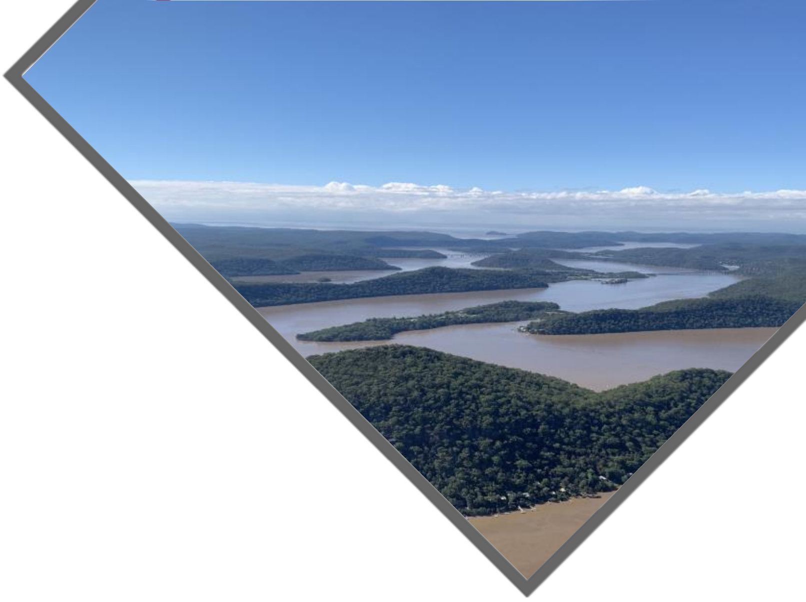

Hawkesbury-Nepean River Flood Study

Technical Volume 4

Coastal Water Level Joint Probability Analysis

Final Report

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Cover photo – photo of the Hawkesbury River looking toward Brooklyn and the ocean in the background, 26 March 2021.

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Acknowledgement of Country

The NSW Reconstruction Authority, Rhelm and Catchment Simulation Solutions acknowledge the Traditional Custodians of the lands where we work and live. We celebrate the diversity of Aboriginal peoples and their ongoing cultures and connections to the lands and waters of NSW.

We pay our respects to Elders past, present and emerging and acknowledge the Aboriginal and Torres Strait Islander people that contributed to the development of this report.

We advise this resource may contain images, or names of deceased persons in photographs or historical content.

Note

In July 2023, the Hawkesbury-Nepean Valley Flood Risk Management Directorate transitioned from Infrastructure NSW (INSW) to the NSW Reconstruction Authority. Any references to INSW should be read as referring to the Authority.

Executive Summary

The Hawkesbury-Nepean River catchment covers some 22,000 square kilometres, including the Warragamba and Nepean catchments, extending as far as Goulburn, Lithgow and Bowral, and downstream to Broken Bay. The focus of the Hawkesbury-Nepean River Flood Study is on the part of the catchment within the Sydney Basin, including much of the urban growth areas of western and north western Sydney.

The key objective of the Hawkesbury-Nepean River Flood Study is:

To improve the understanding of flood behaviour and better inform management of flood risk in the study area, considering available information, together with the relevant standards and guidelines.

This objective was achieved through:

a) Compiling and reviewing all available flood-related information
b) Updating and refining a hydrologic model to reflect contemporary catchment conditions
c) Developing a new, detailed 2-dimensional hydraulic flood model of the Hawkesbury-Nepean River, major tributaries and adjoining floodplain areas
d) Calibrating and validating the hydrologic and hydraulic computer models against information from 11 historical floods, including the 2020, 2021 and 2022 flood events
e) Updating the Monte Carlo model framework described in the 2019 Flood Study to reflect learnings from the 2-dimensional hydraulic flood model and the recent floods
f) Using the calibrated models to simulate flood behaviour for a range of design floods up to and including the probable maximum flood (PMF)
g) Completing various sensitivity and climate change simulations to gain an understanding of how modelling uncertainty and climate change may impact on the results produced by the models.

The various stages of the project are detailed in a number of technical volumes. This **Technical Volume 4** represents a key input to item e) above. It provides an analysis of the joint probability of coastal water levels and catchment driven flooding. It is intended to be read in conjunction with the main Flood Study Report and other associated Technical Volumes.

Through an analysis of historical storms over the Hawkesbury-Nepean River catchment and coastal water levels, Baird derived a joint probability relationship between catchment rainfall and elevated coastal water levels. The derived model has a weak positive linear trend between coastal residual water level (excluding astronomical tide) and rainfall across the Hawkesbury-Nepean River catchment. The model has a larger random residual component which has a normal distribution. Whilst the linear trend between Hawkesbury-Nepean River catchment and coastal water levels is weak, the resulting model follows the observed trend from a large sample of historical and synthetic (Monte Carlo) storm events.

Utilising the Baird dataset of over 1,100 ECL historical storm events, 1,000-year MC ECL dataset, hydrograph data and long-term coastal water levels, this relationship can be applied over a range of storm events that could induce flooding in the Hawkesbury-Nepean River. Additionally, analysis of hydrograph flow data at Windsor and Upper Colo determined that maximum flow rates rarely correlate to maximum residual coastal water level, with the latter tending to occur first (ranging from 0 to 2.8 days earlier). A coastal water level time series was generated that follows the typical residual response of larger rainfall events from the period of 1970 to 2016. The residual coastal water level tends to peak earlier than the river flow, then residual coastal water level decreases slowly to normal conditions once storm conditions ease.

The outcomes of this report provide an input to the Monte Carlo analysis in **Technical Volume 7**.

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Acronyms

1D	One Dimensional
2D	Two Dimensional
AEP	Annual Exceedance Probability
AHD	Australian Height Datum
ARI	Average Recurrence Interval
ARR	Australian Rainfall and Runoff
ARR87	Australian Rainfall and Runoff (Pilgrim et al, 1987)
ARR2019	Australian Rainfall and Runoff (Ball et al, 2019)
ASS	Assumed datum
BoM	Bureau of Meteorology
DCP	Development Control Plan
DEM	Digital Elevation Model
ECL	East Coast Low
IFD	Intensity Frequency Duration
FFA	Flood Frequency Analysis
GH	Gauge Height
ha	hectare
km	kilometres
km^2	square kilometres
LEP	Local Environment Plan
LGA	Local Government Area
LiDAR	Light Detection and Ranging
m	metre
m^2	square metres
m^3	cubic metres
mAHD	metres to Australian Height Datum
mm	millimetres
m/s	metres per second
m^3/s	cubic metres per second
ML	megalitres
NSW	New South Wales
OSD	On-site Stormwater Detention
PMF	Probable Maximum Flood

PMP	Probable Maximum Precipitation
SES	State Emergency Service (NSW)
SRTM	Shuttle Radar Topography Mission
SWC	Sydney Water Corporation
WBNM	Watershed Bounded Network Model

1 Introduction

The Hawkesbury-Nepean River Catchment covers some 22,000 square kilometres, including the Warragamba and Nepean catchments, extending as far as Goulburn, Lithgow and Bowral, and downstream to Broken Bay. The focus of the Hawkesbury-Nepean River Flood Study is on the part of the catchment within the Sydney Basin, including much of the urban growth areas of western and north western Sydney.

1.1 Hawkesbury-Nepean Flood Strategy

The former NSW Government’s *Resilient Valley, Resilient Communities: Hawkesbury–Nepean Valley Flood Risk Management Strategy* (2017) identified the risks and challenges in the Valley and recognised there is no simple solution to managing or reducing the valley’s high flood risk. The NSW Government is building on the strategy to deliver a high-priority regional Disaster Adaptation Plan focused on managing flood risk, together with local councils, businesses and the community. The plan will be aligned with the State Emergency Management Plan and the National Strategy for Disaster Resilience to ensure the considerable flood risk across the Valley is appropriately managed. This includes the need for access to contemporary flood risk information.

1.2 Scope of this Report

This report forms **Technical Volume 4** of the Hawkesbury-Nepean River Flood Study. It summarises the analysis of the joint probability of catchment rainfall and elevated coastal waters over a range of historical and synthetic events, to inform the assessment of flood behaviour in the lower sections of the Hawkesbury-Nepean River. The relationship between catchment rainfall and residual coastal water level informs the specification of coastal water level conditions for design events and is consistent with guidance for floodplain management in NSW regarding catchment and oceanic inundation (OEH, 2015).

This report outlines the analysis performed on Baird’s historical East Coast Low (ECL) dataset, residual coastal water levels and hydrograph data to determine how the rainfall in the Hawkesbury-Nepean River catchment is linked to coastal water levels during storm events. For the purposes of this report, ‘coastal water level’ refers to the water level observed near the coastline or within an open coastal embayment (including Sydney Harbour and the Hawkesbury River entrance at Broken Bay), which is the result of both astronomical tide and a residual coastal water level. The residual coastal water level is influenced by many meteorological-ocean (met-ocean) processes, including storm surge generated from coastal wind and atmospheric pressure variations. For events where peak residual coastal water level exceeds 0.2 m, storm surge is normally the largest component in the coastal residual water level.

The following report presents the data, methods and outcomes of these analyses. The final deliverable in this report is a mathematical function to relate event maximum residual coastal water level to event maximum daily rainfall, and a time function to apply the residual coastal water level over the duration of an event.

2 Data

2.1 East Coast Low Datasets

ECLs are the governing storm system for the NSW coastal region, with impacts frequently intensified by the combination of intense precipitation, extreme wind and coastal waves. Whilst ECLs are not the only storm system capable of generating flooding in the Hawkesbury-Nepean River, they represent the most likely storm system for moderate to major flooding in the Hawkesbury-Nepean River.

Baird has developed a 46-year historical and 1,000-year synthetic database of ECL systems, with the data flow and spatial extent presented in Figure 2-1 (Taylor et al, 2017). These datasets incorporate the multiple hazards of extreme precipitation, wind, and waves, which were used to determine the relationship between precipitation within the Hawkesbury-Nepean River catchment and the jointly occurring elevated (residual) coastal water levels.

Daily rainfall data was sourced from the Australian Water Data Availability Project (AWAP) dataset (Raupach et al, 2009) with 0.05-degree resolution (≈5km), and was applied to determine catchment-averaged daily and event total rainfall for each ECL over the Hawkesbury-Nepean River catchment. Long-term wind records were sourced from wind measurement sites along the NSW coastline, hindcast models and scatterometry data, with extensive bias correction across datasets and time periods. The ocean wave dataset comprises of a 1970-2016 measured and hindcast dataset, with the NSW wave transfer function applied to calculate coastal waves. Coastal water level data used long-term measured residual and predicted tide data from numerous locations along the NSW coastline, including Fort Denison in Sydney Harbour as the closest long-duration tidal gauge to the Hawkesbury River. Using these datasets, Baird created three separate hazard models, combined into a multi-hazard event set based on Monte Carlo (MC) modelling of ECL storm systems. The synthetic MC event dataset covers a 1,000-year period of over 5000 events, with wind and rainfall resolution of 0.05 degree (≈5km), and coastal wave and water levels to 100 m along the open coast. This database has been utilised by the insurance industry to understand combined wind, rain, coastal inundation and coastal erosion hazard, and also for flood studies in NSW that have a coastal influence, for example the Eden, Twofold Bay and Towamba River Flood Study recently adopted by Bega Shire Council (Rhelm and Baird, 2019).

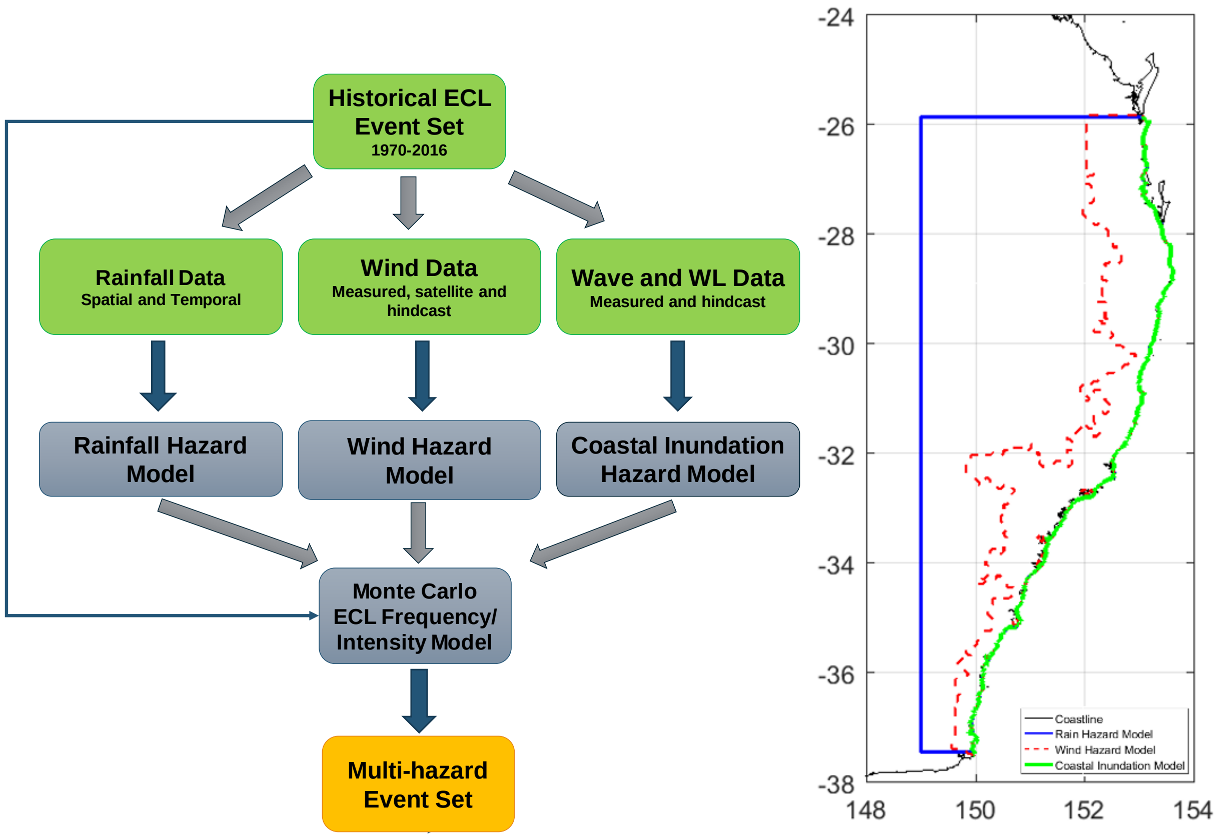

Figure 2-1. Baird ECL database components and data flow (left), spatial extent of ECL hazard model components (right)

2.2 Coastal Water Level

Historical coastal water levels were obtained from the Sydney (Fort Denison) tide gauge in Sydney Harbour. With data spanning 1866 to present, it is one of the longest water level records in the world. It is currently operated by the Port Authority of NSW. This study utilised the hourly 1914-2019 Sydney water level dataset, when reliable hourly recordings started (Hamon, 1987). Comparison between the predicted and measured tidal level gives the residual coastal water level, which was applied in this study. Hourly Fort Denison water level data was also obtained for the February 2020 East Coast Low which was the largest rainfall event in the Sydney region in 30 years.

2.3 Hydrographs

Rhelm provided hydrograph data for nine large ECL events comprised of flow measurements at Windsor, Upper Colo and Lower Portland, and a combined dataset of Windsor and Upper Colo. The combined dataset was based on an estimate at Colo Junction.

3 Methodology

3.1 Historical ECL Dataset

The historical Baird ECL dataset was used to determine the catchment averaged total event maximum rainfall and maximum daily rainfall for over 1,100 storm events that occurred over the Hawkesbury-Nepean River catchment. This analysis focussed on the model points within the Hawkesbury-Nepean River catchment boundary provided by Rhelm (Figure 3-1). The residual coastal water levels for each of the 1,100 events were also determined. Comparison of residual coastal water levels to precipitation over each of these events was performed, with a particular focus on mean and maximum residual water level in relation to event total rainfall and maximum daily rainfall values. This analysis provides a comprehensive understanding of the relationship between precipitation over the Hawkesbury-Nepean River catchment and coastal water levels from ECL storm systems.

The maximum catchment-averaged daily mean rainfall was used to analyse the 1100 historical ECL events, with 7 events within the highest 10 events selected that conformed to a consistent time series pattern with respect to the residual coastal water level. The analyses of the residual water level time series indicated that coastal water level residuals generally increased over a 36-hour period as the ECL developed, and then remained near the event peak water level for 24 hours (approximately) before gradually receding over the following 3 to 4 days. Residual coastal water levels were aligned to each event and plotted so that the maximum residual was aligned to hour 48 of the storm. The peak residual coastal water level period occurring between 36 to 60 hours after the system initially developed off the NSW coast generally coincided with the event maximum daily (24 hour) rainfall occurring along the coastal fringe and the Great Dividing Range. As a result of this analysis, the phasing of event peak daily rainfall and coastal water level residual have been specified as coincident over the 24-hour period that the event maximum rainfall occurs. Following analysis of the described previously time series, a proposed residual water level time function was determined, based on when the storm initially developed and the time which peak daily rainfall across the Hawkesbury-Nepean River catchment occurred.

Figure 3-1. Baird ECL rainfall model points within the Hawkesbury-Nepean River catchment

3.1.1 1,000 Year Monte Carlo Dataset

To evaluate the mathematical function developed from the historical ECL dataset for a large data sample of Monte Carlo (MC) events, the function was applied to the 1,000-year ECL database developed by Baird (Taylor et al, 2017). The mathematical function was then applied to the top 250 rainfall events from the MC data to evaluate the variation in residual coastal water level for a large event sample.

3.2 Hydrographs

Nine combined hydrograph datasets provided by Rhelm were analysed in conjunction with the residual coastal water level, derived from the Sydney (Fort Denison) tidal gauge. The Fort Denison tidal gauge was chosen over the Patonga tidal gauge (which is at the entrance of the Hawkesbury River), as the former has a longer time record that covers all events that are the subject of analysis in this study. Baird accessed and analysed quality-controlled Fort Denison tide data from 1914 to 2020.

For each hydrograph event, the maximum residual coastal water level was calculated. The maximum flow rate over the event was determined using the “combination” flow rate, that combines time-adjusted Windsor and Upper Colo flow rates. The residual coastal water level at the time of maximum combined flow was also calculated. The time difference between maximum flow and maximum residual was calculated to ascertain if peak water levels were aligned to peak flow, or if a delay existed.

4 Results

4.1 ECL Historical Dataset

Analysis of the historical ECL dataset is based on 1,119 storms that occurred over the Hawkesbury-Nepean River catchment over the 46-year dataset. Precipitation rates varied spatially and temporally across the catchment for each event. For example, the spatial variation demonstrated through the total event precipitation for an ECL occurring over the period 5-8 August 1986 is shown in Figure 4-1. Given the spatial and temporal variations, each storm is expected to have different flow and flooding characteristics, in different areas of the catchment.

Comparisons between event total rainfall and catchment-averaged maximum daily rainfall from each historical event to mean and maximum residual coastal water levels are presented in Figure 4-2 to Figure 4-5. An overall positive correlation relationship exists for all comparisons but in all cases the relationship is very weak. The most significant correlation is between the maximum average daily rainfall across the catchment, and the maximum residual daily coastal water level (Figure 4-2). For this relationship, the 95% confidence interval is presented based on the residual between the data value and the linear trend equation.

The residual water level model based on all events in the 1970-2016 dataset for the Hawkesbury-Nepean Catchment is:

Equation 1

$$Max\ Res.WL = 0.0015\ \times Max\ Daily\ Rainfall + 0.0904 + \mathcal{N}(\mu, \sigma^2)$$

Where:

- Maximum Res. WL = maximum coastal residual water level over a 24-hour period (excluding tide)
- Maximum Daily Rainfall = maximum average 24-hour rainfall within the catchment based on a 0.05-degree geographic grid
- $\mathcal{N}(\mu, \sigma^2)$ = standard normal distribution error function with $\mu = 0$, $\sigma = 0.095$ m.

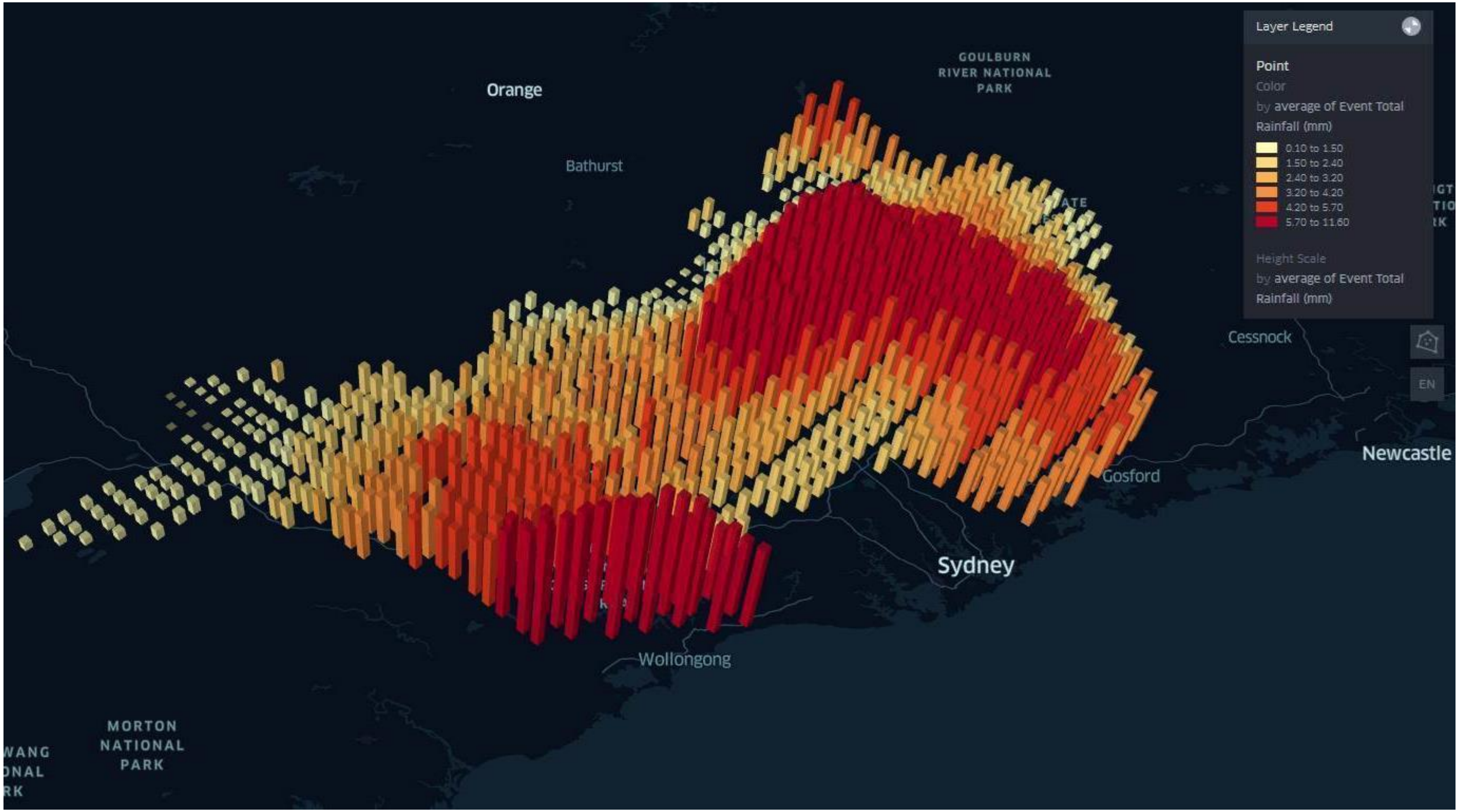

Figure 4-1. Total event precipitation (mm) for an ECL, 5-8 August 1986

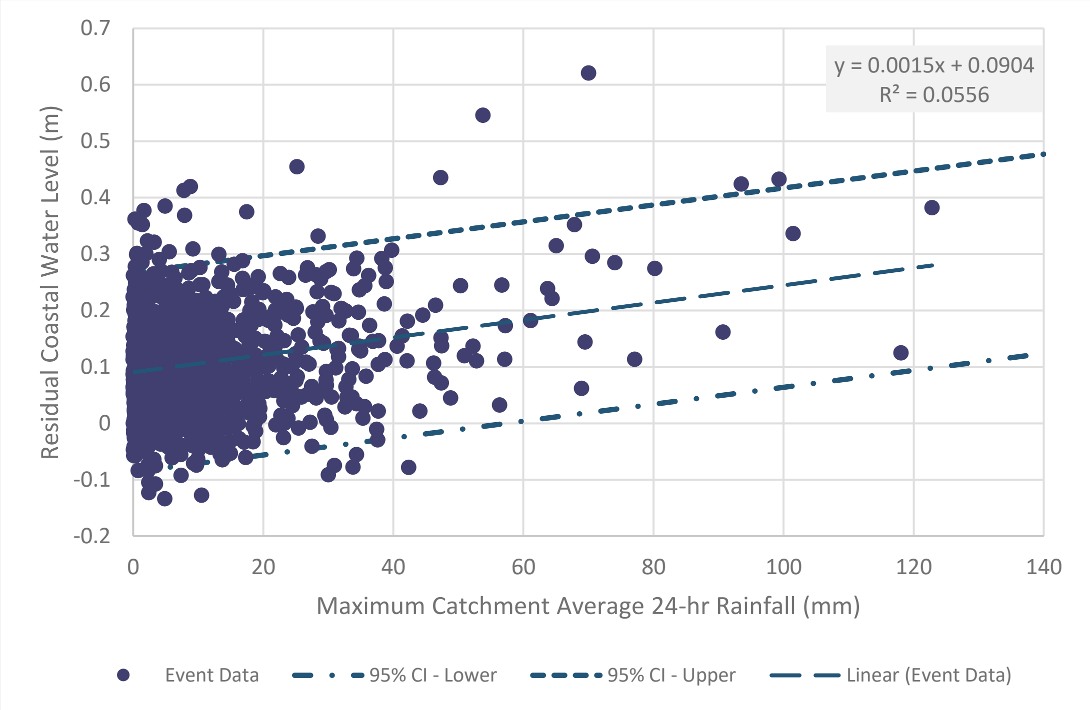

Figure 4-2. Cross plot of average maximum daily rainfall (in the Hawkesbury-Nepean River catchment from Baird ECL historical dataset) and maximum daily residual coastal water level (Fort Denison)

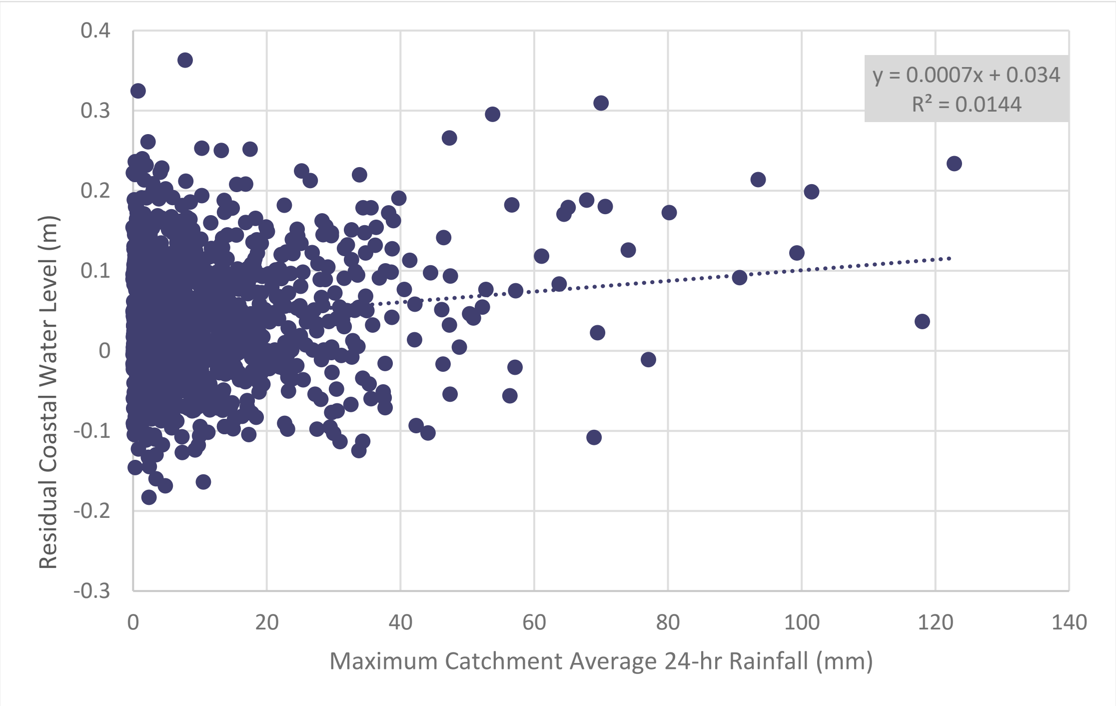

Figure 4-3. Cross plot of average maximum daily rainfall (in the Hawkesbury-Nepean River catchment from Baird ECL historical dataset) and mean residual coastal water level (Fort Denison)

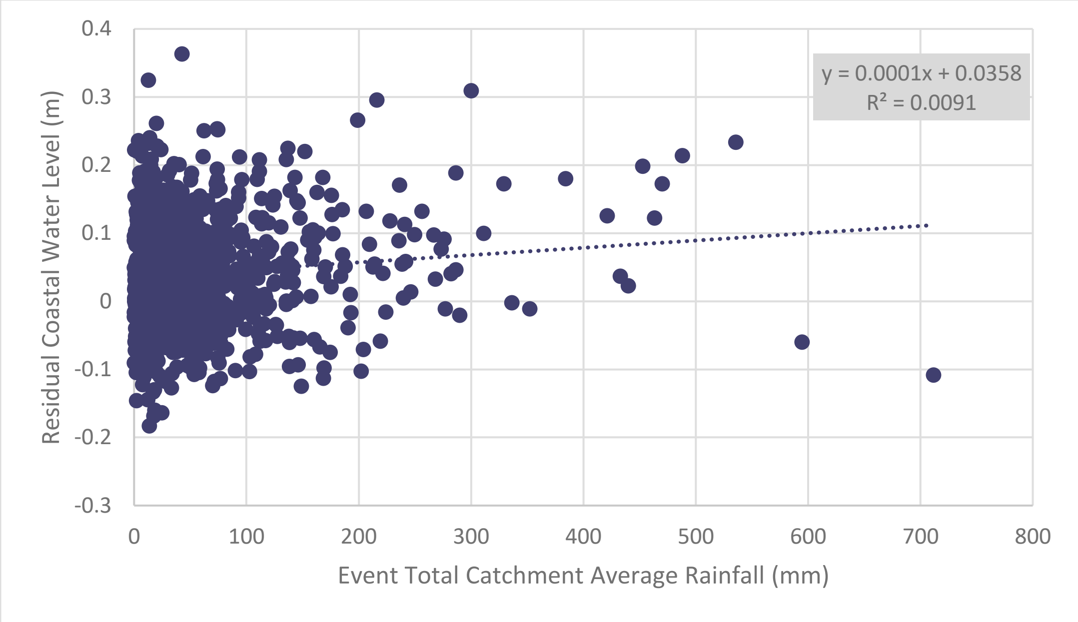

Figure 4-4. Cross plot of event total rainfall (in the Hawkesbury-Nepean River catchment from Baird ECL historical dataset) and corresponding mean residual coastal water level (Fort Denison)

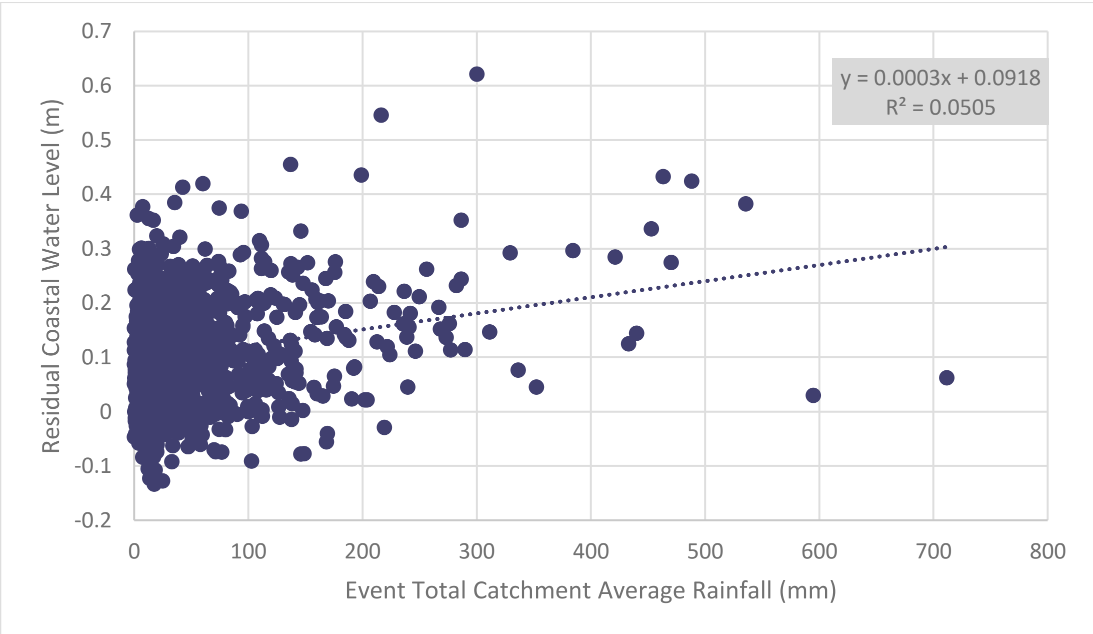

Figure 4-5. Cross plot of event total rainfall (in the Hawkesbury-Nepean River catchment from Baird ECL historical dataset) and corresponding maximum residual coastal water level (Fort Denison)

The ECL events presented in Figure 4-2 to Figure 4-5 include a large sample of events with relatively small rainfalls across the catchment and those events are not relevant to the assessment of floods within the Hawkesbury-Nepean River. The data set has been filtered for larger rainfall events with a catchment average daily rainfall (24-hour total) of 40 mm adopted. The residual water level model based on the events with a catchment average daily rainfall exceeding 40 mm is presented in Equation 2.

Equation 2

$$Max\ Res.WL = 0.0029\ \times Max\ Daily\ Rainfall + 0.0267 + \mathcal{N}(\mu, \sigma^2)$$

Where:

- Maximum Res. WL = maximum coastal residual water level over a 24-hour period (excluding tide)
- Maximum Daily Rainfall = maximum average 24-hour rainfall within the catchment based on a 0.05-degree geographic grid
- $\mathcal{N}(\mu, \sigma^2)$ = standard normal distribution error function with μ = 0, σ = 0.132 m.

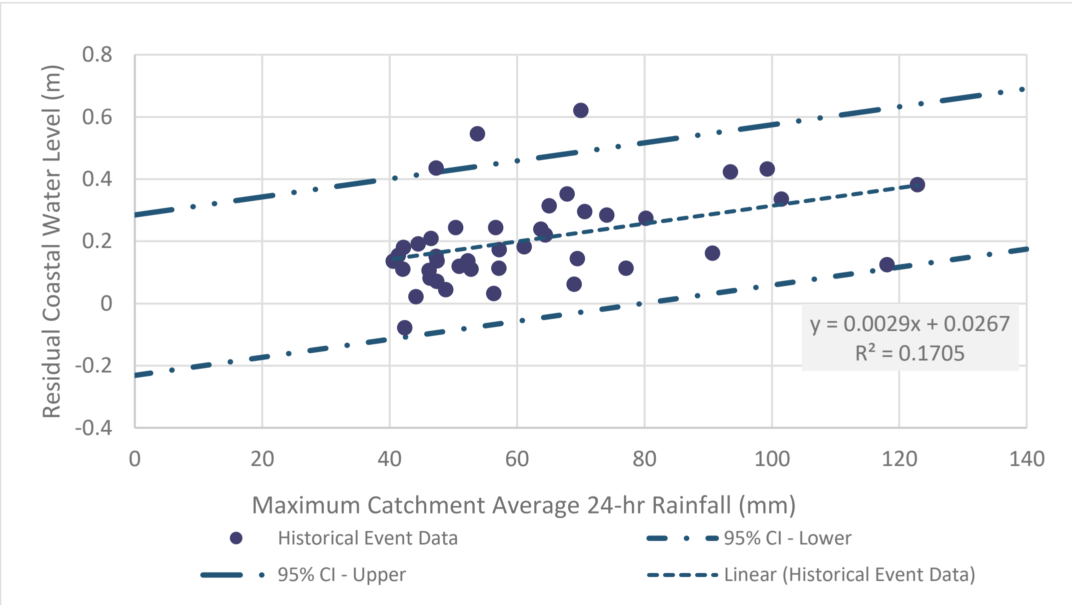

Figure 4-6. Cross plot of average maximum daily rainfall for events exceeding 40 mm (in the Hawkesbury-Nepean River catchment from Baird ECL historical dataset) and maximum daily residual coastal water level (Fort Denison)

The model presented in Figure 4-6 still has weak linear correlation between residual water level and rainfall; however, compared to Figure 4-2 the relationship is statistically more significant. Equation 2 has been adopted to estimate maximum residual coastal water level for moderate to large rainfall events in the Hawkesbury-Nepean River catchment as presented in the following sections.

4.1.1 1,000-Year Monte Carlo ECL Dataset

The maximum residual coastal water level and rainfall Equation 2 was applied to a sample of the top 250 rainfall events from Baird's 1,000-year Monte Carlo ECL model (Taylor et al, 2017). Figure 4-7 presents the top Monte Carlo rainfall events after applying Equation 2 in conjunction with the historical data shown in Figure 4-6. Across the 250 Monte Carlo events, the maximum residual coastal water level is within a realistic range for the coastal entrance of the Hawkesbury River. The proposed relationship between catchment averaged maximum daily rainfall and elevated residual coastal water level is similar to that proposed by Zheng et al (2014), which found a weak positive relationship in daily rainfall from Sydney Observatory Hill rain gauge and maximum daily residual coastal water level, using the Fort Denison tide gauge to calculate residual as applied in this study. Despite using different datasets of catchment-averaged maximum daily rainfall over an event (present study) and daily rainfall at Sydney Observatory Hill (Zheng et al, 2014), and different methods to determine relationship between rainfall and residual, both studies determined that a weak positive relationship exists. The key difference between Zheng et al (2014) and this report is that this study applied catchment-averaged rainfall, giving a more robust identification of large rainfall events which can induce elevated coastal water levels and coincident coastal flooding. Figure 4-7 includes the February 2020 event where the catchment rainfall has been derived from all available gauges within the Hawkesbury-Nepean catchment, and the residual water level calculated from Baird's analysis of the 1-hourly measured Fort Denison tide data. The February 2020 residual water is near the lower 95% confidence interval of the model. The timing of the peak residual coastal water level and rainfall for the February 2020 event was consistent with the majority of events (see Figure 4-8 and Figure 4-9) with the peak residual coastal water level occurring within the 12 to 36 hours prior to the peak catchment rainfall.

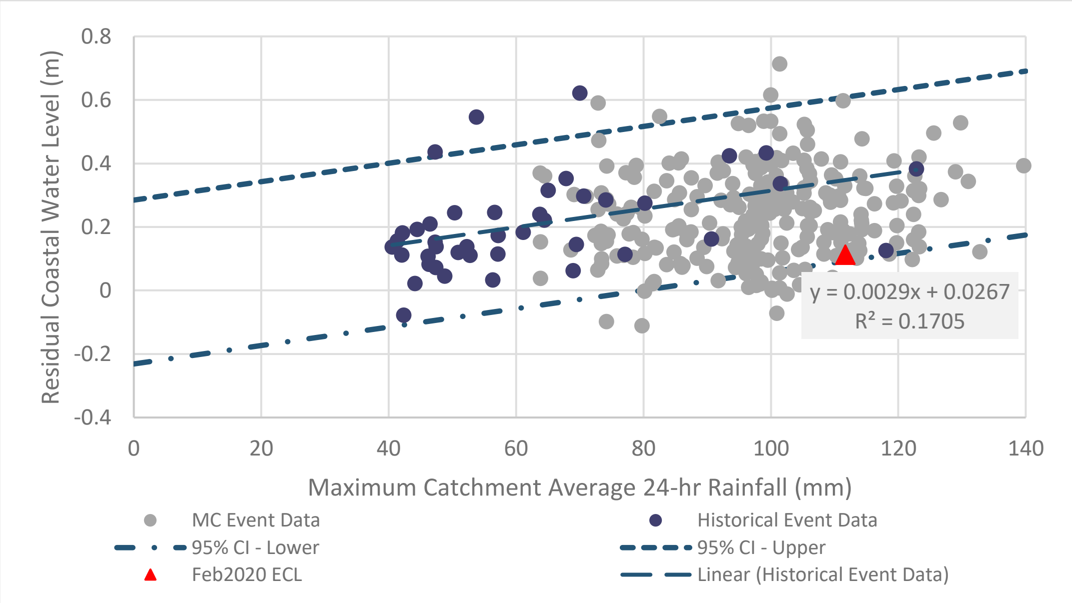

Figure 4-7. Cross plot of average maximum daily rainfall (in the Hawkesbury-Nepean River catchment from Historical and Monte Carlo Data) and maximum daily residual coastal water level (Fort Denison)

4.1.2 Residual Time series Analysis – Top ECL Events

A selection of the largest rainfall events based on Hawkesbury-Nepean River catchment maximum average daily rainfall summary statistics is presented in Table 1. Each event yielded similar residual coastal water level time series (Figure 4-8), where maximum residual is aligned to hour 48 of the storm. Whilst each storm presents a slightly different rate of increase and decrease, they all follow a similar curve. Baird identified that from baseline normal conditions, maximum residual level was reached by 36 hours, and held at that level for 24 hours. This is followed by a slower decrease down to normal conditions over 108 hours, by which time the storm has usually dissipated.

For comparison to the normalised residual water level ratio presented in Figure 4-8, Figure 4-9 presents the water level residual water level for the seven top ECL storms over the Hawkesbury-Nepean River catchment to confirm that all events have a similar trend of a residual water level near zero before the ECL develops, and then the residual builds over a 36 to 48 hour period, before gradually receding over the following days. Event 201304 has the residual water level falling quicker than the other six events and trends to a small negative residual after the peak of the storm. However, this event has a relatively small water level residual compared to the other six events. This is consistent with the trends shown in Figure 4-6 and Figure 4-2, whereby some ECL events can have small or negative residual as not all events have strong onshore winds or reductions in atmospheric pressure (below seasonal mean air pressure).

Table 4-1. Top ECL events based on maximum average daily rainfall over the Hawkesbury-Nepean River catchment and associated maximum residual coastal water level

Storm Event	Event Start	Event Finish	Maximum Coastal Water Level Residual (m)	Maximum Catchment Average Daily Rainfall (mm)
536	05/08/1986	07/08/1986	0.38	122.8
12	30/07/1990	03/08/1990	0.44	99.3
3	02/02/1990	05/02/1990	0.42	93.5
201613	05/06/2016	07/06/2016	0.27	80.2
201304	20/02/2013	23/02/2013	0.11	77.1
200705	08/06/2007	10/06/2007	0.28	74.1
201512	21/05/2015	24/ 4/2015	0.30	70.6

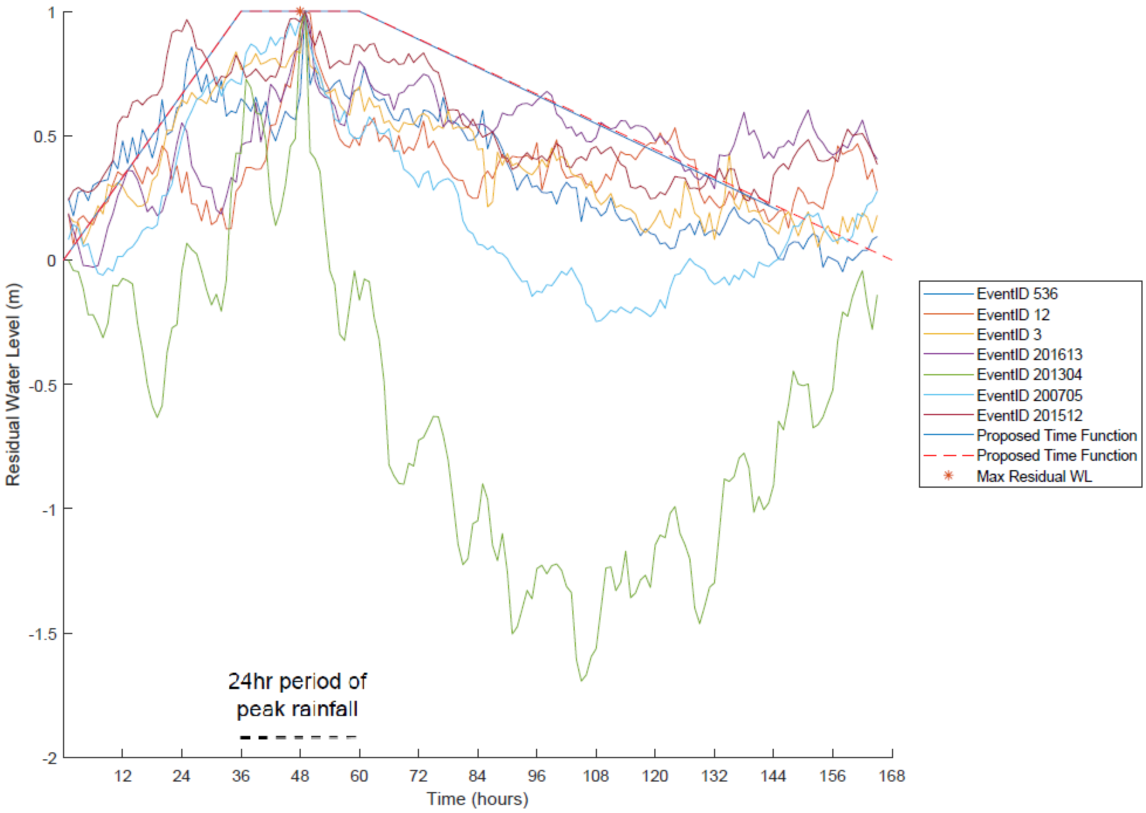

Figure 4-8. Residual coastal water levels as a ratio of event maximum, from top historical ECL events over the Hawkesbury-Nepean River catchment with a proposed time function

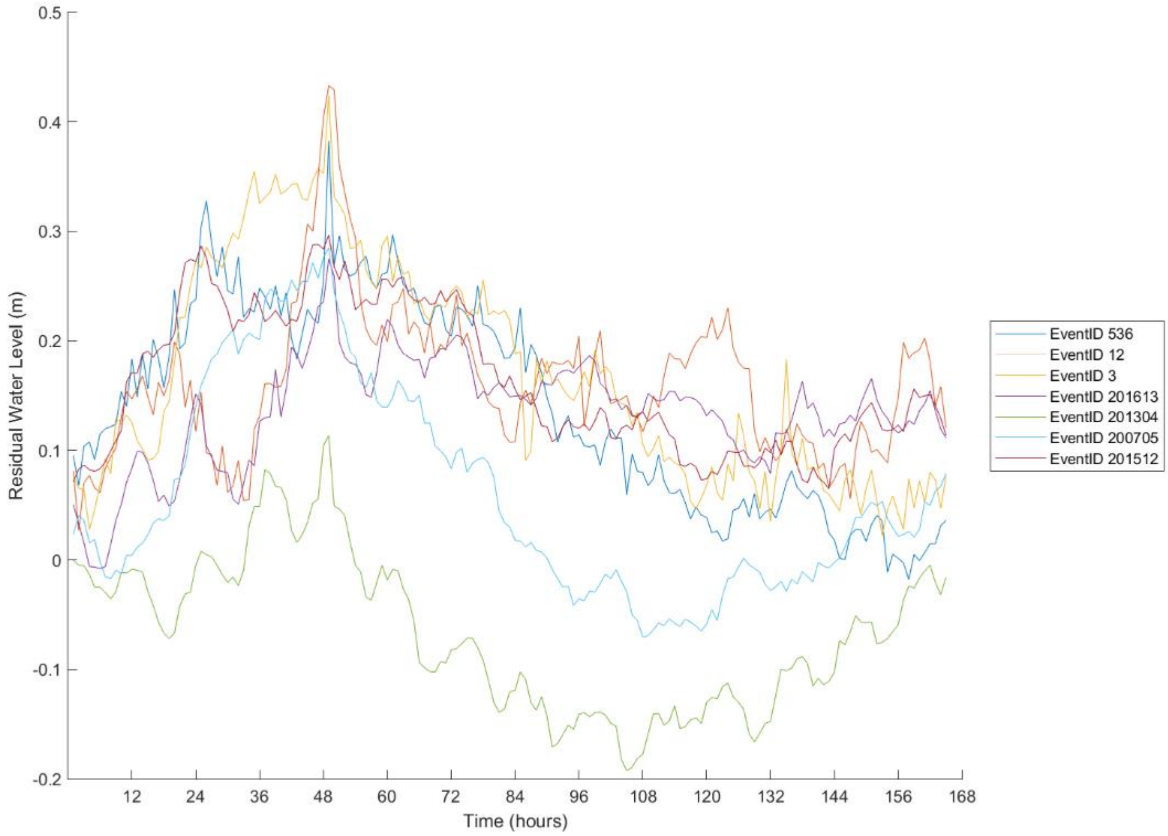

Figure 4-9. Residual coastal water levels from top historical ECL events over the Hawkesbury-Nepean River catchment

4.2 Phasing of Peak Residual Coastal Water Level and Lower Hawkesbury River Flow

River flow data (hydrographs) was analysed in conjunction with residual coastal water level time series, with results presented in Table 4-2. The maximum residual did not typically occur at the same time as maximum flow rate, with an average of 1.5 days between maximum residual and maximum flow (standard deviation = 0.87). For this analysis, an estimate of the combined rate of the Hawkesbury (at Windsor) and Colo River (at Upper Colo) has been adopted. This is to provide a representation of the discharges from the catchment upstream of the likely coastal influence for these flood events.

Table 4-2. Comparison of times of maximum residual coastal water level and maximum flows, for 9 historical events

Storm	Max Residual (m)	Time at Max Residual	Max Flow (m/s)[1]	Residual at Max Flow (m)	Time at Max Flow	Time between Max Flow and Max Residual (days)
Jun-64	0.26	11/06/1964 21:00	7378	-0.005	13/06/1964 10:00	1.5
Jun-75	0.34	21/06/1975 10:00	4113	0.30	23/06/1975 3:00	1.7
Mar-78	0.17	19/03/1978 20:00	8187	0.04	22/03/1978 12:00	2.7
Aug-86	0.38	6/08/1986 14:00	5284	0.22	6/08/1986 14:00	0.1
Apr-88	0.14	30/04/1988 5:00	5533	-0.013	02/05/1988 0:00	1.8
Apr-89	0.019	03/04/1989 0:00	2199	-0.21	05/04/1989 18:00	2.8
Aug-90	0.43	03/08/1990 1:00	7106	0.21	03/08/1990 18:00	0.7
Aug-98	0.19	08/08/1998 4:00	1054	0.12	09/08/1998 1:00	0.9
Feb-20	0.11	09/02/2020 2:00	4397	-0.09	10/02/2020 15:00	1.5

[1] These flow estimates are based on an approximation of the flows at Colo Junction, based on analysis by Rhelm.

5 Conclusion

Through an analysis of historical storms over the Hawkesbury-Nepean River catchment and coastal water levels, Baird derived a joint probability relationship between catchment rainfall and elevated coastal water levels (Equ. 2). The derived model has a weak positive linear trend between coastal residual water level (excluding astronomical tide) and rainfall across the Hawkesbury-Nepean River catchment. The model has a larger random residual component which has a normal distribution. Whilst the linear trend between Hawkesbury-Nepean River catchment and coastal water levels is weak, the resulting model (Equ. 2) follows the observed trend from a large sample of historical and synthetic (Monte Carlo) storm events as presented in Figure 4-7.

Utilising the Baird dataset of over 1,100 ECL historical storm events, 1,000-year MC ECL dataset, hydrograph data and long-term coastal water levels, this relationship can be applied over a range of storm events that could induce flooding in the Hawkesbury-Nepean River. Additionally, analysis of hydrograph flow data at Windsor and Upper Colo determined that maximum flow rates rarely correlate to maximum residual coastal water level, with the latter tending to occur first (ranging from 0 to 2.8 days earlier). A coastal water level time series was generated that follows the typical residual response of larger rainfall events from the period of 1970 to 2016. The residual coastal water level tends to peak earlier than the river flow, then residual coastal water level decreases slowly to normal conditions once storm conditions ease.

5.1 Application of Proposed Residual Coastal Water Level Model

Provided that the sample set of Monte Carlo events is sufficiently large to account for all catchment, hydraulic and coastal joint occurrence relationships, Baird propose the following application of the residual coastal water level model presented in this report:

1. Calculate the daily catchment averaged rainfall for the duration of all synthetic events in the adopted Monte Carlo suite of floods.
2. Apply Equation 2 as presented above to the maximum value of daily catchment average rainfall from each event.
3. If the resultant maximum residual water level is less than zero, apply a zero-water level residual; otherwise develop a time series of water level residuals as follows:
    a. For the 24-hour period of peak catchment-averaged daily rainfall, apply the calculated maximum residual water level.
    b. For the 36-hours prior to peak daily rainfall, linearly increase residual from 0 to the peak value.
    c. For the 108-hours following peak daily rainfall, linearly decrease the residual water level to 0.
4. Apply the residual coastal water level to a random astronomical tide using an 18.5-year astronomical tide cycle at the coastal boundary of the Hawkesbury-Nepean River two-dimensional model.

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