	22	-0.13	0.15	2.8	86.1	0.2	88.9	22	-0.13	0.14	2.8
	204056	31.9	129.4	-0.27	33.2	128.6	-0.2	44.6	0.4	103.6	18.5	-0.28	0.19	2.5	45.3	0.4	102.7	18.6	-0.24	0.19	2.5
	204067	62.3	226.7	-0.09	63.1	221.8	-0.06	34.3	2.9	232.6	21.9	0.04	0.31	2.6	37.1	3	229.8	21.8	0.06	0.31	2.6
	204068	255	138.1	-0.06	263.3	175.5	-0.07	234.3	31.9	93	27.5	-0.43	0.08	2.6	236.6	31.9	120	27.6	-0.43	0.08	2.6
	204069	1008.7	1192.1	-0.09	1005.3	1178.7	-0.12	952.2	16.2	981.7	23.5	-0.1	0.08	2.9	951.9	16.3	969.2	23.5	-0.14	0.08	2.9
	204900	-26.4	3038.2	0.01	1.7	3017.2	0.02	408.4	2.1	2084.8	11	-0.09	0.11	3.2	400.1	2.1	2099.6	11	-0.09	0.1	3.2
	204906	277.4	272.4	0.02	276.7	272.9	0.02	241.9	26.4	206.9	24	-0.22	-0.05	3.1	242.2	26.5	207.5	23.8	-0.21	-0.05	3.1
Richmond																					
	203002	157.3	150.4	-0.15	170.9	182.9	-0.17	148.3	35.2	126.4	21.9	-0.16	-0.07	2.6	160.7	35.4	157.5	21.6	-0.18	-0.08	2.6
	203004	448.3	403.7	-0.03	446.9	402.7	-0.04	427.9	11	358.3	10.9	-0.2	-0.28	3.9	425.8	11	355.6	10.9	-0.22	-0.27	4
	203005	255	590.5	0.01	256	583	0.03	272.3	14.8	439.2	11.8	-0.24	-0.18	3.2	274	14.8	435.4	11.8	-0.21	-0.19	3.2
	203010	240.4	287.3	0.06	226.7	360.5	0.05	234.4	19.8	283.8	18	0.1	-0.11	3.9	218.7	19.8	358.9	18	0.09	-0.11	3.9
	203012	48.1	118.2	0.04	48.9	116.8	0.04	52	32.6	90.9	20.6	-0.14	-0.04	2.3	52	32.6	90.4	20.5	-0.13	-0.04	2.3
	203014	180.1	161.4	0.14	181.4	157	0.1	174.1	29.7	130.2	19.2	0.01	-0.15	2.6	174.7	29.7	128.7	19.3	-0.01	-0.15	2.6
	203024	145.7	157.1	-0.12	146.1	160.4	-0.14	133.8	29.4	136.4	21.5	0.04	-0.04	3	133.6	29.4	137.7	21.5	0.04	-0.04	3
	203030	43	104.2	0.71	47.3	87.3	0.48	46.2	4.6	91.2	16.3	0.68	0.11	3.9	49.1	4.7	82.4	16.3	0.54	0.11	3.8
	203034	256.8	278.2	0.17	255.8	299.6	0.15	258.6	10.1	196	12.6	0.08	-0.09	3.4	259	10.1	215	12.6	0.08	-0.09	3.3

BASIN	STATION ID	NO COVARIATE (UNIVARIATE FITTING)						USE AWRA COVARIATE													
		NO STREAMFLOW ERROR			INCLUDING STREAMFLOW ERROR			NO STREAMFLOW ERROR							INCLUDING STREAMFLOW ERROR						
		OBS. TAU τ_y (m³/sec)	OBS. ALPHA α_y (m³/sec)	OBS. KAPPA κ_y (-)	OBS. TAU τ_y (m³/sec)	OBS. ALPHA α_y (m³/sec)	OBS. KAPPA κ_y (-)	OBS. TAU τ_y (m³/sec)	AWRA TAU τ_z (mm/day)	OBS. ALPHA α_y (m³/sec)	AWRA ALPHA α_z (mm/day)	OBS. KAPPA κ_y (-)	AWRA KAPPA κ_z (-)	COPULA M (-)	OBS. TAU τ_y (m³/sec)	AWRA TAU τ_z (mm/day)	OBS. ALPHA α_y (m³/sec)	AWRA ALPHA α_z (mm/day)	OBS. KAPPA κ_y (-)	AWRA KAPPA κ_z (-)	COPULA M (-)
	203041	70.5	96.3	-0.31	71.4	96.3	-0.26	62.1	7.3	78.1	13.9	-0.55	-0.09	2.3	62.5	7.3	79	13.8	-0.49	-0.09	2.3
	203900	330.8	334.3	-0.06	331.5	332	-0.08	343.9	14.7	276.1	13.7	-0.04	-0.07	2.6	343.4	14.7	268.9	13.8	-0.1	-0.06	2.6
	LISPARTINF	431.4	270.6	-0.09	425.8	299.7	-0.09	359.1	24.1	328.4	20.3	0.04	-0.02	3.5	350.7	24.2	355.4	20.3	0.03	-0.02	3.5
Tweed																					
	201001	370.3	374.7	0.07	370.6	382.5	0.15	345.1	26.8	347.1	23.5	0.02	-0.04	2.7	345	26.8	358.7	23.6	0.11	-0.03	2.7
	201012	29.8	31.2	-0.14	31.3	41.6	-0.15	25.8	33.8	22.8	21.6	-0.4	-0.15	2.2	25.9	33.8	30.3	21.5	-0.41	-0.15	2.2
	201900	414	441.1	-0.1	404.5	545.8	-0.11	400.5	32	418.4	20.2	-0.01	-0.1	2.7	388.3	32	521.2	20.2	-0.01	-0.1	2.7
Brunswick																					
	202001	60.8	73	-0.29	60.8	72.8	-0.32	52.5	35.8	68.2	22.8	-0.19	-0.05	2.7	52.6	35.8	67.8	22.8	-0.21	-0.05	2.6

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