PATERSON RIVER FLOOD STUDY
VACY TO HINTON

FINAL REPORT

June 2017

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Project **Paterson River Flood Study**	**Project Number** **114084**
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PATERSON RIVER FLOOD STUDY

TABLE OF CONTENTS

LIST OF APPENDICES

LIST OF DIAGRAMS

LIST OF PHTOGRAPHS

LIST OF TABLES

LIST OF FIGURES

APPENDIX B Figures

APPENDIX C Figures

APPENDIX D Figures

LIST OF ACRONYMS

AEP	Annual Exceedance Probability
AHD	Australian Height Datum
AR&R	Australian Rainfall and Runoff
BoM	Bureau of Meteorology
CSIRO	Commonwealth Scientific and Industrial Research Organisation
CFERP	Community Flood Emergency Response Plan
DSC	Dungog Shire Council
DWR	Department of Water Resources
ERP	Emergency Response Classification
EY	Exceedances per Year
GEV	Generalised Extreme Value probability distribution
GSAM	General Southeast Australia Method
GSDM	Generalised Short Duration Method
IFD	Intensity, Frequency and Duration of Rainfall
IPCC	Intergovernmental Panel on Climate Change
LEP	Local Environmental Plan
LiDAR	Light Detection and Ranging (also known as ALS)
LPI	Land and Property Information
LP3	Log Pearson III probability distribution
m	metre
MCC	Maitland City Council
MHL	Manly Hydraulics Laboratory
m^3/s	cubic metres per second (flow measurement)
m/s	metres per second (velocity measurement)
NOW	NSW Office of Water
OEH	Office of Environment and Heritage
PINNEENA	Database of water resources information
PMF	Probable Maximum Flood
PMP	Probable Maximum Precipitation
PSC	Port Stephens Council
TUFLOW	one-dimensional (1D) and two-dimensional (2D) flood and tide simulation software program (hydraulic computer model)
WBNM	Watershed Bounded Network Model (hydrologic computer model)
1D	One dimensional hydraulic computer model
2D	Two dimensional hydraulic computer model

TERMINOLOGY USED IN REPORT

Australian Rainfall and Runoff have produced a set of draft guidelines for appropriate terminology when referring to the probability of floods. In the past, AEP has generally been used for those events with greater than 10% probability of occurring in any one year, and ARI used for events more frequent than this. However, the ARI terminology is to be replaced with a new term, EY.

Annual Exceedance Probability (AEP) is expressed using percentage probability. It expresses the probability that an event of a certain size or larger will occur in any one year, thus a 1% AEP event has a 1% chance of being equalled or exceeded in any one year. For events smaller than the 10% AEP event however, an annualised exceedance probability can be misleading, especially where strong seasonality is experienced. Consequently, events more frequent than the 10% AEP event are expressed as X Exceedances per Year (EY). Statistically a 0.5 EY event is not the same as a 50% AEP event, and likewise an event with a 20% AEP is not the same as a 0.2 EY event. For example an event of 0.5 EY is an event which would, on average, occur every two years. A 2 EY event is equivalent to a design event with a 6 month average recurrence interval where there is no seasonality, or an event that is likely to occur twice in one year.

While AEP has long been used for larger events, the use of EY is to replace the use of ARI, which has previously been used in smaller magnitude events. The use of ARI, the Average Recurrence Interval, which indicates the long term average number of years between events, is now discouraged. It can incorrectly lead people to believe that because a 100-year ARI (1% AEP) event occurred last year it will not happen for another 99 years. For example there are several instances of 1% AEP events occurring within a short period, for example the 1949 and 1950 events at Kempsey.

The PMF is a term also used in describing floods. This is the Probable Maximum Flood that is likely to occur. It is related to the PMP, the Probable Maximum Precipitation.

This report has adopted the approach of the ARR draft terminology guidelines and uses % AEP for all events greater than the 10% AEP and EY for all events smaller and more frequent than this.

FOREWORD

The NSW State Government's Flood Policy provides a framework to ensure the sustainable use of floodplain environments. The Policy is specifically structured to provide solutions to existing flooding problems in rural and urban areas. In addition, the Policy provides a means of ensuring that any new development is compatible with the flood hazard and does not create additional flooding problems in other areas.

Under the Policy, the management of flood liable land remains the responsibility of local government. The State Government subsidises flood mitigation works to alleviate existing problems and provides specialist technical advice to assist Councils in the discharge of their floodplain management responsibilities.

The Policy provides for technical and financial support by the Government through four sequential stages:

1. Flood Study
- Determine the nature and extent of the flood problem.

2. Floodplain Risk Management Study
- Evaluates management options for the floodplain in respect of both existing and proposed development.

3. Floodplain Risk Management Plan
- Involves formal adoption by Council of a plan of management for the floodplain.

4. Implementation of the Plan
- Construction of flood mitigation works to protect existing development, use of Local Environmental Plans to ensure new development is compatible with the flood hazard.

EXECUTIVE SUMMARY

BACKGROUND

The Paterson River catchment is located in the Hunter Valley, approximately 50 km west of Newcastle. The catchment lies within the Local Government Area (LGA) of Maitland City Council (MCC), Port Stephens Council (PSC) and Dungog Shire Council (DSC). The Paterson River has a total catchment area of approximately 1200 km^2. The area of interest for this study is the floodplain from Vacy (near of the confluence of the Paterson and Allyn Rivers) to the confluence with the Hunter River at Hinton. This portion of the catchment has an area of approximately 105 km^2.

The components of the study are to:

- collate available historical flood related data;
- analyse historical rainfall and flooding data;
- undertake a community consultation program;
- develop robust computational hydrologic and hydraulic models and calibrate them against multiple historical events;
- undertake a flood frequency analysis based on the historical record
- determine the flood behaviour including design flood levels, velocities and flood extents within the catchments;
- to assess the sensitivity of flood behaviour to potential climate change effects such as increase in rainfall intensities
- to assess the floodplain categories in accordance with Council policy and undertake provisional hazard mapping; and
- to determine and map the flood planning area in accordance with the floodplain development manual

COMMUNITY CONSULTATION

In collaboration with Maitland City Council, Port Stephens Council and Dungog Council a questionnaire was distributed to residents in the study area. The purpose of the questionnaire was to identify what residents had experienced problems with flooding and to collate as much historical flood data as possible. From this, 175 responses were received. Of those that responded 90% are aware of flooding issues in the catchment, with 40 respondents having their properties affected by flooding with a further 7 properties flooded above floor level.

The questionnaire was distributed shortly before a major flood in April 2015. Subsequent to this flood, WMAwater personnel visited the catchment to collect flood observations, and spoke with community members about their flood observations. There is a relatively high level of flood awareness and preparedness generally in the Paterson Valley, as several major floods have occurred in the last ten years.

MODELLING SUMMARY

The study comprises two distinct modelling components:

- WBNM (Hydrologic) – The model was used to calculate the flow hydrographs for input into the TUFLOW model.
- TUFLOW (Hydraulic) – The 2D hydraulic model was used to assess the complex flow regimes of Paterson River and its tributaries and how these flows interact with the floodplain and levee system.

CALIBRATION

A joint calibration of the hydrologic and hydraulic model was chosen as the best approach for the study area for the following reasons:

- The only gauge with a rating curve inside the study area is Gostwyck PINNEENA (210079). This is the only gauge that the hydrologic model could be calibrated to inside the study area. The highest recent gauging was 10.53m recorded in March 2000. All the historical events that have been used for calibration have recorded stage heights greater than 10.53m. Therefore there is little confidence in the rating curve beyond this point.
- The Allyn River Flying Fox Lane (210043) gauge has only one gauging above 1.5m therefore the rating curve can't be confidently applied for calibration of flows.
- The Paterson River Lostock Dam (210021) gauge and the Allyn River Halton (210022) gauge are located approximately 25 km upstream of the Hydraulic model boundary. This distance was considered too great for an independent hydrologic model calibration.
- There are five gauges inside the study area that record water levels that the hydraulic model can be calibrated to. The only calibration event that does not have records for all five gauges is March 1978 which only has records for Gostwyck PINNEENA - 210079.

The approach to model calibration was to adjust the rainfall loss parameters and the stream routing parameter in the WBNM (hydrologic) model and adjust the Manning's 'n' roughness values in the TUFLOW hydraulic model. Multiple combinations of these parameters were investigated until the best fit to the recorded water levels in the study area could be achieved across the whole range of calibration events.

For most events, the adopted rainfall depths and temporal patterns were found to have the most influence on the calibration results. The levels obtained at the gauges were more sensitive to the rainfall assumptions than to the other model parameters available for tuning the model calibration. This indicates that it is unreasonable to try and obtain a perfect fit in the model calibration results, since the available rainfall data is inherently unable to reflect the true spatial and temporal rainfall distribution across the catchment for the floods investigated.

The models were calibrated to the March 1978, March 2001, June 2007, June 2001, March 2013, November 2013 and April 2015 events. The model produced a good match to the recorded historical flood behaviour.

DESIGN FLOOD ESTIMATION

Two approaches were investigated to determine design flood magnitude. Flood Frequency Analysis and design rainfall modelling were both undertaken with similar results for peak flow at key gauges. The design rainfall approach was adopted as it provides a more holistic result for the entire study area, especially in regard to flood mapping of the Paterson River floodplains and tributaries.

The study included modelling of the 20%, 10%, 5%, 2%, 1%, 0.5%, 0.2% AEP and PMF design flood events, with mapping provided for peak flood depths and levels, peak velocities, hydraulic hazard and hydraulic categories.

KEY OUTCOMES

The study has quantified flood behaviour in the study area and the modelling tools that have been developed will assist Maitland City Council, Port Stephens Council and Dungog Council to undertake flood related planning decisions for future and existing development. A summary of key outcomes is as follows:

- The April 2015 flood event was equivalent to between a 2% and 1% AEP event in the study area;
- Vacy Bridge is above the 1% AEP flood level but overtopped in the 0.5% AEP event;
- Gostwyck Bridge is above the 0.5% AEP level but overtopped in the 0.2% AEP event;
- Paterson Road Bridge is above the 0.5% AEP level but overtopped in the 0.2% AEP event;
- Webbers Creek Bridge is above the 10% AEP level but overtopped in the 5% AEP event;
- Dunmore Bridge is above the 0.2% AEP level;
- The Horns Crossing causeway on the Allyn River is impassable in all events modelled.
- Major roads throughout the catchment are cut in events beginning at the 20% AEP event. This has implications for emergency response planning as well as planning future development in the catchment;
- The primary damages resulting from flooding in the study area are likely to be infrastructure damage to roads, bridges and railway lines, damages to agricultural equipment (farm machinery, structures, fences, etc.), and loss of crops and livestock;
- Existing residential and commercial buildings are generally at a low risk from flooding.
- This flood study will provide planning tools for Council to mitigate flood risk to future development in the catchment.

The outcomes relating to road closures are expected to be mainly of interest to the SES in formulating flood response procedures.

Note that the results presented in this study are for Paterson River flooding, in combination with smaller coincident Hunter River flood events. In the lower Paterson River floodplain, the Hunter River design flood levels (from Reference 5) are often the critical level for flood planning and development control purposes. The results from both studies should be considered for floodplain management decision-making.

For areas downstream of Dunmore Bridge the 1% AEP flood levels from the Hunter River Flood Study (Reference 5) are to be used for developmental purposes.

PUBLIC EXHIBITION

A draft of this study was placed on public exhibition to invite feedback from the community. From the month long public exhibition period, two public submissions were received, which are attached in Appendix E. The submissions related to levee modification works undertaken by OEH on the Wallalong levee in early 2016.

In response to the public submissions received WMAwater notes the following:

- The modelling completed for this study does not include the levee modification works carried out in early 2016. The levee topography utilised in the study is based on pre-modification levels from aerial survey collected in 2012 and 2013. The results and mapping outputs reflect pre-modification conditions.
- A separate modelling analysis undertaken for OEH quantified the changes to peak flood levels resulting from the levee modifications, for both Hunter River flooding and Paterson River flooding (attached in Appendix E).
- OEH is currently investigating further modifications to the levee with the intention of minimising the changes in flood behaviour compared to pre-modification conditions (as mapped for this study). WMAwater understands this process will involve community consultation.

RECOMMENDATIONS

It is recommended that following the conclusion and adoption of the Paterson River Flood Study; combined flood level and DCP mapping be developed utilising results from the Paterson River Flood Study and the Hunter River Flood Study (Reference 5). The DCP mapping can be tailored to meet each Council's individual needs or developed after a consultation process with all stakeholders.

1. INTRODUCTION

1.1. Background

The Paterson River is located within the Hunter Valley of NSW, approximately 50 km north-west of Newcastle. The catchment lies within the Local Government Area (LGA) of Maitland City Council (MCC), Port Stephens Council (PSC) and Dungog Shire Council (DSC). The Paterson River has a total catchment area of approximately 1200 km^2 and is shown in Figure 1. The area of interest for this study is the floodplain from Vacy (near of the confluence of the Paterson and Allyn Rivers) to the confluence with the Hunter River at Hinton. This portion of the catchment has an area of approximately 105 km^2 and is shown in Figure 2.

1.2. Objectives

The primary objective of this Flood Study is to develop a robust hydrologic and hydraulic modelling system that defines flood behaviour for the 20%, 10%, 5%, 2%, 1%, 0.5%, 0.2% AEP and the Probable Maximum Flood design events on the Paterson River. This will be used to assist MCC, PSC and DSC in determining existing flood risk, peak flood levels and inundation extents within the study area. The system may subsequently be used within a Floodplain Risk Management Study and Plan to assess the effectiveness and suitability of potential flood risk mitigation measures.

This Flood Study includes:

- a description of the study area;
- a summary of available historical flood-related data;
- analysis of rainfall and river level data;
- outcomes of the community consultation program
- identification of suitable historical events for calibration and verification;
- the modelling methodology adopted
- description of the hydrological and hydraulic model set up;
- the calibration methodology and results.
- flood frequency analysis methodology and results
- design flood event results
- sensitivity analysis including climate change

2. BACKGROUND

2.1. Study Area

The Paterson River and its main tributary the Allyn River are significant features of the Hunter Valley. The river systems course through the fertile farming land of the Paterson and Allyn River Valleys. The Paterson and Allyn Rivers originate as mountainous streams in the Barrington Tops National Park and flow parallel in a general southerly direction until their confluence near Vacy. The Paterson River continues south through the rich Paterson Plains until its confluence with the Hunter River at Hinton.

The catchment has been mainly cleared for agriculture, but pockets of forest remain especially in the upper reaches of the catchment near Barrington Tops. The gradient of the Paterson River is quite steep with limited floodplain until it reaches the township of Paterson. Intermittent floodplain areas begin to form south of the town of Paterson but they are still separated by ridges and topographic features which influence overbank flood conveyance. At a point approximately 4km upstream of the town of Woodville the floodplain widens significantly, and the floodplain is relatively broad through to the confluence with the Hunter River.

A major levee system was constructed in the 1960s and 1970s by the Department of Public Works. The levee system is built on the major floodplains, beginning at the township of Tocal and continuing to the confluence of the Hunter River where it meets the Hunter River levee system. The levee system has a considerable influence on flood behaviour especially in smaller events, which are contained within the river by the levee system.

2.2. Historical Flooding

2.2.1. Flood Mechanisms

Flooding in the Paterson Valley is influenced by two flood mechanisms:

1. Paterson River Flooding – Flooding on the Paterson River can occur due to heavy rainfall over the Paterson and Allyn River catchments. This mechanism influences flooding the entire length of the Paterson Valley
2. Hunter River Flooding – Flooding on the Hunter River can be caused by rainfall over the broader Hunter River and Goulburn River catchments. This mechanism influences flooding on the lower reaches and floodplains of the Paterson River.

Flooding on the Paterson and Hunter Rivers can occur independently of one another or concurrently. Concurrent flooding has a significant influence on flood levels on the lower reaches of the Paterson River and floodplains.

2.2.1. Historical Events

The Paterson River has flooded historically on a regular basis with 16 floods above the “major” flood level classification since 1929. The flood classifications for the Paterson River at Gostwyck Bridge and Paterson Bridge as well as the Hunter River at Belmore Bridge are shown in Table 1. A summary of recorded major historical floods for the Paterson River is listed in Table 2 along with their recorded stage heights and classification for both the Paterson and Hunter Rivers.

Table 1 – BOM Flood Classifications

Station	Flood Classifications (Gauge Readings)		
	Minor	Moderate	Major
Paterson River Gostwyck	9.1	10.7	12.2
Paterson River Railway Bridge	6.1	7.6	9.1
Hunter River Belmore Bridge	5.9	8.9	10.5

Table 2 – Historical Flood Events

Event	Paterson River Gostwyck Bridge mAHD	Classification	Hunter River Belmore Bridge mAHD	Classification
1929	13.9	Major	8.5	Minor
1930	13.6	Major	11.2	Major
1946	14.3	Major	9.3	Moderate
1955	13.7	Major	12.1	Major
1963	14.5	Major	8.0	Minor
1967	14.1	Major	8.7	Minor
1972	13.6	Moderate	8.9	Moderate
1977	13.1	Major	10.8	Major
1978	15.5	Major	9.6	Moderate
1985	15.2	Major	9.3	Moderate
1990	14.7	Major	8.8	Minor
1995	10.3	Minor	2.6	Below Minor
2001	13.5	Major	7.2	Minor
2007	13.6	Major	10.7	Major
2011	13.9	Major	7.2	Minor
Mar 2013	12.9	Major	8.2	Minor
Nov 2013	12.0	Moderate	4.8	Below Minor
Apr 2015	16.1	Major	8.9	Moderate

3. AVAILABLE DATA

3.1. Topographic Data

Light Detection and Ranging (LiDAR) survey of the study area and its immediate surroundings was provided for the study by LPI (see Figure 3). LiDAR is aerial survey data that provides a detailed topographic representation of the ground with a survey mark approximately every square metre. The data for the Maitland area was collected in 2012 and the Raymond Terrace area in 2013. The accuracy of the ground information obtained from LiDAR survey can be adversely affected by the nature and density of vegetation, the presence of steeply varying terrain, the vicinity of buildings and/or the presence of water. The accuracy is typically ± 0.15 m for clear terrain. The accuracy within creek channels is typically much less, and the LiDAR must be supplemented with detail survey and bathymetric survey.

3.2. Bathymetric Survey

OEH provided detailed bathymetric survey of the tidal portions of the Paterson River and Hunter River. The Paterson River survey begins 5km upstream of Dunmore Bridge at Woodville and concludes at the confluence with the Hunter River. The Hunter River survey begins in between Oakhampton Railway Bridge and Belmore Bridge and concludes outside the study area at Hexham Bridge. The survey locations are shown in Figure 3.

The survey was undertaken in 2013 and river cross sections can vary over time especially after large flood event were erosion and sediment deposits can alter bathymetry. It should be noted that a change in river cross sections will generally have more influence in a smaller events, and will have less influence in the 1% AEP or similar events when 50% or more of the flow is in the overbank areas.

3.3. Levee Survey

OEH provided detailed survey of the Paterson River levee system. The levee survey begins at Tocal and continues through to the confluence with the Hunter River.

3.4. Flood Level Survey

In April 2015, after the study was already underway, there was a major flood on the Paterson River. The storm event of April 2015 affected much of the east coast of New South Wales, particularly along the coast from the Illawarra region to the Hunter Valley, causing widespread flooding and other storm damage.

WMAwater personnel undertook post-flood data collection in the Hunter Valley from Tuesday 28th April to Friday 1st May, approximately one week after the peak of the flooding. The focus was to collect photographs and flood marks that could be used for model calibration as part of the study. WMAwater personnel spoke with several residents about their observations of the flood behaviour.

The Paterson River flood marks identified during the data collection exercise were surveyed on 23 October 2015 by surveyors from MCC, to obtain accurate flood levels. The location of the flood levels obtained from the survey are shown on Figure 3, and a comparison with modelled flood levels is provided in Section 8.

3.5. Stream Gauges

In order to calibrate hydrologic and hydraulic models, water level recorders (stream gauges) are required in a river. For this study nine gauges are located in or adjacent to the study area and are listed in Table 3 with their locations shown in Figure 4.

Table 3 – Stream Gauges

Station No	Station Name	Opened	Closed
210022	AR - Halton	Dec-40	Current
210143	AR - Flying Fox Lane	May-06	Current
210021	PR - D/S Lostock Dam	Nov-40	Current
210102	PR - Lostock Dam (Storage)	Feb-71	Current
210079	PR - Gostwyck PINNEENA	May-28	Current
210402	PR - Gostwyck MHL	Oct-88	Current
210406	PR - Paterson Railway Bridge	Dec-84	Current
210409	PR - Dunmore	Nov-84	Current
210410	PR - Hinton Bridge	Mar-85	Current
210430	HR - Morpeth	Apr-85	Current
210432	HR - Green Rocks	Dec-84	Current
210455	HR - McKimms Corner	Mar-86	Current
210458	HR - Belmore Bridge	Jun-92	Current
210475	HR - Oakhampton Bridge	Dec-95	Current

The flow corresponding to a given water level is estimated from a rating curve which provides a relationship between the water level and flow at each gauge. This relationship is derived from velocity measurements (using a current meter) at a known water level and cross sectional water area (obtained by survey). Many of these velocity readings are taken over a period of years at different water levels (termed gaugings) and in this way a rating curve is developed as a “line of best fit” between the gaugings. For the region above the highest gauging measurement the rating curve must be extrapolated, and this portion of the curve is often subject to significant uncertainty and inaccuracy.

Four gauges in the Paterson River catchment controlled by the Office of Water from the Department of Primary Industries have available rating curves. The gauges are:

- 210022 – Allyn River Halton
- 210143 – Allyn River Flying Fox Lane
- 210021 – Paterson River D/S Lostock Dam
- 210079 – Paterson River Gostwyck

The rating curves and the recorded gaugings are shown in Figure 5 to Figure 8.

It is relatively easy to obtain "low flow" gaugings as small rises in water levels occur frequently and the gauging party has therefore ample opportunity to undertake them. It is much harder to obtain "high flow" gaugings as they can only be obtained during large floods (which occur infrequently) and it may be that the gauging party cannot get access to the site or are otherwise engaged. Safe access to the site can also be an issue. Thus all rating curves generally have few "high flow" gaugings, and there is considerable uncertainty about the flow estimates at high water levels. A graph of the gaugings indicates how many "high flow" gaugings were undertaken and the height at which they were taken, and from this an estimate of the accuracy of the high flows can be made. Generally there are few gaugings taken at the peak of a flood and thus the highest gaugings may be several metres below the highest recorded flood levels, and the rating curve must be extrapolated.

3.5.1. Analysis of Stream Gauge Records

The stream gauge records were analysed for the ten significant historical events. The recorded peak stage heights for each event are shown in Table 4 and the stage hydrographs are shown in Figure 9 to Figure 19.

Table 4 – Peak Stage Heights (m)

Station Name	Mar77	Mar78	Oct85	Feb90	Mar95	Mar01	Jun07	Jun11	Mar13	Nov13	Apr15
AR - Halton 210022	5.94	6.73	3.96	6.57	4.49	4.53	5.37	5.03	5.62	2.57	4.66
AR – Flying Fox Lane 210143	-	-	-	-	-	-	7.78	11.69	10.29	10.47	-
PR – Lostock Dam 210021	4.06	-	3.96	5.16	3.51	4.52	4.12	4.64	4.51	0.89	3.37
PR - Gostwyck 210079	12.99	14.37	13.60	13.37	9.13	12.16	12.57	13.12	11.70	11.05	15.50
PR - Gostwyck 210402	-	-		14.7	10.33	13.49	13.64	13.93	12.85	12.02	16.12
PR - Paterson Railway Bridge 210406	-	-	11.17	11.12	7.19	10.42	10.16	10.35	9.66	8.43	11.99
PR - Dunmore 210409	-	-	-	6.43	4.05	6.48	6.36	6.32	6.34	5.03	6.06
PR - Hinton Bridge 210410	-	-	-	5.67	2.57	5.44	5.78	5.35	5.49	3.77	5.76
HR - Morpeth 210430	-	-	-	6.12	2.49	5.64	6.52	5.52	5.7	3.75	6.11
HR - Green Rocks 210432	-	-	3.86	-	1.81	4	3.98	3.93	4.07	3.75	4.37
HR - McKimms Corner 210455	-	-	-	7.4	2.5	6.23	8.22	6.19	6.84	4.04	7.33
HR - Belmore Bridge 210458	-	-	-	-	2.63	7.22	10.47	7.23	8.18	4.83	8.92
HR - Oakhampton 210475	-	-	-	-	-	8.09	12.24	8.18	9.49	5.58	10.43

3.6. Rainfall Stations

3.6.1. General

There are a number of rainfall stations within a 50 km radius of the study area. These include daily read stations and continuous pluviometer stations.

The daily read stations record total rainfall for the 24 hours to 9:00 am of the day being recorded. For example the rainfall received for the period between 9:00 am on 3 February 2008 until 9:00 am on 4 February 2008 would be recorded on the 4 February 2008.

The continuous pluviometer stations record rainfall in sub-daily increments (with output typically reported every 5 or 6 minutes). These records were used to create detailed rainfall hyetographs, which form a model input for historical events against which the model is calibrated. Table 5 and Table 6 presents a summary of the continuous pluviometer and daily rainfall gauges available for use in this study. The locations of these gauges are shown in Figure 20 and Figure 21. These gauges are operated by Sydney Catchment Authority (SCA), Hunter Water (HWC), Manly Hydraulics Laboratory (MHL) and the Bureau of Meteorology (BOM).

Table 5 - Continuous read rainfall stations

Station No	Station Name	Opened	Closed
61158	Glendon Brook (Lilyvale)	1964	Current
61174	Millfield Composite	1958	1981
61183	Pokolbin (Mount Bright)	1962	1971
61237	Pokolbin (Kiera)	1962	1973
61238	Pokolbin (Somerset)	1962	Current
61250	Paterson (Tocal AWS)	1975	Current
61288	Lostock Dam	1969	Current
61314	Mount Bright (Mount View Range)	1972	1981
210022	Halton	1986	2009
210458	Belmore Bridge	1995	Current
210402	Gostwyck	1999	Current

Table 6 - Daily read rainfall stations

Station No	Station Name	Opened	Closed
60042	Craven (Longview)	1961	Current
60075	Gloucester (Upper Bowman)	1965	Current
60096	Cabbage Tree Mountain	2002	Current
60152	Cobark	2008	Current
60153	Moppy Lookout (Barrington Tops)	2008	Current
61010	Clarence Town (Prince St)	1895	Current
61014	Branxton (Dalwood Vineyard)	1863	Current
61017	Dungog Post Office	1897	Current
61024	Gresford Post Office	1895	Current
61031	Raymond Terrace (Kinross)	1894	Current
61071	Stroud Post Office	1889	Current

Station No	Station Name	Opened	Closed
61072	Tahlee (Carrington (Church St))	1887	Current
61078	Willamtown RAAF	1942	Current
61092	Elderslie	1927	Current
61095	Rouchel Brook (Albano)	1932	Current
61096	Paterson Post Office	1901	Current
61097	Moonan Flat (High St)	1897	Current
61100	Broke (Harrowby	1887	Current
61106	Dungog (Monkerai Hill (Urimbirra))	2001	Current
61135	Upper Rouchel (Mount View)	1961	Current
61143	Bulga (Downtown)	1960	Current
61146	Carrow Brook	1960	Current
61151	Chichester Dam	1942	Current
61158	Glendon Brook (Lilyvale)	1960	Current
61160	Hilldale (Sundance)	1960	2012
61170	Dungog - Main Creek (Yeranda)	1960	Current
61191	Bulga (South Wambo)	1959	Current
61241	Carrabolla (Woodbury)	1965	2011
61250	Paterson (Tocal AWS)	1967	Current
61260	Cessnock Airport AWS	1968	Current
61268	Maitland Belmore Bridge (Hunter River)	1906	Current
61270	Bowmans Creek (Grenell)	1969	Current
61288	Lostock Dam	1969	Current
61290	Upper Allyn Township	1969	Current
61311	Grahamstown (Hunter Water Board)	1971	2013
61315	Rouchel (Bonnie Doon)	1972	Current
61339	Clarencetown (Mill Dam Falls (Williams River))	1927	Current
61346	Hunter Springs (Wondecla)	1971	Current
61349	Gostwyck Bridge (Paterson River)	1929	Current
61350	Upper Chichester (Simmonds)	1981	Current
61364	Dungog (Leawood)	1981	Current
61388	Maitland Visitor Centre	1997	Current
61390	Newcastle University	2013	2013
61395	Tanilba Bay WWTP	2001	Current
61397	Singleton STP	2002	Current
61399	Moonan Brook (Pampas)	2003	Current
61405	Woodville (Clarence Town Rd)	2004	Current
61413	Careys Peak (Barrington Tops)	2008	Current
61414	Heddon Greta (Kurri Kurri Golf Club)	2007	Current
61415	Dungog (Upper Myall Creek(	2007	Current
61418	Barrington Tops (Mount Barrington)	2009	Current
61420	Mirannie (Maeranie Station)	2010	Current
61421	Cranky Corner (Tangory Moutain)	2010	Current
61422	Milbrodale School	2010	Current

3.6.2. Analysis of Daily Read Data

The daily rainfall gauges within 10 km of the catchment were analysed for each of the ten significant events identified in Section 3.5. Each event was analysed for the maximum 1-day, 2-day, 3-day and entire event totals. The results of the analysis are shown in Table 7 to Table 10.

The rainfall totals for each event at each available rain gauge were used to create rainfall isohyets for the entire catchment. These rainfall isohyets were used to determine the rainfall depths for each individual subcatchment in the hydrological model and are shown in Figure 30 to Figure 33. The rainfall isohyets were developed using the natural neighbour interpolation technique

Table 7 – Highest Daily Read Rainfall Readings (mm) for 1 day event.

Event	Station No	Station Name	Total Rainfall (mm)
1977	61031	Raymond Terrace (Kinross)	171
1978	61290	Upper Allyn Township	248
1985	61017	Dungog Post Office	187
1990	61311	Grahamstown	235
1995	61151	Chichester Dam	110
2001	61290	Upper Allyn Township	142
2007	61405	Woodville (Clarence Town Rd)	201
2011	61413	Careys Peak (Barrington Tops)	198
Mar 2013	61151	Chichester Dam	179
Nov 2013	61096	Paterson Post Office	215
April 2015	61096	Paterson Post Office	237

Table 8 – Highest Daily Read Rainfall Readings (mm) for 2 day event.

Event	Station No	Station Name	Total Rainfall (mm)
1977	61290	Upper Allyn Township	214
1978	61151	Chichester Dam	346
1985	61024	Gresford Post Office	244
1990	61311	Grahamstown	393
1995	61350	Upper Chichester (Simmonds)	158
2001	61290	Upper Allyn Township	227
2007	61405	Woodville (Clarence Town Rd)	320
2011	61413	Careys Peak (Barrington Tops)	278
Mar 2013	61413	Careys Peak (Barrington Tops)	238
Nov 2013	61096	Paterson Post Office	274
April 2015	61096	Paterson Post Office	223

Table 9 – Highest Daily Read Rainfall Readings (mm) for 3 day event.

Event	Station No	Station Name	Total Rainfall (mm)
1977	61290	Upper Allyn Township	278
1978	61290	Upper Allyn Township	460
1985	-	-	-
1990	61311	Grahamstown	456
1995	61350	Upper Chichester (Simmonds)	224
2001	61290	Upper Allyn Township	284
2007	61405	Woodville (Clarence Town Rd)	334
2011	61413	Careys Peak (Barrington Tops)	278
Mar 2013	61413	Careys Peak (Barrington Tops)	294
Nov 2013	61096	Paterson Post Office	288
April 2015	61096	Paterson Post Office	460

Table 10 – Highest Daily Read Rainfall Readings (mm) for entire event.

Event	Station No	Station Name	Duration	Total Rainfall (mm)
1977	61290	Upper Allyn Township	5	387
1978	61290	Upper Allyn Township	5	489
1985	61024	Gresford Post Office	2	244
1990	61311	Grahamstown	5	456
1995	61350	Upper Chichester (Simmonds)	6	299
2001	61290	Upper Allyn Township	7	320
2007	61405	Woodville (Clarence Town Rd)	4	341
2011	61413	Careys Peak (Barrington Tops)	5	459
Mar 2103	61413	Careys Peak (Barrington Tops)	12	658
Nov 2013	61096	Paterson Post Office	4	291
April 2015	61096	Paterson Post Office	3	460

3.6.3. Analysis of Pluviometer Data

The pluviometer gauges were analysed for the historical events that had corresponding rainfall data. This data was used to determine the temporal patterns of each storm event that were subsequently used in the model calibration process. The temporal patterns for the historical event are shown in Figure 22 to Figure 29.

3.7. Suitable Events for Calibration and Verification

In order to identify the most suitable events for model calibration on a catchment wide basis it is important that there is sufficient available water level data recorded on river gauges and sub-hourly rainfall data that is recorded on pluviometer gauges. Table 11 provides a matrix of the significant events and the available rainfall and water level data.

Table 11 – Available Rainfall and Water Level Records

Station Name	Mar77	Ma7r8	Oct85	Feb90	Mar95	Mar01	Jun07	Jun11	Mar13	Nov13	Apr15
Pluviograph Rain Gauges	3	4	1	0	0	6	5	6	4	5	5
Pluviograph Rain Gauges in Catchment	1	1	0	0	0	4	2	3	2	3	3
Daily Rain Gauges	27	26	30	26	26	31	35	40	43	40	38
Paterson River Stream Gauges	1	1	3	6	6	6	6	6	6	6	6
Hunter River Stream Gauges	0	0	2	2	4	5	5	5	5	5	6
Allyn River Stream Gauges	0	1	1	1	1	1	2	2	2	2	0

MARCH 1977 – Selected for calibration

- moderate size flood on the Paterson River
- water level data at Gostwyck Bridge
- good coverage of daily gauges and data for one pluviometer gauge in the catchment
- event was modelled in the Paterson River Flood Study 1997 (Reference 3) allowing for comparison
- Hunter River modelled in the Hunter River: Branxton to Green Rocks Flood Study (Reference 5)

MARCH 1978 – Selected for calibration

- major flood on the Paterson River
- water level data at Gostwyck Bridge
- good coverage of daily gauges and data for one pluviometer in the catchment
- event was modelled in the 1997 Paterson River Flood Study (Reference 3) allowing for comparison

OCTOBER 1985 – Not selected for calibration

- major flood on the Paterson River but slightly lower than 1978
- water level data at Gostwyck Bridge and Paterson Railway Bridge
- no pluviometer data in the catchment

FEBRUARY 1990 – Not selected for calibration

- major flood on the Paterson River
- water level data at four Paterson River gauges
- no pluviometer data in the catchment

MARCH 1995 – Not selected for calibration

- minor flood on the Paterson River with little influence on the Hunter River
- water level data at four Paterson River gauges
- water level data at four Hunter River gauges
- no pluviometer data in the catchment

MARCH 2001 – Selected for calibration

- major flood on the Paterson River and a minor flood on the Hunter River
- water level data at four Paterson River gauges
- water level data at five Hunter River gauges
- good coverage of daily gauges and data for four pluviometer gauges in the catchment

JUNE 2007 - Selected for calibration

- major flood on the Paterson River and a major flood on the Hunter River
- water level data at four Paterson River gauges
- water level data at five Hunter River gauges
- good coverage of daily gauges and data for two pluviometer gauges in the catchment
- Hunter River modelled in the Hunter River: Branxton to Green Rocks Flood Study (Reference 5)

JUNE 2011 – Selected for calibration

- major flood on the Paterson River and a minor flood on the Hunter River
- water level data at four Paterson River gauges
- water level data at five Hunter River gauges
- good coverage of daily gauges and data for three pluviometer gauges in the catchment

MARCH 2013 – Selected for calibration

- major flood on the Paterson River and a minor flood on the Hunter River
- water level data at four Paterson River gauges
- water level data at five Hunter River gauges
- good coverage of daily gauges and data for two pluviometer gauges in the catchment

NOVEMBER 2013 – Selected for calibration

- major flood on the Paterson River and a minor flood on the Hunter River
- water level data at four Paterson River gauges
- water level data at five Hunter River gauges
- good coverage of daily gauges and data for three pluviometer gauges in the catchment

APRIL 2015 – Selected for calibration

- major flood on the Paterson River and a minor flood on the Hunter River
- water level data at six Paterson River gauges
- water level data at six Hunter River gauges
- good coverage of daily gauges and data for four pluviometer gauges in the catchment

3.8. Design Rainfall

The design rainfall intensities for the catchment centroid are shown in Table 12.

Table 12 - IFD table for the catchment centroid

Storm Duration	1EY (1 in 1 year)	0.5EY (1 in 2 year)	0.2EY (1 in 5 year)	10% (1 in 10 year)	5% (1 in 20 year)	2% (1 in 50 year)	1% (1 in 100 year)
1 hour	22.2	28.8	37.5	42.8	49.7	58.9	65.9
2 hour	15	19.4	25.3	28.8	33.4	39.6	44.4
3 hour	11.9	15.4	20	22.8	26.5	31.3	35.1
6 hour	7.97	10.3	13.5	15.3	17.8	21.1	23.7
12 hour	5.34	6.93	9.08	10.4	12.1	14.3	16.1
24 hour	3.53	4.6	6.09	7	8.18	9.78	11
36 hour	2.73	3.57	4.78	5.52	6.49	7.79	8.81
48 hour	2.26	2.96	4	4.63	5.46	6.58	7.46
72 hour	1.7	2.24	3.05	3.55	4.22	5.09	5.8

3.9. Previous Studies

3.9.1. Paterson River Flood Study – WBM Oceanics 1997

The study defined flood behaviour for the Paterson River from the Gostwyck Bridge to the Hunter River, including the floodplains on both banks and those in common with the Hunter River east of Hinton. The purpose of the study was to develop suitable computer flood models in order to understand and quantify flood behaviour in the lower Paterson River and to assist Port Stephens, Maitland and Dungog Councils in the development of a Floodplain Risk Management Plan for the study area to consider both existing and future development.

A RAFTS-XP hydrological model was used to determine inflows for the Paterson River and its tributaries which were input into the MIKE-11 hydraulic model in order to determine flood behaviour in the catchment. A flood frequency analysis was carried out to provide an alternative assessment of peak design flows at Gostwyck Bridge, using an annual series approach.

The models were calibrated to the March 1977, March 1978 and March 1995 events and then used for design flood estimation.

3.9.2. Paterson River Floodplain Risk Management and Plan – Bewsher Consulting 2001

The study identified practical measures to minimise the impacts of floods on the community of the Paterson River Valley. A range of possible measures were examined to find the most suited based on economic, technical, social and environmental criteria and the likely level of community support. Floodplain Management Plans for the Paterson River floodplain within the Dungog and Port Stephens Council areas were prepared. Within the Dungog LGA the cost of the recommended measures totalled $100,000 and within the Port Stephens Council area the recommended measures were estimated to cost between $1.2 million to $2.4 million.

As part of the current floodplain management study, the flood study was updated to provide flood behaviour information upstream of Paterson town (extending to Vacy). Events modelled included the 20%, 10%, 2%, 1% and 0.2% annual exceedance probability (AEP) events and an extreme flood (EF).

The updated modelling was documented in Volume 3 of the 2001 study. Port Stephens Council indicated that these are the model results relied upon for design flood and planning control purposes.

3.9.3. Hunter River: Branxton to Green Rocks Flood Study – WMAwater 2010

The study covered the Hunter River and its floodplain from approximately 3 km upstream of the Black Creek tributary at Branxton to Green Rocks (approximately 8 km downstream of Morpeth at the Maitland LGA boundary). The purpose of the study was to develop a suitable hydraulic model that could be used to assist Maitland and Cessnock Councils in the development of an updated Floodplain Risk Management Plan for the study area to consider both existing and future development.

A flood frequency analysis was used to determine the peak flows for the Hunter River and WBNM models were used to determine the smaller tributary flows. These inflows were input into TUFLOW hydraulic models to determine flood behaviour in the study area.

Due to the size of the computer models, two separate TUFLOW models were established with an overlapping intermediate area at Oakhampton. The models were calibrated to historical flood height data (1955, 1971, 1977 and 2007) where data was available and then used for design flood estimation.

4. COMMUNITY CONSULTATION

4.1. Information Brochure and Survey

In collaboration with MCC, PSC and DSC an information brochure with survey was distributed to residents with the study area. The function of this was to describe the role of the Flood Study in the flood plain risk management process and to request records of historical flooding. 175 responses were received from the questionnaire. From the survey 90% of respondents are aware of flooding issues in the catchment, with 40 respondents having their properties affected by flooding with a further 7 properties being flooded above floor level.

4.2. Community Responses

Photo 1 – Phoenix Park Road 2015

Photo 2 – Morpeth Bridge 2015

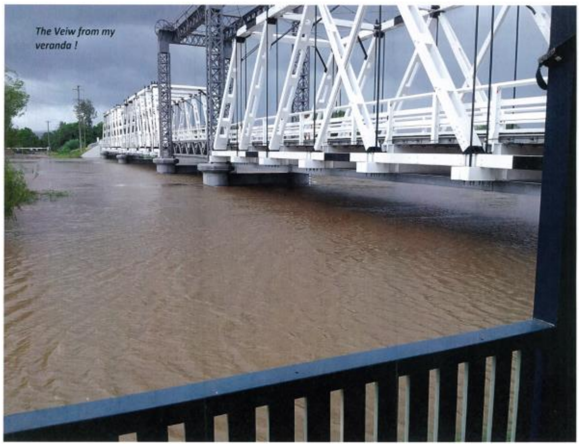


Photo 3 - Dunmore Bridge 2015

Photo 4 - Dunmore Bridge 2015

Photo 5 – Martins Creek during 2015 flood

Photo 6 – Martins Creek after 2015 flood

The responses are summarised in graphs in Figure 36 and the flood affected properties are shown in Figure 37. The following issues were raised by the respondents:

- Residents on the Paterson River, especially the upper reaches, described the 2015 event as the biggest they have witnessed
- The majority of landowners are acutely aware of flooding risks and are generally prepared for flood events and the potential for isolation until the floodwaters recede. Even with this knowledge and preparedness some residents were caught off guard by the rapidly rising floodwaters of the April 2015 event which prevented them from buying additional supplies or implementing their flood plans in time.
- Although residents are prepared for isolation they feel that they are neglected by the SES and there is inadequate real-time flood information. Residents have suggested that there be more information provided on ABC radio and that the post office be provided with information so that there is someone they can contact for information.
- Many residents are concerned about the erosion of the river banks on both the Paterson and Hunter Rivers which they say is getting worse after every flood. Some residents have taken preventative action and planted trees along the banks including Hunter River Red Gums. In some cases these trees were destroyed in the April 2015 flood.
- Some residents feel that they levee system is being neglected by the government.
- Some residents believe that the release of waste from Hunter Valley mines is polluting and contaminating the Hunter and Paterson Rivers during flood events killing fish.
- Some residents are concerned about future development in areas that are isolated during flood events. They are concerned that this will be dangerous to new residents and stretch the resources of community and emergency services during flood events.

5. APPROACH

The approach adopted in flood studies to determine design flood levels largely depends upon the objectives of the study and the quantity and quality of the data (survey, flood, rainfall, flow etc.). For the Paterson River, there are stream gauges with sufficient record length that flood frequency analysis can be used to estimate peak design flood flows. There is a thorough record of daily rainfall data for the catchment and some sub-hourly rainfall data from pluviometer gauges, which can be used for event-based model calibration. A diagrammatic representation of the flood study process undertaken in this manner is shown below.

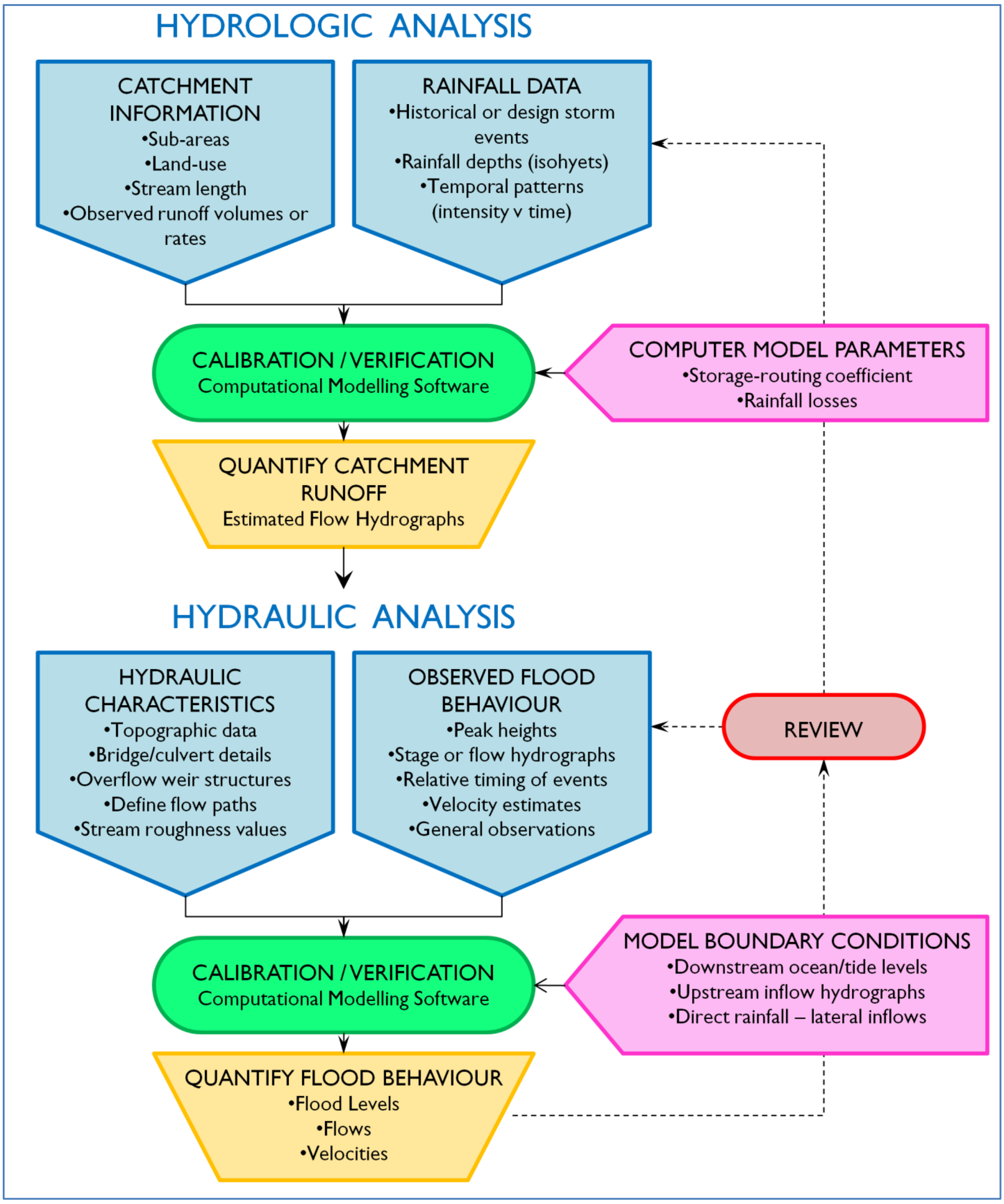


Diagram 1: Flood Study Process

6. HYDROLOGICAL MODEL

6.1. Introduction

Inflow hydrographs are required as inputs at the boundaries of the hydraulic model. Typically in flood studies a rainfall-runoff hydrologic model (converts rainfall to runoff) is used to provide these inflows. A range of runoff routing hydrologic models is available as described in AR&R 1987 (Reference 2). These models allow the rainfall depth to vary both spatially and temporarily over the catchment and readily lend themselves to calibration against recorded data.

The WBNM hydrologic run-off routing model was used to determine flows from each sub-catchment in the study area. The WBNM model has a relatively simple but well supported method. If flow data is available at a stream gauge, then the WBNM model can be calibrated to this data through adjustment of the model parameters including the stream lag factor, storage lag factor, and/or rainfall losses.

A hydrological model for the entire Paterson River catchment was created and used to:

- calibrate the Paterson River and Allyn River flows to hydrographs determined from the rating curves;
- calculate Paterson River an Allyn River flows for input into TUFLOW model at upstream boundary
- calculate the flows for each individual subcatchment and tributary creeks in the study area for inclusion in the TUFLOW model

6.2. Sub-catchment delineation

The total catchment represented by the WBNM model was 1186 km^2. This area was represented by a total of 63 catchments. The subcatchment delineation is shown in Figure 34. The subcatchment delineation was split into two zones.

1. The section of catchment upstream of the study area – 21 subcatchments
2. The section of catchment inside the study area – 42 subcatchments

This method was undertaken in order to further refine the subcatchments inside the study area so that the hydrological model could provide flow inputs for the hydraulic model that more accurately represent the topographic, riverine and floodplain conditions within the hydraulic model area. The subcatchments were derived from LiDAR topographic data and 1:25000 topographic maps of the region.

6.3. Impervious Surface Area

Runoff from connected impervious surfaces such as roads, gutters, roofs or concrete surfaces occurs significantly faster than from vegetated surfaces. This results in a faster concentration of flow within the downstream area of the catchment, and increased peak flow in some situations. This is less important in rural studies as they consist of very little impervious areas, and those areas are typically not hydraulically connected to the waterway (i.e. the water flows across pervious areas on the route between the impervious surface and the receiving waterway). Due to the rural nature and minimal consolidated urban development of the study area all subcatchments were modelled with 0% imperviousness.

6.4. Model Parameters

The model input parameters for each subcatchment are:

- A lag factor (termed C), which can be used to accelerate or delay the runoff response to rainfall;
- A stream flow routing factor, which can speed up or slowdown in-channel flows occurring through each subcatchment;
- An impervious area lag factor;
- An aerial reduction factor
- The percentage of catchment area with a pervious/impervious surface; and
- Rainfall losses calculated by initial and continuing losses to represent infiltration.

A typical regional value of 1.7 for the lag factor ‘C’ hydrologic model parameter was found to be appropriate. A value of 0.8 was used for the stream flow routing factor in order to speed up in-channel flows, relative to a typical value of 1.0 for natural channels. This was found to be required to correctly produce the rate of rise and time to peak of the historical flood hydrographs, and is considered reasonable due to the relatively steep gradient of the river and tributaries, and the incised nature of the channel. This stream flow routing factor was determined through the calibration process and is discussed in Section 8. The aerial reduction factor was determined based on catchment area and location. The model parameters adopted for use in the calibration and design events are summarised in Table 13.

Table 13 – WBNM model parameters

Parameter	Value
C (Catchment Routing)	1.7
Impervious Catchment Area	0%
Stream Routing Factor	0.8
Aerial Reduction Factor	0.84
Initial loss	Varies
Continuing loss	2 mm/hr

6.5. Rainfall Losses

Methods for modelling the proportion of rainfall that does not occur as runoff (i.e. “lost”) are outlined in AR&R (Reference 2). The methods are of varying degrees of complexity, with the more complex options only suitable if sufficient data are available. The method most typically used for design flood estimation is to apply an initial and continuing loss to the rainfall. The initial loss represents the wetting of the catchment prior to runoff starting to occur and the filling of localised depressions, and the continuing loss represents the ongoing infiltration of water into the saturated soils while rainfall continues. The rainfall losses adopted as a result of the calibration process are discussed in Section 8 and the loss values used in design flood estimation are discussed in Section 10.

7. HYDRAULIC MODEL

7.1. Introduction

The availability of high quality LiDAR as well as detailed aerial photographic data enables the use of 2D hydraulic modelling for the study. Various 2D software packages are available (SOBEK, TUFLOW, RMA-2) and the TUFLOW package was adopted as it is the most widely used model of this type in Australia for riverine flood modelling.

The TUFLOW modelling package includes a finite difference numerical model for the solution of the depth averaged shallow water equations in two dimensions. The TUFLOW software has been widely used for a range of similar floodplain projects both internationally and within Australia and is capable of dynamically simulating complex overland flow regimes.

The TUFLOW model version used in this study was 2013-12-AE-w64 and further details regarding TUFLOW software can be found in the User Manual (Reference 9).

In TUFLOW the ground topography is represented as a uniform grid with a ground elevation and Manning's 'n' roughness value assigned to each grid cell. The size of grid is determined as a balance between the model result definition required and the computer processing time needed to run the simulations. The greater the definition i.e. the smaller the grid size the greater the processing time need to run the simulation. A cell size of 10 m by 10 m was adopted as it provided an appropriate balance between providing sufficient detail for the river channels and bridges, while still resulting in workable computational run times.

7.2. TUFLOW Hydraulic Model

The Digital Elevation Model (DEM) was generated from a triangulation of filtered ground points from the LiDAR dataset, discussed in Section 3.1. The DEM is shown in Figure 3. The model extent for the catchment was determined in conjunction with MCC and PSC. The upstream boundaries are the Paterson and Allyn Rivers upstream of the town of Vacy. The downstream boundaries are located on the Hunter River. The western boundary is located just downstream of McKimms Corner and the eastern boundary is located 1.5 km downstream of the confluence of the Hunter and Paterson Rivers. The model extent is shown in Figure 35.

7.3. Boundary Locations

7.3.1. Inflows

For sub-catchments within the TUFLOW model domain, local runoff hydrographs were extracted from the WBNM model (see Section 6). These were applied to the downstream end of the sub-catchments within the 2D domain of the Paterson River hydraulic model. The hydraulic model has three separate inflows:

- Paterson River upstream of Vacy
- Allyn River upstream of Vacy
- Hunter River at McKimms Corner

Paterson River Inflow

The inflow hydrographs from the WBNM hydrological model enter the upstream boundary of the model approximately 2.6 km upstream of the confluence of the Paterson and Allyn Rivers.

Allyn River Inflow

The inflow hydrographs from the WBNM hydrological model enter the upstream boundary of the model approximately 1 km upstream of the confluence of the Paterson and Allyn Rivers.

Hunter River Inflow

The Hunter River inflows are located 800m downstream of the McKimms Corner gauge. The Hunter River inflows were split into three sections:

1. Main channel inflow
2. Left overbank inflow
3. Right overbank inflow

The inflows hydrographs for the design events were taken from (Reference 5). In order to determine the inflow hydrographs for the historical events a relationship between each of the three inflows and the water level at McKimms Corner was identified from the design events in (Reference 5). This relationship was applied to the recorded water level at McKimms corner for each of the seven historical events used in calibration. The resulting inflows were applied at the three inflow boundaries for the modelled historical events

7.3.2. Downstream Boundary

The hydraulic model has two separate downstream boundary conditions;

- Hunter River
- McClymonts Swamp

Hunter River

Dynamic tailwater levels were applied as the downstream boundary condition for the Hunter River. The boundaries are located 1.5 km downstream of the confluence of the Hunter and Paterson Rivers. The Hunter River boundaries were split into two sections:

1. Main channel outflow
2. Right bank outflow

The dynamic tailwater levels for the design events were taken from (Reference 5). In order to determine the tailwater levels for the historical events a relationship between the water level at the boundaries and the water levels at Green Rocks and Hinton was identified for the design events. This relationship was applied to the recorded water levels at Green Rocks and Hinton for each of the seven historical events used in calibration. The resulting dynamic tailwater levels were applied at the two outflow boundaries for the modelled historical events

McClymonts Swamp

A water level vs flow curve was applied to the McClymonts Swamp boundary. This curve is generated by TUFLOW using the gradient and cross-section of the flow path. The flood gradient was assumed based on the topographic gradient of the DEM.

7.4. Mannings 'n' Roughness

Roughness, represented by the Manning's 'n' coefficient, is an influential parameter in hydraulic modelling. As part of the calibration process roughness values are adjusted within ranges defined in the literature so that the model may match observed peak flood levels at a variety of locations. The calibration process is discussed in Section 8. The manning's values chosen are justified by the following literature.

Chow (Reference 10) provides the definitive reference work in regards to the setting of the of the roughness values for hydraulic calculations. Chow presents a series of channel "scenarios" with varying characteristics and the derived roughness values for each. Chow also proposes a custom roughness calculation implementing the following equation (equation 5-12 from Reference 10).

$$n = (n0 + n1 + n2 + n3 + n4).m5$$

In this table various categories are assessed and a representative 'n' is aggregated from addition of different elements. Value ranges are defined in Table 5-5 (Chow, 1959) and for the case of Paterson River the following value ranges are obtained:

- Earth channel hence n_0 = 0.02 (only value appropriate for a natural channel);
- Irregularity is minor ("slightly eroded or scoured side slopes") n_1 = 0.005;
- Variation of channel cross-section is "gradual" (change in size or shape of cross section occurs gradually) n_2 = 0.00 (mid value);
- Relative effect of obstructions is negligible, refers to debris deposits, stumps, exposed roots, boulders and fallen and lodged logs) n_3 = 0.00;
- Vegetation is low (low is for conditions comparable to the following; dense growths of flexible turf grasses so n_4 = 0.005 to 0.01 (mid value); and
- Degree of meandering is minor (low value) and so m_5 = 1.0

Use of these values generates a Manning's n value ranging from 0.03 (lower end estimate) to 0.035 (upper end estimate). Henderson (Reference 11) also provides roughness values for various land use and flow conditions. Table 4-2 of Henderson (1966) states that for a natural channel, roughness may vary between 0.025 to 0.03 for a clean and straight channel, from 0.033 to 0.04 for a winding channel with pools and shoals, and from 0.075 to 0.15 for a very winding and overgrown channel.

The main channels of Paterson River, Allyn River and Hunter River are clean earth channels with very limited obstructions that meander gradually as they travel downstream. There are some riparian sections of dense weeds and shrubs on each river which is vastly different compared to the in-bank channel therefore separate values were chosen for the river channels and the riparian edge.

The in-bank section of each river was modelled using a Manning's 'n' value of 0.03 and the dense riparian vegetation was modelled using a Manning's 'n' value of 0.07, recognising that some of the reeds and grass on the banks will be knocked flat in a major flood event.

The Manning's 'n' values adopted are shown in Table 14.

Table 14 – Adopted Manning's *n* values – TUFLOW model

Surface	Manning's *n*
Rural farmland	0.04
Towns	0.04
River	0.03
Riparian Vegetation	0.07
Dense Vegetation	0.10

7.5. Rivers

The river channels were defined in the 2D grid domain. The DEM was modified to provide a continuous flow path with gradient determined from available data. The LiDAR was able to survey the river channels above the water level on the day of the survey. The bathymetric survey supplied by OEH, river gauge data from the Department of Water as well as the LiDAR survey upstream of the Gostwyck PINNEENA (210079) gauge was used to determine cross sectional data below the water level and an assumed river gradient. The subsequent data was used to carve out the river channels from the DEM.

7.6. Levees, Roads and Railway

The levees, roads and railway were all modelled using break lines which alter the topography of the DEM. The elevations of the levee system were determined using a combination of the levee survey supplied by OEH and the LiDAR survey. The elevations of the road and railway system were determined using the LiDAR survey.

7.7. Hydraulic Structures

7.7.1. Bridges

Photo 7 – Paterson Road Bridge

Photo 8 – Vacy Bridge

The bridges traversing Paterson River, Allyn River and Hunter River are shown in Figure 35. The bridges were modelled in the 2D domain for the purpose of maintaining continuity in the model. The modelling parameter values for the bridges were based on the geometrical properties of the structure, which were obtained from measurements and photographs taken during site inspections and previous experience modelling similar structures. Examples of bridges included in the model are shown in Photo 7 and Photo 8.

7.7.2. Culverts

Large road culverts were modelled in the 2D domain. The modelling parameter values for the culverts/bridges were based on the geometrical properties of the structure, which were obtained from measurements and photographs taken during site inspections and previous experience modelling similar structures. For several of the culverts, dimensions had to be estimated from topographic information due to lack of available detail survey data or plans. An example of a culvert included in the model is shown in Photo 9.

Photo 9 – Road Culverts Mindaribba

7.7.3. Buildings

Due to the rural nature of the study area and the limited development on the floodplain no buildings were included in the model as they were assumed to have a negligible effect on broader flood conveyance.

8. CALIBRATION

8.1. Objectives

The objective of the calibration process is to build a robust hydrologic and hydraulic modelling system that can replicate historical flood behaviour in the catchment being investigated. If the modelling system can replicate historical flood behaviour then it can more confidently be used to estimate design flood behaviour. The resulting outputs from design flood modelling are used for planning purposes and for infrastructure design. For this study, a wide range of historical events were available to use for calibration purposes. The historical events chosen for calibration were:

- March 1978
- March 2001
- June 2007
- June 2011
- March 2013
- November 2013
- April 2015

8.2. Methodology

A joint calibration of the hydrologic and hydraulic model was chosen as the best approach for the study area for the following reasons:

- The only gauge with a rating curve inside the study area is Gostwyck PINNEENA (210079). This is the only gauge that the hydrologic model can be calibrated to inside the study area. The highest recent gauging was 10.53 m recorded in March 2000. All the historical events that have been used for calibration have recorded stage heights greater than 10.53 m. Flow breakouts in the overbank area play a more significant role for events above this level, which are not accounted for in the rating curve extrapolation, and therefore there is little confidence in the rating curve beyond this point.
- The Allyn River Flying Fox Lane (210043) gauge has only one gauging above 1.5m therefore the rating curve could not be confidently applied for calibration of flows.
- There are five gauges inside the study area that record water levels that the hydraulic model can be calibrated to. The only calibration event that does not have records for all five gauges is March 1978 which only has records for Gostwyck PINNEENA - 210079.

The approach to model calibration was to adjust the rainfall loss parameters and the stream routing parameter in the WBNM (hydrologic) model and adjust the Manning's 'n' roughness values in the TUFLOW hydraulic model. Multiple combinations of these parameters were investigated until the best fit to the recorded water levels in the study area could be achieved across the whole range of calibration events.

For most events, the adopted rainfall depths and temporal patterns were found to have the most influence on the calibration results. The levels obtained at the gauges were more sensitive to the rainfall assumptions than to the other model parameters available for tuning the model calibration. This indicates that it is unreasonable to try and obtain a perfect fit in the model calibration results, since the available rainfall data is inherently unable to reflect the true spatial and temporal rainfall distribution across the catchment for the floods investigated.

8.3. Rainfall Losses (WBNM)

The initial loss / continuing loss model was used to estimate rainfall losses over the catchment. The approach taken was to vary the initial loss across the calibration events and to use an identical continuing loss for all the events in order to provide the best fit to recorded water levels. This can be justified as there would be different antecedent conditions in the catchment for the historical events. Antecedent conditions in the catchment may change but the rate of ongoing infiltration of water into the saturated soil (continuing loss) should theoretically be relatively consistent in the historical events.

A continuing loss that provided the best average fit for all the historical events was determined through multiple model runs. A better fit to recorded levels could have been achieved by changing the continuing loss values across the historical events but it was deemed to be an exercise in curve fitting rather an accurate representation of catchment conditions. The rainfall loss values applied to the historical events are shown in Table 15.

Table 15 – Calibration Event Rainfall Losses

Event	Initial Loss	Continuing Loss
March 1978	40mm	2mm/h
March 2001	20mm	2mm/h
June 2007	80mm	2mm/h
June 2011	30mm	2mm/h
March 2013	50mm	2mm/h
November 2013	80mm	2mm/h
April 2015	40mm	2mm/h

8.4. Stream Routing Parameter (WBNM)

The typical stream routing value in WBNM is 1.0 for natural channels. An increase to this parameter will reduce stream velocity and a decrease will increase stream velocity. A stream routing value of 0.8 was applied to provide to best fit to historical events. This value can be justified by the steep nature of the Paterson and Allyn River catchments upstream of Vacy, the relative lack of meanders in the river channels, and the relatively incised in-bank channel profiles.

8.5. Manning's 'n'

Multiple combinations of Manning's 'n' parameters were modelled in order to determine the values that provided the best fit to recorded water levels. The values modelled were justified in the literature discussed previously in Section 7.4. The Manning's 'n' values that provided the best fit are shown in Table 16.

Table 16 – Adopted Manning's *n* values – TUFLOW model

Surface	Manning's *n*
Rural farmland	0.04
Towns	0.04
River	0.03
Riparian Vegetation	0.07
Dense Vegetation	0.10

8.6. Calibration Results

The flow hydrographs for the Lostock Dam (210021) and Halton (210022) gauges from the calibration of the historical events are shown in

Figure B1 to Figure B6. The same rainfall loss and stream routing parameters that were used as part of the joint calibration were adopted. A better calibration for each event could have been achieved if they were calibrated independently but this would not have been consistent with the methodology adopted for the study.

The modelled flows at the Gostwyck PINNEENA (210079) gauge were consistently higher that the estimated flows determined from the rating curve, but a reasonable match was obtained for the flood levels. It was found that in order to force the models to produce flows matching the rating curve flows, the model parameters needed to be pushed beyond reasonable limits for those parameters. It is concluded that the official rating curve is not accurate for flood events above the 10.53 m gauging undertaken in 2000. An updated rating curve was therefore developed using the hydraulic model (see Figure 8 and Figure 38).

MARCH 1978

The March 1978 event was modelled over 5 days with a maximum total rainfall of 489 mm recorded at the Upper Allyn Township (61290) daily rainfall gauge. The temporal pattern from the Lostock Dam (61288) pluviometer produced the best fit to recorded levels. The results are shown in Figure B7 and Table 17.

Table 17 – Peak Flood Levels March 1978

Gauge	Recorded (mAHD)	Modelled (mAHD)	Difference	Percentage	Calibration
Gostwyck - 210079	17.69	17.42	-0.27	-1.5%	Good

MARCH 2001

The March 2001 event was modelled over 7 days with a maximum total rainfall of 320 mm recorded at the Upper Allyn Township (61290) daily rainfall gauge. The temporal pattern from the Halton (210022) pluviometer produced the best fit to recorded levels. The results are shown in Figure B8 to Figure B10 and Table 18.

Table 18 – Peak Flood Levels March 2001

Gauge	Recorded (mAHD)	Modelled (mAHD)	Difference	Percentage	Calibration
Gostwyck - 210079	15.83	14.64	-1.19	-7.5%	Fair
Gostwyck Bridge - 210402	13.49	12.67	-0.82	-6.1%	Fair
Paterson RB -210406	10.42	9.36	-1.06	-10.2%	Poor
Dunmore - 210409	6.48	6.33	-0.15	-2.3%	Good
Hinton Bridge - 210410	5.44	5.27	-0.17	-3.1%	Good

JUNE 2007

The June 2007 event was modelled over 4 days with a maximum total rainfall of 341 mm recorded at the Woodville – Clarence Town Road (61405) daily rainfall gauge. The temporal pattern from the Gostwyck (210402) pluviometer produced the best fit to recorded levels. The results are shown in Figure B11 to Figure B13 and Table 19.

Table 19 – Peak Flood Levels June 2007

Gauge	Recorded (mAHD)	Modelled (mAHD)	Difference	Percentage	Calibration
Gostwyck - 210079	15.78	16.44	0.66	4.2%	Good
Gostwyck Bridge - 210402	13.64	14.33	0.69	5.1%	Good
Paterson RB -210406	10.16	10.47	0.31	3.1%	Good
Dunmore - 210409	6.36	6.38	0.02	0.3%	Good
Hinton Bridge - 210410	5.78	4.9	-0.88	-15.2%	Poor

JUNE 2011

The June 2011 event was modelled over 5 days with a maximum total rainfall of 459 mm recorded at the Careys Peak – Barrington Tops (61413) daily rainfall gauge. A combination of the temporal patterns form the Halton (210022) and Gostwyck (210402) pluviometers produced the best fit to recorded levels. The results are shown Figure B14 and Figure B16 and Table 20.

Table 20 – Peak Flood Levels June 2011

Gauge	Recorded (mAHD)	Modelled (mAHD)	Difference	Percentage	Calibration
Gostwyck - 210079	16.34	16.26	-0.08	-0%	Good
Gostwyck Bridge - 210402	13.93	14.24	0.31	2%	Good
Paterson RB - 210406	10.35	10.55	0.2	2%	Good
Dunmore - 210409	6.32	6.39	0.07	1%	Good
Hinton Bridge - 210410	5.35	4.97	-0.38	-7%	Fair

MARCH 2013

The March 2013 event was modelled over 12 days with a maximum total rainfall of 658 mm recorded at the Careys Peak – Barrington Tops (61413) daily rainfall gauge. A combination of the temporal patterns form the Halton (210022) and Gostwyck (210402) pluviometers produced the best fit to recorded levels. The results are shown Figure B17 to Figure B19 and Table 21.

Table 21 – Peak Flood Levels March 2013

Gauge	Recorded (mAHD)	Modelled (mAHD)	Difference	Percentage	Calibration
Gostwyck - 210079	14.91	15.85	0.94	6.3%	Fair
Gostwyck Bridge - 210402	12.85	13.89	1.04	8.1%	Fair
Paterson RB -210406	9.66	10.28	0.62	6.4%	Fair
Dunmore - 210409	6.34	6.39	0.05	0.8%	Good
Hinton Bridge - 210410	5.49	5.26	-0.23	-4.2%	Good

NOVEMBER 2013

The November 2013 event was modelled over 4 days with a maximum total rainfall of 291 mm recorded at the Paterson Post Office (61096) daily rainfall gauge. The temporal pattern from the Gostwyck (210402) pluviometer produced the best fit to recorded levels. The results are shown in Figure B20 to Figure B22 and Table 22.

Table 22 – Peak Flood Levels November 2013

Gauge	Recorded (mAHD)	Modelled (mAHD)	Difference	Percentage	Calibration
Gostwyck - 210079	14.26	14.39	0.13	0.9%	Good
Gostwyck Bridge - 210402	12.02	12.42	0.4	3.3%	Good
Paterson RB -210406	8.43	8.87	0.44	5.2%	Fair
Dunmore - 210409	5.03	5.74	0.71	14.1%	Poor
Hinton Bridge - 210410	3.77	3.69	-0.08	-2.1%	Good

APRIL 2015

The April 2015 event was modelled over 3 days with a maximum total rainfall of 460 mm recorded at the Woodville – Clarence Town Road (61405) daily rainfall gauge. The temporal pattern from the Gostwyck (210402) pluviometer produced the best fit to recorded levels. The results are shown in Figure B23 and Table 23.

A flood level survey was undertaken for the April 2015 event. The flood marks were obtained by WMAwater personnel after the event and survey by Maitland Council surveyors. The locations of the surveyed points are shown in Figure B26 to Figure B28 and the results shown in Table 24.

A reasonable match is made to all the flood marks except for flood mark 16 which was considered to be of low accuracy due to poor visibility of the actual mark inside the culvert. A good match was made to the flood extent marks shown in Figure B27 at Bolwarra Heights and the levee on Phoenix Park Road. The flood mark recorded on the levee shows the levee did not overtop which was replicated in the model. The break out at Iona is shown Figure B28 with a good match to the flood extent recorded.

Table 23 – Peak Flood Levels April 2015

Gauge	Recorded (mAHD)	Modelled (mAHD)	Difference	Percentage	Calibration
Gostwyck - 210079	18.72	17.85	-0.87	-4.6%	Good
Gostwyck Bridge - 210402	16.12	15.75	-0.37	-2.3%	Good
Paterson RB -210406	11.99	11.66	-0.33	-2.8%	Good
Dunmore - 210409	6.06	6.45	0.39	6.4%	Fair
Hinton Bridge - 210410	5.76	5.68	-0.08	-1.4%	Good

Table 24 – Survey Flood Levels

ID	Location	Assessed Flood Mark Accuracy	Surveyed Level	Modelled Level	Difference
1	Paterson Railway Bridge Picnic Ground	High	12.24	11.83	-0.41
2	63 Maitland Road (Tocal Road) Paterson	Medium	10.57	10.69	0.12
3	88 Hinton Road Phoenix Park	Low	6.10	5.70	-0.4
4	Park on Old Punt Road Hinton across from Victoria Hotel downstream of Hinton Bridge	Medium	5.50	5.37	-0.13
5	Victoria Hotel - 2 Paterson Street Hinton	Medium	5.58	5.36	-0.22
6	Victoria Hotel - 2 Paterson Street Hinton	Medium	5.57	5.63	-0.21
7	Woodville General Store - 229 Clarence Town Road Woodville	High	6.30	6.05	-0.25
8	Woodville General Store Coffee Hut - 229 Clarence Town Road Woodville	High	6.06	6.05	-0.01
9	Paterson Road Iona	Medium	6.01	6.07	0.06
10	2 Iona Lane Dunns Creek	Low	6.68	6.88	0.2
11	Paterson Road Bridge	Medium	10.48	10.41	-0.07
12	63 Maitland Road (Tocal Road) Paterson	High	10.66	10.76	0.1
13	John Tucker Park Queen Street Paterson	High	10.99	11.07	0.08
14	Vacy Bridge Gresford Road	Medium	20.21	19.83	-0.38
15	27 Lang Drive Bolwarra Heights	High	Flood Extent		
16	Culverts Maitland Road Mindaribba	Low	5.28	6.86	1.49
17	Rail Underpass Mindaribba	Low	8.36	8.57	-0.11
18	Levee Phoenix Park Road	Medium	Flood Extent		

9. FLOOD FREQUENCY ANALYSIS

9.1. Overview

Flood Frequency Analysis (FFA) enables the magnitude of floods (5%, 1% AEP etc.) to be estimated based on statistical analysis of recorded floods. It can be undertaken graphically or using a mathematical distribution. This approach has the following advantages in design flood estimation:

- no assumptions are required regarding the relationship between probabilities of rainfall and runoff,
- all factors affecting flood magnitude are already integrated into the data,
- estimation of rainfall losses are not required,
- confidence limits can be estimated, and
- historic rainfall data are not required.

However this approach also has several limitations:

- The underlying distribution of flooding is not known for certain, thus different distributions will provide different answers.
- As most flood records are relatively short (compared to the design event for which a magnitude is required) there is considerable uncertainty (the broken record at Gostwyck is an example). With the use of rainfall data for design flood estimation there is less uncertainty as there are longer records and more spatial homogeneity of the data.
- The data cannot be adjusted to account for a change in catchment or climatic conditions.
- There are many issues with the accuracy of rating curves, especially at high flows. However this is less of an issue with the use of hydraulic models based on high quality survey (ALS) to obtain rating curves.

9.2. Gauges and Rating Curve

The stream flow gauge at Gostwyck (210079) has records for the period 1928 to 1946 and 1969 to 2016, a total of 67 years. During this time the gauge was situated at three different locations:

- Location 1: (1928 to 1946) – Gostwyck Bridge
- Location 2: (1969 to 1977) – 1.5 km upstream of Gostwyck Bridge
- Location 3: (1978 to present) – 4 km upstream of Gostwyck Bridge

As discussed previously, the official rating curve developed by the Department of Water is not accurate for the high flows that were of interest to this study. Rating curves for the high flow extrapolated area were developed from the calibrated TUFLOW hydraulic model at each location. The revised rating curve for the current Gostwyck gauge location (Location 3) is shown Figure 38.

9.3. Methodology

It would be desirable to have a continuous record at the same gauge location to undertake a FFA. This is not the case at Gostwyck with a broken record and gaugings at three different locations.

There is a continuous record of 38 years at the current location. After examining the results from the historical events used for calibration it was determined that there are no major overbank breakouts between the current gauge - Location 3 (4 km upstream of Gostwyck Bridge) and Location 1 (Gostwyck Bridge) for the events making up the dataset, and that the differences in flow due to attenuation are within an acceptable margin of error for the purpose of FFA. A continuous flow record was therefore developed by estimating flows at each of the separate gauging locations and combining the records together. The estimated flow rates using the developed rating curves at both locations for the calibration events are shown in Table 25.

Table 25 – Estimated Peak Flow (m³/s) Historical Events

Historical Event	Gostwyck – 210079 Current Location	Gostwyck Bridge	% Difference
March 1978	1721	-	
March 2001	963	978	-1.6%
June 2007	1072	1014	5.4%
June 2011	1239	1083	12.6%
March 2013	851	833	2.1%
November 2013	719	683	5.0%
April 2015	2315	2030	12.3%

The annual series approach was adopted as recommended by AR&R. The maximum gauge height for each year was converted to a flow using the corresponding rating curve. The annual series is shown in Table 26.

Table 26 – Annual Series Paterson River Gostwyck (210079)

Year	Gauge (m)	Level (mAHD)	Flow (m³/s)
Location 1 – Gostwyck Bridge			
1928	11.93	11.63	632
1929	14.16	13.86	1066
1930	13.86	13.56	994
1931	13.02	12.72	810
1932	8.05	7.75	239
1933	6.09	5.79	132
1934	8.53	8.23	275
1935	4.9	4.6	88
1936	8.21	7.91	249
1937	5.68	5.38	115
1938	9.21	8.91	332
1939	6.85	6.55	168
1940	3.35	3.05	46
1941	6.47	6.17	149
1942	12.63	12.33	739
1943	5.48	5.18	107
1944	4.59	4.29	79
1945	11.11	10.81	529

Year	Gauge (m)	Level (mAHD)	Flow (m^3/s)
1946	14.62	14.32	1222
Location 2 – 1.5km Upstream Gostwyck Bridge			
1969	10.12	11.12	473
1970	8.52	9.52	322
1971	12.64	13.64	837
1972	13.4	14.4	1004
1973	7.2	8.2	224
1974	10.09	11.09	470
1975	9.79	10.79	439
1976	12.41	13.41	797
1977	12.99	13.99	898
Location 3 – 4km Upstream Gostwyck Bridge			
1978	14.37	17.66	1721
1979	9.05	12.34	428
1980	2.98	6.27	62
1981	5.25	8.54	155
1982	7.89	11.18	321
1983	3.78	7.07	89
1984	11.6	14.89	832
1985	13.6	16.89	1406
1986	7.66	10.95	304
1987	8.79	12.08	402
1988	10.49	13.78	621
1989	7.74	11.03	310
1990	13.37	16.66	1324
1991	2.37	5.66	45
1992	7.34	10.63	281
1993	4.95	8.24	140
1994	2.54	5.83	50
1995	9.13	12.42	436
1996	4.47	7.76	117
1997	4.54	7.83	120
1998	9.16	12.45	439
1999	9.62	12.91	494
2000	11.25	14.54	759
2001	12.16	15.45	963
2002	4.65	7.94	125
2003	5.76	9.05	182
2004	7.79	11.08	314
2005	6.5	9.79	225
2006	3.77	7.06	89
2007	12.55	15.84	1067
2008	11.77	15.06	870
2009	11.47	14.76	804
2010	6.34	9.63	216
2011	13.07	16.36	1223
2012	8.03	11.32	332
2013	11.68	14.97	849
2014	2.98	6.27	62

Year	Gauge (m)	Level (mAHD)	Flow (m^3/s)
2015	15.5	18.79	2316
2016	11.75	15.04	865

Various underlying distributions were tested, and a Log-Pearson III distribution was found to produce the best fit, with the results shown in Figure 39. The design flows as determined by the FFA are shown in Table 27.

Table 27 – Peak Flows Determined by FFA

Event	Peak Flow m^3/s
20% AEP	820
10% AEP	1190
5% AEP	1570
2% AEP	2100
1% AEP	2520
0.5% AEP	2950
0.2 % AEP	3520

10. DESIGN EVENT MODELLING

10.1. Overview

Design flood levels in the study area are a combination of inflows from the Paterson and Allyn Rivers upstream of Vacy, rainfall over the catchment downstream of Vacy and Hunter River inflows upstream of McKimms Corner (Reference 5). The design flows determined from the design rainfall approach were very similar to the flows determined from the FFA. Therefore the design rainfall approach has been used as it provides a more holistic result for the entire study area, especially in regard to flood mapping of the Paterson River floodplains and tributaries. A comparison of the flows at the Gostwyck PINEENA gauge (210079) for the design rainfall and FFA approach are shown in Table 28.

Table 28 – Comparison of Flows (m^3/s) – Design Rainfall vs FFA

Event	Design Rainfall (m^3/s)	FFA (m^3/s)
20% AEP	1000	820
10% AEP	1280	1190
5% AEP	1680	1570
2% AEP	2130	2100
1% AEP	2530	2520
0.5% AEP	2990	2950

10.2. Upstream Inflows

Design peak inflows from the Paterson River and Allyn River are shown in Table 29.

Table 29 – Paterson River and Allyn River Design Peak Inflows

Event	Paterson River (m^3/s)	Allyn River (m^3/s)
20% AEP	566	487
10% AEP	726	610
5% AEP	936	795
2% AEP	1172	1015
1% AEP	1403	1222
0.5% AEP	1647	1439
0.2 % AEP	1979	1736
PMF	4568	3855

10.3. Critical Duration

To determine the critical storm duration for the catchment (i.e. produce the highest flood level), modelling of the 1% AEP event was undertaken for a range of design storm durations from 6 hr to 72 hr using temporal patterns from AR&R (Reference 2). The peak flows at a number of locations throughout the study area were analysed and it was determined that the 36 hr event would be used for all design event up to the 0.2% AEP.

The same process was undertaken for the PMF and it was determined that the 72 hr duration was the critical duration for the PMF event.

10.4. Losses

Table 6.2 of AR&R (1987) recommends that for catchments east of the Great Dividing Range in New South Wales, an initial loss of between 10 mm and 30 mm is appropriate. An initial loss of 20mm was determined to be appropriate for the catchment. A continuing loss of 2mm/h was chosen based on the calibration results as it was shown to provide the best possible fit to recorded flood levels. The rainfall losses for the design event are shown in Table 30.

Table 30 – Design Event Rainfall Losses

Rainfall Losses	
Initial Loss	**Continuing Loss**
20 mm	2 mm/h

10.5. Coincident Hunter River Flooding

There is sufficient data to investigate the historical comparison of flooding on Paterson River and the Hunter River. The annual maximum gauge levels at Gostwyck and Belmore Bridge are plotted in Figure 40 in order to try and understand the historical correlation. The only floods plotted are those where there is a record available from both gauges. The observations from Figure 40 are:

- For all the Hunter River floods above the "Major" level at Belmore Bridge (10.5 m), there was also a "Major" flood on the Paterson (above 12.2 m). There are 5 of these floods in the record. Large Hunter River floods are usually associated with a large Paterson flood.
- The inverse is less true. For all the major floods on the Paterson River, only a small proportion coincided with the major Hunter River floods. This is partially to do with there being more floods above the "major flood level" specified the Bureau - 25 events above this level on the record. If we look at the largest 5 or 6 Paterson floods (above 14m), they all coincide with Hunter floods that were between the Minor and Major flood levels at Belmore Bridge.
- The major level of 10.5 m at Belmore is roughly a 10% AEP flood on the Hunter River. The 20% AEP level is about 9.8 m at Belmore Bridge. So when the largest floods on the Paterson have occurred, it has typically been in conjunction with a Hunter flood of 20% AEP or less.
- April 2015 is the largest Paterson flood on record (somewhere between a 2% AEP and

1% AEP based on the Flood Frequency Analysis). The corresponding flood on the Hunter was about 8.9 m, which is smaller than a 20% AEP flood.

- The next largest Paterson flood (1978) occurred in conjunction with about a 20% AEP Hunter River flood.

This is not a robust statistical analysis, but it does indicate that major floods on the Paterson are less likely to be accompanied by major floods on the Hunter, whereas major Hunter floods are more likely to involve significant Paterson flooding. There are some logical arguments to support this. The rainfall producing a large Hunter flood would need to be widespread and sustained over large parts of the Hunter valley, including the Paterson valley. However as observed in April 2015, the Paterson can be affected by more localised storm cells which do not extend over the upper Hunter Valley.

The above also does not consider timing. Given the relative size of the catchments, if flooding is produced by the same rainfall system, the Paterson flood would be expected to peak earlier than the Hunter in general. However for the purposes of modelling it is often assumed that the peaks coincide, which may overstate the Hunter tailwater influence on the Paterson design levels. Based on the above arguments, this study adopted a lower level of coincident flooding in the Hunter River than the previous Paterson River Flood Study (Reference 3). The coincident flood assumptions for the design flood events in this study are shown in Table 31.

Table 31 – Paterson River Design Events

Design Event	Paterson River	Hunter River
20% AEP	20% AEP	50% AEP
10% AEP	10% AEP	50% AEP
5% AEP	5% AEP	50% AEP
2% AEP	2% AEP	20% AEP
1% AEP	1% AEP	10% AEP
0.5% AEP	0.5% AEP	5% AEP
0.2% AEP	0.2% AEP	2% AEP
PMF	PMF	1% AEP

10.6. Hunter River Inflows and Tailwater

The dominant flood mechanism in the downstream reaches of the Paterson River is the Hunter River. That is, the flood level at Hinton from a 1% AEP Hunter River Flood is significantly higher that the levels from a 1% AEP flood on the Paterson (assuming some coincident flooding in both scenarios). Dynamic design flood inflows for the Hunter River were used for this study, they were based on model results from (Reference 5). The max flows at the three Hunter River inflow locations are shown in Table 32.

Table 32 – Hunter River Inflows (m^3/s)

Event	Hunter In-bank (m^3/s)	Hunter Left Over-bank (m^3/s)	Hunter Right Over-bank (m^3/s)
50% AEP	713	0	0
20% AEP	1345	0	290
10% AEP	1700	0	631
5% AEP	1781	325	851
2% AEP	1830	1047	1049
1% AEP	1851	1558	1331
0.5% AEP	2060	2653	2845
0.2 % AEP	2100	6274	4533
PMF	2096	9287	7356

Dynamic design tailwater levels for the Hunter River were modelled, based on model results from (Reference 5). The max tailwater levels at the two Hunter River outflow locations are shown in Table 33.

Table 33 – Hunter River Tailwater (mAHD)

Event	Hunter In-bank (mAHD)	Hunter Left Over-bank (mAHD)
50% AEP	3.7	Ground Level
20% AEP	5.0	2.6
10% AEP	5.2	4.3
5% AEP	5.4	4.9
2% AEP	5.7	5.7
1% AEP	5.9	5.9
0.5% AEP	6.3	6.3
0.2 % AEP	7.2	7.3
PMF	8.1	8.2

Note that the results presented below are for Paterson River flooding, in combination with smaller Hunter River flood events as outlined in Table 33. In the lower Paterson River floodplain, the Hunter River design flood levels (from Reference 5) are often the critical level for flood planning and development control purposes. The results from both studies should be considered for floodplain management decision-making.

10.7. Design Flood Modelling Results

The results for the study are presented as:

- Peak flood depth and level contours in Figure C1 to Figure C8

- Peak flood velocities in Figure C9 to Figure C16
- Provisional Hydraulic Hazard in Figure C17 to Figure C19
- Provisional Hydraulic Categorisation in Figure C20 Figure C22

10.7.1. Summary of Results

Peak flood levels, depths and flows at key location in the catchment are summarised below. These key locations coincide with those used for the sensitivity analysis discussed in Section 11. A tabulated summary of peak flood levels and depths at locations displayed in Figure 35 are shown in Table 34 and Table 35.

Table 34 – Peak Flood Levels (mAHD) at Key Locations

Point	Location	20% AEP	10% AEP	5% AEP	2% AEP	1% AEP	0.5% AEP	0.2% AEP	PMF
1	Paterson River Upstream of Vacy	18.1	19.4	20.5	21.2	21.8	22.4	23.1	27
2	Vacy Bridge	16.9	18.2	19.2	19.9	20.7	21.3	22.2	26
3	Horns Crossing	16.8	18	19	19.7	20.3	21	21.9	25.9
4	Gostwyck PINEENA Gauge	15.3	16.4	17.5	18.4	19.3	20.1	21.1	25.2
5	Gostwyck Bridge	13.3	14.4	15.3	16.3	17.1	17.9	19.1	23.2
6	Paterson Rail Bridge	9.5	10.5	11.3	12.1	12.7	13.2	13.9	18.7
7	Paterson Road Bridge	8.8	9.6	10.1	10.6	11	11.4	11.9	14.8
8	Webbers Creek Bridge	8.4	9.2	9.7	10.2	10.6	11	11.5	14.4
9	Dunns Creek Floodplain	4.5	5.1	8.9	9.7	10.2	10.6	11.1	13.6
10	Mindaribba Floodplain	3.7	4.2	4.8	6.3	6.9	7.1	7.5	9
11	Iona Floodplain	1.9	2.6	4.2	6	6.6	7	7.5	8.9
12	Woodville Floodplain	1.4	2.9	3.7	5.5	6.9	7	7.4	8.8
13	Dunmore Bridge	6.2	6.3	6.3	6.5	6.6	6.9	7.3	8.6
14	Clarence Town Road Floodplain	1.3	1.7	1.9	5.9	6.4	6.8	7.2	8.2
15	Largs Floodplain	3.3	3.6	4.1	6.1	6.4	6.8	7.2	8.2
16	Hinton Floodplain	1.9	2	2	2.7	3.5	4	4.6	6.2
17	Hinton Bridge	4.2	4.3	4.4	5.6	6	6.3	6.6	7.3
18	Phoenix Park Floodplain	3.5	3.6	3.7	4.7	6.1	6.4	6.8	7.5
19	Morpeth Bridge	4.2	4.2	4.3	6	6.6	6.8	7.1	7.8

Table 35 – Peak Flood Depths (m) at Key Locations

Point	Location	20% AEP	10% AEP	5% AEP	2% AEP	1% AEP	0.5% AEP	0.2% AEP	PMF
1	Paterson River Upstream of Vacy	9.2	10.5	11.6	12.3	12.9	13.5	14.2	18.1
2	Vacy Bridge	11.2	12.5	13.5	14.2	15	15.6	16.5	20.3
3	Horns Crossing	11.6	12.9	13.8	14.5	15.2	15.8	16.8	20.7
4	Gostwyck PINEENA Gauge	12	13.1	14.1	15.1	15.9	16.8	17.8	21.8
5	Gostwyck Bridge	12.5	13.6	14.6	15.5	16.3	17.2	18.3	22.4
6	Paterson Rail Bridge	12.9	13.9	14.7	15.4	16	16.6	17.3	22
7	Paterson Road Bridge	12.4	13.2	13.7	14.2	14.6	15	15.5	18.4
8	Webbers Creek Bridge	10.5	11.3	11.8	12.3	12.7	13.1	13.6	16.4
9	Dunns Creek Floodplain	1.9	2.5	6.4	7.1	7.6	8	8.5	11.1
10	Mindaribba Floodplain	2.6	3.1	3.8	5.3	5.8	6	6.5	7.9
11	Iona Floodplain	0.8	1.5	3	4.8	5.4	5.9	6.4	7.8
12	Woodville Floodplain	0.9	2.3	3.1	5	6.3	6.5	6.9	8.2
13	Dunmore Bridge	10.6	10.8	10.8	10.9	11	11.3	11.8	13.1
14	Clarence Town Road Floodplain	0.5	0.8	1.1	5.1	5.6	5.9	6.4	7.4
15	Largs Floodplain	0.7	1.1	1.5	3.6	3.9	4.2	4.7	5.6
16	Hinton Floodplain	0.5	0.5	0.6	1.3	2.1	2.6	3.1	4.7
17	Hinton Bridge	9.2	9.3	9.4	10.5	11	11.3	11.6	12.2
18	Phoenix Park Floodplain	0.9	1	1.2	2.2	3.6	3.9	4.3	5
19	Morpeth Bridge	8.7	8.8	8.8	10.5	11.1	11.4	11.6	12.3

The peak flows (m^3/s) modelled at the bridges and gauge at locations displayed in Figure 35 are shown in Table 36.

Table 36 – Peak Flows (m^3/s) at Bridge and Gauge Locations

Point	Location	20% AEP	10% AEP	5% AEP	2% AEP	1% AEP	0.5% AEP	0.2% AEP	PMF
2	PR – Vacy Bridge	560	710	920	1150	1380	1610	1930	4410
3	AR – Horns Crossing	470	610	800	1010	1220	1440	1730	3820
4	PR – Gostwyck PINEENA	1000	1280	1680	2120	2550	2990	3590	8370
5	PR – Gostwyck Bridge	970	1250	1650	2090	2510	2940	3520	8500
6	PR – Paterson Rail Bridge	930	1200	1590	2070	2500	2920	3500	8540
7	PR – Paterson Road Bridge	900	1170	1540	1860	2060	2200	2320	3280
13	PR - Dunmore Bridge	780	850	860	870	900	930	880	1310
17	PR - Hinton Bridge	790	850	860	760	450	340	250	620

10.7.2. Comparison with the 1997 Flood Study

A comparison flows with the Paterson River 1997 Flood Study by WBM (Reference 3) was undertaken at Gostwyck Bridge (see Table 37). The current study matches the flows within 2% for the 2% AEP and 1% AEP event. The flows for the PMF event and the more frequent events were consistent within 20% or less. The main reason for the discrepancies in the smaller events is the 1997 study based the model inflows on the FFA where the current study uses the design rainfall approach for the full range of flood events. This approach was considered reasonable as it matches the design flows from the FFA in the larger events and provides a more holistic approach with regard to catchment modelling and mapping. It is also noted that the updated FFA undertaken for this study produced higher flows for the more frequent flood events than the 1997 Flood Study.

Table 37 – Peak Flows (m^3/s) Comparison 2016 and 1997 Flood Studies

Design Event	WMAwater (2016)	BMT WBM (1997)	Difference
10% AEP	1250	1050	16%
5% AEP	1650	1450	12%
2% AEP	2090	2050	2%
1% AEP	2500	2500	0%
PMF (Extreme)	8500	7500	12%

A comparison of peak flood levels from the previous study is provided in Table 38. The levels from this study are notably lower at the tabulated locations, typically by about 0.5 m to 1.5m for the range of events modelled. As discussed above, the peak design flows from Flood Frequency

Analysis for the two studies were very similar, particularly for the 1% AEP event. The main reason for the changes in peak flood levels are as follows:

- the change in the hydraulic modelling methodology from 1D (node and branch) model to 2D grid-based model with 10 m resolution;
- the availability of more comprehensive aerial survey data for the overbank floodplain (LIDAR on a 1 m grid compared to photogrammetry for the previous study);
- the reduced level of Hunter River flooding assumed to be coincident with the 1% AEP Paterson River flow (10% AEP Hunter River flow for this study, compared to 2% AEP Hunter River flow for the previous study).

Table 38 – Peak Levels (mAHD) Comparison 2016 and 1997 Flood Studies

Location	Studies	%5 AEP	2% AEP	1% AEP	PMF
Gostwyck Bridge	BMT WBM (1997)	15.4	17.1	18.1	25.6
	WMA (2016)	15.3	16.3	17.1	23.9
	Difference	-0.1	-0.8	-1.0	-1.7
Paterson Railway Bridge	BMT WBM (1997)	11.8	13.2	14.1	20.9
	WMA (2016)	11.3	12.1	12.7	18.7
	Difference	-0.5	-1.1	-1.4	-2.2
Paterson Road Bridge	BMT WBM (1997)	10.0	10.6	11.1	15.0
	WMA (2016)	10.1	10.6	11	14.8
	Difference	+0.1	-	-0.1	-0.2
Floodplain Mindaribba	BMT WBM (1997)	5.4	6.9	7.4	10.8
	WMA (2016)	4.8	6.3	6.9	9
	Difference	-0.6	-0.6	-0.5	-1.8
Floodplain Iona	BMT WBM (1997)	6.3	6.8	7.4	10.8
	WMA (2016)	4.2	6	6.6	8.9
	Difference	-2.1	-0.8	-0.8	-1.9

The present study used a more sophisticated 2D hydraulic modelling approach compared with the previous study (which used a 1D modelling approach). The DEM used in the TUFLOW model in the current study is based on LiDAR processed in 2012/2013 which is more accurate that the DEM used in the 1997 study. The 2D approach reflects changes to current industry best practice for catchment-wide flood studies since the previous study was undertaken. For the hydraulic analysis of complex overland flow paths, a 2D model provides several key advantages when compared to a traditional 1D model. For example, in comparison to a 1D approach, a 2D model can:

- provide localised detail of any topographic and /or structural features that may influence flood behaviour,
- better resolve the flow behaviour of overland flow paths and flood problem areas,
- inherently represent the available flood storage within the floodplain.

Importantly, a 2D hydraulic model can better define the spatial variations in flood behaviour across the study area. Information such as flow velocity, flood levels and hydraulic hazard can be readily mapped in detail across the model extent. It is likely that the modelling for the present study more accurately defines the amount of available flood storage in the overbank floodplain, and the interactions between the main channel flow and the overbank storage areas. It is relatively common for 1D models to underestimate the amount of available flood storage, and therefore over-estimate peak flood levels.

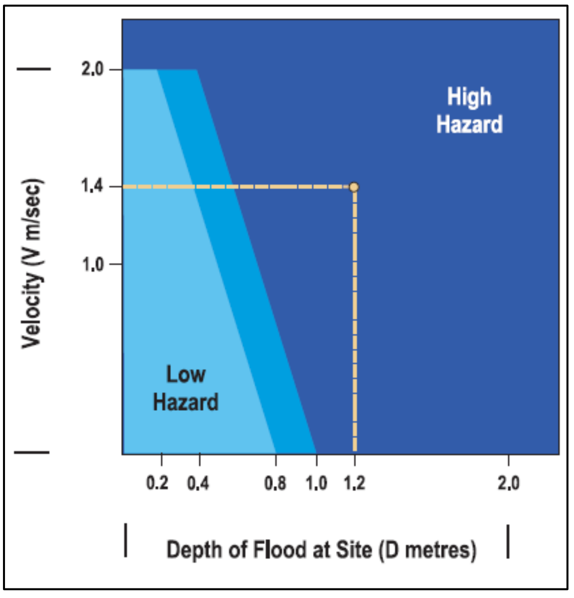
Similarly for velocity results, a 1D model can only provide an average velocity for a given flow cross-section across the floodplain. This average cross-section velocity will not identify localised areas of higher velocity around specific floodplain features, whereas a 2D model can resolve these localised changes in velocity. As identified by WBM in the 1997 flood study report, the 1D modelling "*does not show any localised (high) velocities which occur from obstructions, during overtopping of levees, etc. The velocities shown are indicative of average water velocity across the river or floodplain.*" In light of this constraint, the flood velocities estimated in this study are considered to be reasonably consistent with the previous study. Overbank floodplain velocities are generally estimated to be low (less than 0.5 m/s), with localised pockets of higher velocity.

It is recommended that the flood levels determined in the present study should supersede the previous study for ongoing planning purposes.

10.7.3. Provisional Flood Hazard Categorisation

Provisional hazard categories were determined in accordance with Appendix L of the NSW Floodplain Development Manual (Reference 1), the relevant section of which is shown in Diagram 2. For the purposes of this report, the transition zone presented in Diagram 2 (L2) was considered to be high hazard.

Diagram 2: Provisional "L2" Hydraulic Hazard Categories (Reference 1)



Classification of "true" flood hazard requires consideration of other contributing factors, such as evacuation routes, potential for isolation, and proximity of essential services. Such classification is typically undertaken at the subsequent FRMS&P stage. However the hazard maps (Figure C17 to Figure C19) have been updated to identify obvious areas of potential high hazard resulting from isolation, to inform interim planning decisions until an FRMS&P is completed. This is a preliminary assessment of true hazard and is not comprehensive.

10.7.4. Provisional Hydraulic Categorisation

The hydraulic categories, namely floodway, flood storage and flood fringe, are described in the Floodplain Development Manual (Reference 1). However, there is no technical definition of hydraulic categorisation that would be suitable for all catchments, and different approaches are used by different consultants and authorities, based on the specific features of the study catchment in question.

For this study, hydraulic categories were defined by the following criteria, which is similar to the methodology proposed by Howells et. al, 2003 (Reference 14), but modified slightly to be more consistent with other similar studies undertaken in the Port Stephens and Maitland Council areas (e.g. the Williams River and Hunter River flood studies):

- Floodway is defined as areas where:
    - the peak value of velocity multiplied by depth (V x D) > 0.5 m^2/, **OR**
    - peak velocity > 1.0 m/s **AND** peak depth > 0.2 m

The remainder of the floodplain is either Flood Storage or Flood Fringe,

- Flood Storage comprises areas outside the floodway where peak depth > 1.0 m; and
- Flood Fringe comprises areas outside the Floodway where peak depth < 1.0 m.

The provisional hydraulic categories mapping is shown on Figure C20 to Figure C22.

Port Stephens Council advised that their development control policies also require consideration of a rainfall intensity increase of 20%, as well as sea level rise. It was established in Reference 5 that projected sea level rise benchmarks through to 2100 do not significantly affect design flood levels in the Hunter and Paterson River upstream of Green Rocks. Additional mapping of hydraulic categories was therefore created for the following scenario:

- 1% AEP Paterson River design storm with 20% increased rainfall intensity.

The provisional hydraulic categories mapping incorporating 20% increase in Paterson River rainfall intensity is shown on Figure D2 (Appendix D).

Note that this mapping does not include consideration of the Hunter River 1% AEP design flood event (Reference 5), which should also be considered for development control planning.

10.7.5. Road Inundation

An analysis of road inundation has been undertaken at key locations in the study. The key locations as well as the event in which the road is overtopped is shown in Figure 35. The depth of inundation of on each of the key roads for the full range of design events is shown in Table 39.

Table 39 – Depth of Inundation (m) on Road at Key Locations

Point	Location	Road Level (mAHD)	20% AEP	10% AEP	5% AEP	2% AEP	1% AEP	0.5% AEP	0.2% AEP	PMF
2	Vacy Bridge	21.0	0	0	0	0	0	0.2	1.1	5
R2	Gresford Rd	19.5	0	0	0	0.4	0.8	1.3	2.2	6.2
3	Horns Crossing	10.0	6.8	8	9	9.7	10.3	11	11.9	15.9
5	Gostwyck Bridge	18.0	0	0	0	0	0	0	0.9	4.8
R5	Gresford Rd Paterson	10.6	0	0	0.8	1.6	2.2	2.8	3.5	8.3
R6	Tocal Rd & Queen St	7.8	1.3	2.2	2.9	3.5	3.9	4.4	4.9	8.2
R7	Tocal Rd Paterson	9.7	0	0	0.5	0.8	1.4	1.8	2.3	5.1
7	Paterson Rd Bridge	11.5	0	0	0	0	0	0	0.2	3.1
R9	Tocal Rd Webbers Creek	8.2	0.2	1	1.5	2	2.4	2.8	3.3	6.1
R10	Webbers Creek Bridge	9.5	0	0	0.2	0.7	1.1	1.5	2	4.8
R11	Paterson Rd Dunns Creek	6.1	0	0	2.8	3.5	4	4.4	4.9	7.3
R12	Paterson Rd Iona	4.9	0	0.7	1.1	1.8	2.2	2.5	3	5.2
R13	Iona Public School	2.6	0	0.8	1.6	3.4	4	4.5	4.9	6.3
R14	Clarence Town Road Woodville	3.7	0	0	0.4	2.3	2.8	3.3	3.7	5
13	Dunmore Bridge	8.3	0	0	0	0	0	0	0	0.2
R16	Phoenix Park Rd - Largs	3.4	0	0.2	0.6	2.7	3	3.3	3.8	4.8
R17	Wallalong Rd	2.6	0	0	0	0	0.2	0.5	0.9	2.1
R18	Butterwick Rd	5	0.1	0.1	0.1	1	1.6	2.1	2.5	3.9
R19	High Street (between Hinton and Wallalong)	2..1	0	0	0	0.6	1.4	2	2.5	4.1

Several of the roads in the study area are cut in relatively frequent events such as the 20% AEP. A summary of the frequency of inundation for major roads and bridges is given in Table 40.

Table 40 – Summary of Overtopping Frequency for Major Bridges and Roads

Location ID (Figure 35)	Bridge/Road	Waterway	Overtopping Event
2	Vacy Bridge	Paterson River	Between 1% and 0.5% AEP
R2	Gresford Rd	Floodplain	Between 5% and 2% AEP
3	Horns Crossing	Allyn River	< 20% AEP
5	Gostwyck Bridge	Paterson River	Between 0.5% and 0.2% AEP
R5	Gresford Rd Paterson	Floodplain	Between 10% and 5% AEP
R6	Tocal Rd & Queen St	Floodplain	< 20% AEP
R7	Tocal Rd Paterson	Floodplain	Between 10% and 5% AEP
7	Paterson Rd Bridge	Paterson River	Between 0.5% and 0.2% AEP
R9	Tocal Rd Webbers Creek	Webbers Creek	< 20% AEP
R10	Webbers Creek Bridge	Webbers Creek	Between 10% and 5% AEP
R11	Paterson Rd Dunns Creek	Dunns Creek	Between 10% and 5% AEP
R12	Paterson Rd Iona	Floodplain	Between 20% and 10% AEP
R13	Iona Public School	Floodplain	Between 20% and 10% AEP
R14	Clarence Town Road Woodville	Floodplain	Between 10% and 5% AEP
13	Dunmore Bridge	Paterson River	Between 0.2% AEP and PMF
R16	Phoenix Park Rd - Largs	Floodplain	Between 20% and 10% AEP
R17	Wallalong Rd	Floodplain	Between 2% and 1% AEP
R18	Butterwick Rd	Floodplain	< 20% AEP
R19	High Street (between Hinton and Wallalong)	Floodplain	Between 5% and 2% AEP

Table 41 relates the gauge height at Gostwyck Bridge to anticipated road and bridge overtopping locations. This summary is based on design flood event modelling, and real floods may vary, particularly the further the location of interest from the Gostwyck Bridge gauge. However, the information is intended to assist the SES for planning purposes based on flood warning information provided by the Bureau of Meteorology, since these warnings generally include a predicted flood level at the Gostwyck Bridge gauge.

Table 41 – Major Bridge and Road Overtopping (Gauge Heights at Gostwyck Bridge)

Event & Gauge Level Gostwyck Bridge	Location ID (Figure 35)	Bridge/Road Overtopped
20% AEP = 13.3 m	3	Horns Crossing
	R6	Tocal Rd & Queen St
	R9	Tocal Rd Webbers Creek
	R18	Butterwick Rd
10% AEP = 14.4 m	All of the above, plus:	
	R12	Paterson Rd Iona
	R12	Paterson Rd Iona
	R16	Phoenix Park Rd - Largs
5% AEP = 15.3 m	All of the above, plus:	
	R5	Gresford Rd Paterson
	R6	Tocal Rd & Queen St
	R10	Webbers Creek Bridge
	R11	Paterson Rd Dunns Creek
	R14	Clarence Town Road Woodville
2% AEP = 16.3 m	All of the above, plus:	
	R2	Gresford Rd
	R19	High Street (between Hinton and Wallalong)
1% AEP = 17.1 m	All of the above, plus:	
	R17	Wallalong Rd
0.5% AEP = 17.9 m	All of the above, plus:	
	2	Vacy Bridge
0.2% AEP = 19.1 m	All of the above, plus:	
	5	Gostwyck Bridge
	7	Paterson Rd Bridge
PMF = 23.2 m	All of the above, plus:	
	13	Dunmore Bridge

10.7.6. Spillway Overtopping Hinton

The three spillways at Hinton located on the eastern levee between Wallalong Road and Hinton Bridge allow water to overtop the levee into the Hinton floodplain in a controlled manner especially in the smaller event. Flood waters are contained inside the levee system up to the 5% AEP event.

The flows (m^3/s) over the spillways as well as the entire section of levee between Wallalong Road and Hinton Bridge are shown in Table 42.

Table 42 – Levee Spillway Flows (m^3/s) - Section from Wallalong Rd to Hinton Bridge

Spillway	20% AEP	10% AEP	5% AEP	2% AEP	1% AEP	0.5% AEP	0.2% AEP	PMF
1	0	0	0	80	340	550	850	2330
2	0	0	0	10	60	90	140	490
3	0	0	0	30	100	170	250	710
Entire Levee	0	0	0	140	740	1350	2180	5680

Sections of the Paterson River levee system are overtopped in events starting from the 20% AEP and onwards, with the entire levee system overtopping in the 2% AEP event. The event for which each section of levee is overtopped is displayed in Figure C25.

10.7.7. Preliminary Flood Planning Area

The preliminary Flood Planning Area (FPA) was determined by adding 0.5 m freeboard to the Paterson River 1% AEP flood level, and “stretching” this surface across the topography. This extent was merged with the FPA of the Hunter River taken from the 2015 FRMS&P (Reference 19) to create a combined FPA of the Paterson River and Hunter River for the 1% AEP event. The FPA identifies land that is below the 1% AEP plus freeboard level, and is finalised at the Floodplain Risk Management Study stage when appropriate freeboard levels are determined. The preliminary FPA for Paterson River and its tributary creeks is shown in Figure C23.

The dominant flood mechanism in the downstream reaches of the Paterson River is the Hunter River. That is, the flood level at Hinton from a 1% AEP Hunter River flood is significantly higher that the levels from a 1% AEP flood on the Paterson (assuming some coincident flooding in both scenarios). For areas downstream of Dunmore Bridge the 1% AEP flood levels from the Hunter River Flood Study (Reference 5) are to be used for developmental purposes. An example of the discrepancies in peak flood levels in shown in Table 43.

Table 43 – Paterson River vs Hunter River 1% AEP Flood Levels

Location ID (Figure 35)	Location	1% AEP Paterson River (mAHD)	1% AEP Hunter River (mAHD)	Difference (m)
14	Clarence Town Road Floodplain	6.4	6.9	0.5
15	Largs Floodplain	6.4	6.9	0.5
16	Hinton Floodplain	3.5	5.8	2.3
17	Hinton Bridge	6	6.5	0.5
18	Phoenix Park Floodplain	6.1	6.6	0.5

Port Stephens Council advised that their development control policies also require consideration of potential climate change impacts. Under Council policy, development in Port Stephens is required to be built to climate benchmarks for the year 2100, including consideration of sea level rise and increases to rainfall intensity. Port Stephens Council formally adopted the State Government's sea level rise benchmarks from 2009 which are 0.4m by 2050 and 0.9m by 2100. Port Stephens Council also advised that they typically incorporate an assumption of a 20% increase in rainfall intensity into the 2100 Flood Planning Level.

It was established in Reference 5 that the projected sea level rise benchmarks through to 2100 do not significantly affect design flood levels in the Hunter and Paterson River upstream of Green Rocks. However, increases to design rainfall intensity would result in increases to Flood Planning Levels throughout the Paterson Valley, and a broader extent of land subject to flood planning controls (the FPA). An additional FPA extent was therefore created by combining the following scenarios:

- 1% AEP Paterson River design storm with 20% increased rainfall intensity; and
- Hunter River 1% AEP design event (no rainfall increase).

The FPA extent incorporating 20% increase in Paterson River rainfall intensity is shown on Figure D1 (Appendix D), consistent with the planning requirements of Port Stephens Council.

10.7.8. Peak Flood Level Profiles

Longitudinal profiles of the peak flood level within the Paterson River for the 5% AEP, 1% AEP and PMF events are shown on Figure C24.

The gradient of the 5% AEP flood is relatively even through the study area, although slightly steeper in the upper reaches. This indicates there are no particular reaches of high energy loss for these moderate size events. The steepest parts of the profiles (i.e. where there is a notable afflux or drop in flow energy) are associated with sharp bends in the river, such as near Paterson (chainage 16 km). Similar behaviour is noted for the 1% AEP event, although there is a more pronounced drop around chainage 22.5 km, which is associated with the sharp river bend to the east of the Tocal Agricultural Centre. The afflux at the major bridge and road crossing is not pronounced for the 5% and 1% AEP events, since most of the bridges have high decks that do not influence the flow in these events.

For the PMF event, there is a more pronounced influence on the peak flood profile from some of the bridges (notably Gostwyck Bridge), however the sharp river bends are the locations of most significant energy dissipation, and steeper afflux. These bend losses can be significant for large flood events, due to differences in the direction of the channelized flow (which follows the meandering river) and the broader floodplain flow (which goes more directly downstream), creating significant sheer stresses and energy losses. The 2D modelling approach used or this study is better at resolving this energy dissipation behaviour at bends than the 1D modelling methods used previously, although there are significant vertical turbulence components that are not resolved by the 2D scheme. 1D modelling does not resolve the energy losses around the bends at all unless the modeller makes the decision to include an energy loss parameter for that particular reach.

11. SENSITIVITY ANALYSIS

11.1. Overview

A number of sensitivity analyses were undertaken for the modelling to establish the variation in design flood levels and flow that may occur if different parameter assumptions were made. These sensitivity scenarios are shown in Table 44.

Table 44 – Overview of Sensitivity Analysis

Scenario	Description
Manning's "n"	The hydraulic roughness values were increased and decreased by 20%
Climate Change	Sensitivity to rainfall and runoff estimates were assessed by increasing the rainfall intensities by 10%, 20% and 30% as recommended under the current guidelines;

11.2. Climate Change

Intensive scientific investigation is ongoing to estimate the effects that increasing amounts of greenhouse gases (water vapour, carbon dioxide, methane, nitrous oxide, ozone) are having on the average earth surface temperature. Changes to surface and atmospheric temperatures may affect climate and sea levels. The extent of any permanent climatic or sea level change can only be established with certainty through scientific observations over several decades. Nevertheless, it is prudent to consider the possible range of impacts with regard to flooding and the level of flood protection provided by any mitigation works.

Based on the latest research by the United Nations Intergovernmental Panel on Climate Change, evidence is emerging on the likelihood of climate change and sea level rise as a result of increasing greenhouse gasses. In this regard, the following points can be made:

- greenhouse gas concentrations continue to increase;
- global sea level has risen about 0.1 m to 0.25 m in the past century;
- many uncertainties limit the accuracy to which future climate change and sea level rises can be projected and predicted.

11.2.1. Rainfall Increase

The Bureau of Meteorology has indicated that there is no intention at present to revise design rainfalls to take account of the potential climate change, as the implications of temperature changes on extreme rainfall intensities are presently unclear, and there is no certainty that the changes would in fact increase design rainfalls for major flood producing storms. There is some recent literature by CSIRO that suggests extreme rainfalls may increase by up to 30% in parts of NSW (in other places the projected increases are much less or even decrease); however this information is not of sufficient accuracy for use as yet (Reference 14).

Any increase in design flood rainfall intensities will increase the frequency, depth and extent of inundation across the catchment. It has also been suggested that the cyclone belt may move further southwards. The possible impacts of this on design rainfalls cannot be ascertained at this time as little is known about the mechanisms that determine the movement of cyclones under existing conditions.

Projected increases to evaporation are also an important consideration because increased evaporation would lead to generally dryer catchment conditions, resulting in lower runoff from rainfall. Mean annual rainfall is projected to decrease, which will also result in generally dryer catchment conditions.

The combination of uncertainty about projected changes in rainfall and evaporation makes it extremely difficult to predict with confidence the likely changes to peak flows for large flood events within the Paterson River catchment under warmer climate scenarios.

In light of this uncertainty, the NSW State Government's (Reference 14) advice recommends sensitivity analysis on flood modelling should be undertaken to develop an understanding of the effect of various levels of change in the hydrologic regime on the project at hand. Specifically, it is suggested that increases of 10%, 20% and 30% to rainfall intensity be considered.

11.2.2. Sea Level Rise

Flood levels on the Paterson River are not significantly affected by the currently projected levels for sea level rise. This was examined in Reference 5.

11.3. Sensitivity Analysis Results

The sensitivity scenario results were compared for the 1% AEP rainfall event with the 10% AEP Hunter River flooding. A summary of peak flood level differences at various locations is provided in:

- Table 45 for variations in Mannings 'n' roughness; and
- Table 46 for variations in climate conditions

11.3.1. Roughness Variations

Overall peak flood levels were found to be sensitive to a variation in the roughness parameter which was already ascertained in the calibration process. The greatest variation in peak flood levels was at Gostwyck Bridge with a variation of +/- 0.5m. The flood level modelled at Gostwyck Bridge in the 1% AEP flood event is 17.1 mAHD.

Table 45 – Results of Roughness Variation Sensitivity Analysis – 1% AEP Levels (m AHD)

Point	Location	Peak Flood Level 1% AEP (10% AEP Hunter River)	Difference with 1% AEP (m)	
			Roughness Decreased by 20%	Roughness Increased by 20%
1	Paterson River Upstream of Vacy	21.8	-0.39	0.34
2	Vacy Bridge	20.7	-0.36	0.36
3	Horns Crossing	20.3	-0.39	0.41
4	Gostwyck PINEENA Gauge	19.3	-0.48	0.46
5	Gostwyck Bridge	17.1	-0.5	0.49
6	Paterson Rail Bridge	12.7	-0.23	0.24
7	Paterson Road Bridge	11	-0.17	0.16
8	Webbers Creek Bridge	10.6	-0.14	0.14
9	Dunns Creek Floodplain	10.2	-0.11	0.12
10	Mindaribba Floodplain	6.9	-0.05	0.03
11	Iona Floodplain	6.6	-0.15	0.15
12	Woodville Floodplain	6.9	-0.04	0.03
13	Dunmore Bridge	6.6	-0.08	0.07
14	Clarence Town Road Floodplain	6.4	-0.09	0.08
15	Largs Floodplain	6.4	-0.07	0.07
16	Hinton Floodplain	3.5	-0.19	0.17
17	Hinton Bridge	6	-0.07	0.05
18	Phoenix Park Floodplain	6.1	-0.09	0.07
19	Morpeth Bridge	6.6	-0.16	0.13

11.3.2. Climate Variation

The effect of increasing the design rainfalls by 10%, 20% and 30% was evaluated for the 1% AEP rainfall event with impacts on peak flood levels observed throughout the study area. Generally speaking, each incremental 10% increase in rainfall results in an increase in peak flood levels at most of the locations analysed. The 1% AEP event with a rainfall increase of 30% is approximately equivalent to a 0.2% AEP event in present day conditions. The largest variation in peak flood level occurred on Paterson River at Gostwyck Bridge.

Table 46 - Results of Climate Change Analysis – 1% AEP Levels (m)

Point	Location	Peak Flood Level 1% AEP (10% AEP Hunter River)	Difference with 1% AEP (m)		
			Rain +10%	Rain +20%	Rain +30%
1	Paterson River Upstream of Vacy	21.8	0.5	0.97	1.42
2	Vacy Bridge	20.7	0.58	1.14	1.66
3	Horns Crossing	20.3	0.59	1.16	1.74
4	Gostwyck PINEENA Gauge	19.3	0.72	1.39	2.04
5	Gostwyck Bridge	17.1	0.76	1.51	2.22
6	Paterson Rail Bridge	12.7	0.49	0.93	1.36
7	Paterson Road Bridge	11	0.35	0.66	0.97
8	Webbers Creek Bridge	10.6	0.34	0.65	0.95
9	Dunns Creek Floodplain	10.2	0.37	0.68	0.98
10	Mindaribba Floodplain	6.9	0.14	0.24	0.43
11	Iona Floodplain	6.6	0.3	0.54	0.7
12	Woodville Floodplain	6.9	0.12	0.2	0.34
13	Dunmore Bridge	6.6	0.13	0.26	0.42
14	Clarence Town Road Floodplain	6.4	0.18	0.32	0.48
15	Largs Floodplain	6.4	0.16	0.31	0.46
16	Hinton Floodplain	3.5	0.24	0.41	0.61
17	Hinton Bridge	6	0.12	0.21	0.32
18	Phoenix Park Floodplain	6.1	0.14	0.25	0.37
19	Morpeth Bridge	6.6	0.11	0.19	0.27

12. RECOMMENDATIONS

It is recommended that following the conclusion and adoption of the Paterson River Flood Study; combined flood level and DCP mapping be developed utilising results from the Paterson River Flood Study and the Hunter River Flood Study (Reference 5). The DCP mapping can be tailored to meet each Council's individual needs or developed after a consultation process with all stakeholders.

13. PUBLIC EXHIBITION

13.1. Public Submissions

The Draft Paterson River Flood Study was placed on Public Exhibition from 22nd September to 21st October at the following locations:

- Maitland Council – Website, Citizen Service Centre, Maitland Library, Thornton Library
- Port Stephens Council – Website, Council Administration Centre
- Dungog Council - Website, Council Administration Centre

From the month long public exhibition period, two public submissions were received, which are attached in Appendix E. The submissions related to levee modification works undertaken by OEH on the Wallalong levee in early 2016. The main points raised in the public submissions are as follows:

- Objection of the modification works;
- Questioning of the approval for the works and consultation process or lack thereof;
- Concerns that the modification works will adversely impact flooding on their properties;
- A request that the levee be put back to pre-modification conditions.

13.2. Response to Public Submissions

In response to the public submissions received WMAwater notes the following:

- The modelling completed for this study does not include the levee modification works carried out in early 2016. The levee topography utilised in the study is based on pre-modification levels from aerial survey collected in 2012 and 2013. The results and mapping outputs reflect pre-modification conditions.
- A separate modelling analysis undertaken for OEH quantified the changes to peak flood levels resulting from the levee modifications, for both Hunter River flooding and Paterson River flooding (attached in Appendix E).
- OEH is currently investigating further modifications to the levee with the intention of minimising the changes in flood behaviour compared to pre-modification conditions (as mapped for this study). WMAwater understands this process will involve community consultation.

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