14 CALIBRATION AND VALIDATION

14.1 Introduction

The calibration process comprised two stages, initially involving the hydrologic model and comparison of recorded and simulated hydrographs, followed by a comparison of recorded flood levels and flood levels simulated in the hydraulic model. Once the hydrologic model was calibrated, the modelling outputs provided flows that were used in the calibration of the hydraulic model. Satisfactory results from both models confirmed the adequacy of the modelling parameters for application in modelling design flood events.

14.2 Selection of Events for Calibration

Four flood events were chosen for calibration and validation of the hydrologic and hydraulic flood models. These events were chosen based on the frequency analysis, historic flood reports, availability of continuous flow data, and availability of recorded floodmarks. These events were the February 1971, March 2011, March 1983 and February 2010 events. Larger sized historic flood events were chosen in favour of smaller events for calibration to provide better model results in the less frequent event range, such as the 1%AEP event.

Several gauged hydrographs and floodmarks were available for the selected historic flood events. There were several flow gauging stations positioned spatially throughout the catchment, however, there were none at the outlet (at Mogareeka) or downstream of Bega. Therefore, the calibration of flows needed to be confirmed by comparison of modelled flood levels with floodmarks.

14.3 Hydrologic Model Calibration

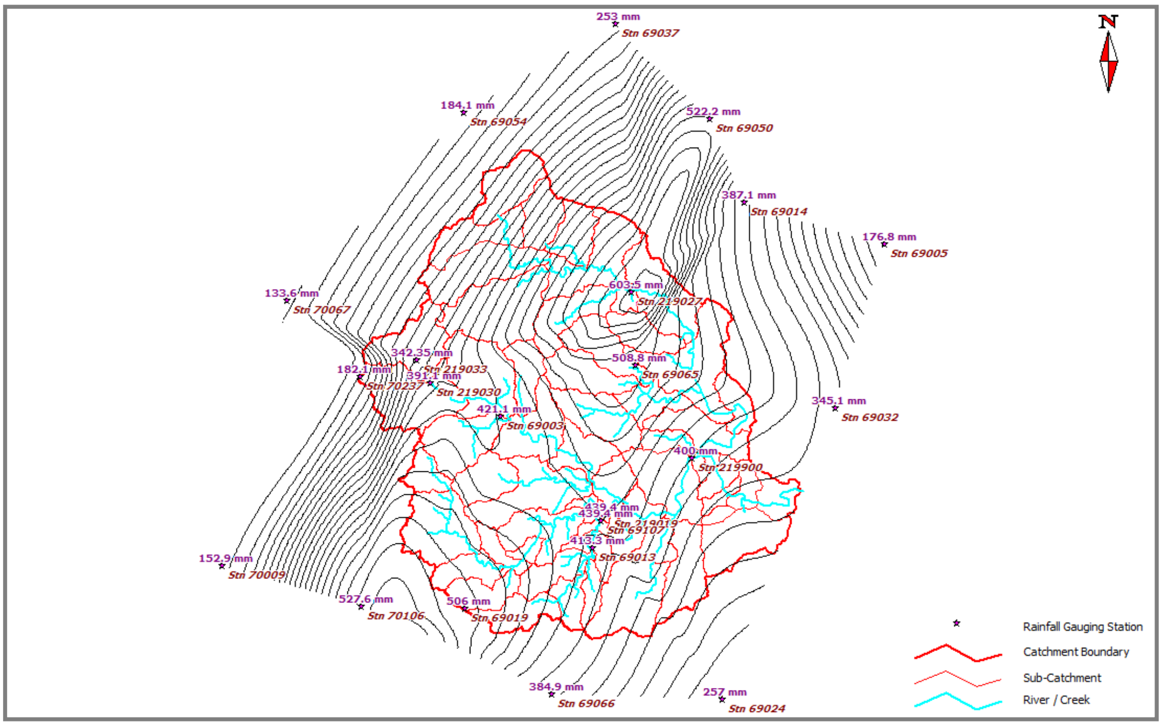
14.3.1 Spatial Distribution of Rainfall / Isohyetal Maps

Rainfall data has shown to vary across the catchment, not only for different events but also in different areas of the catchment. To develop the maps of total rainfall varying across the catchment (i.e. isohyetal maps), daily rainfall data was obtained from the BoM website and NOW and compiled for each event. Three-dimensional (3d) surfaces of rainfall were modelled using the MapInfo GIS software, with the results applied to each sub-area in the hydrologic model.

The spatial distribution (or isohyetal maps) for each historic event are shown in Figures 14.1 to 14.5. The daily read rainfall stations used in developing the maps have also been included, together with the total rainfall for the entire event. In some cases, rainfall stations did not have data, either due to malfunctioning of the equipment or because the station not in operation at that time.

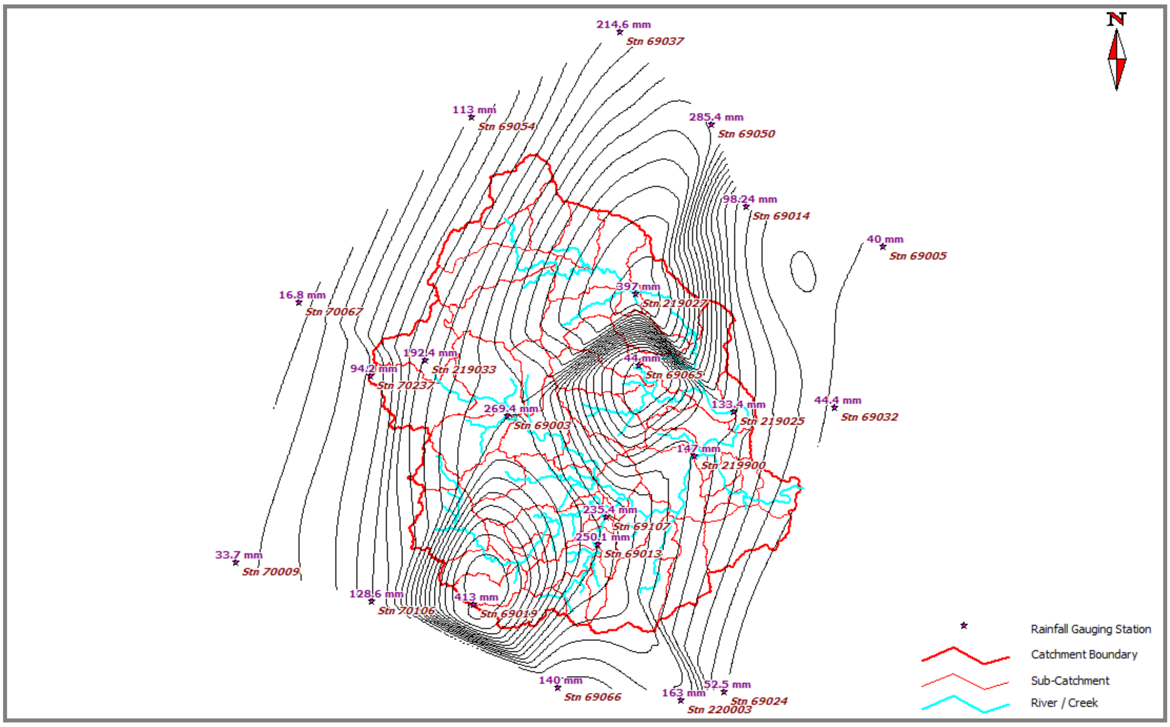
For the March 2011 event a discrepancy was noted at Station 69065. The data indicated that nearby rainfall recordings from the BoM site underestimated the rainfall totals for that event. Therefore, the rainfall from Station 69065 was excluded for the modelling of the March 2011 event.

Figure 14.1: Isohyetal Map Showing Spatial Distribution of Rainfall for February 1971 Event*



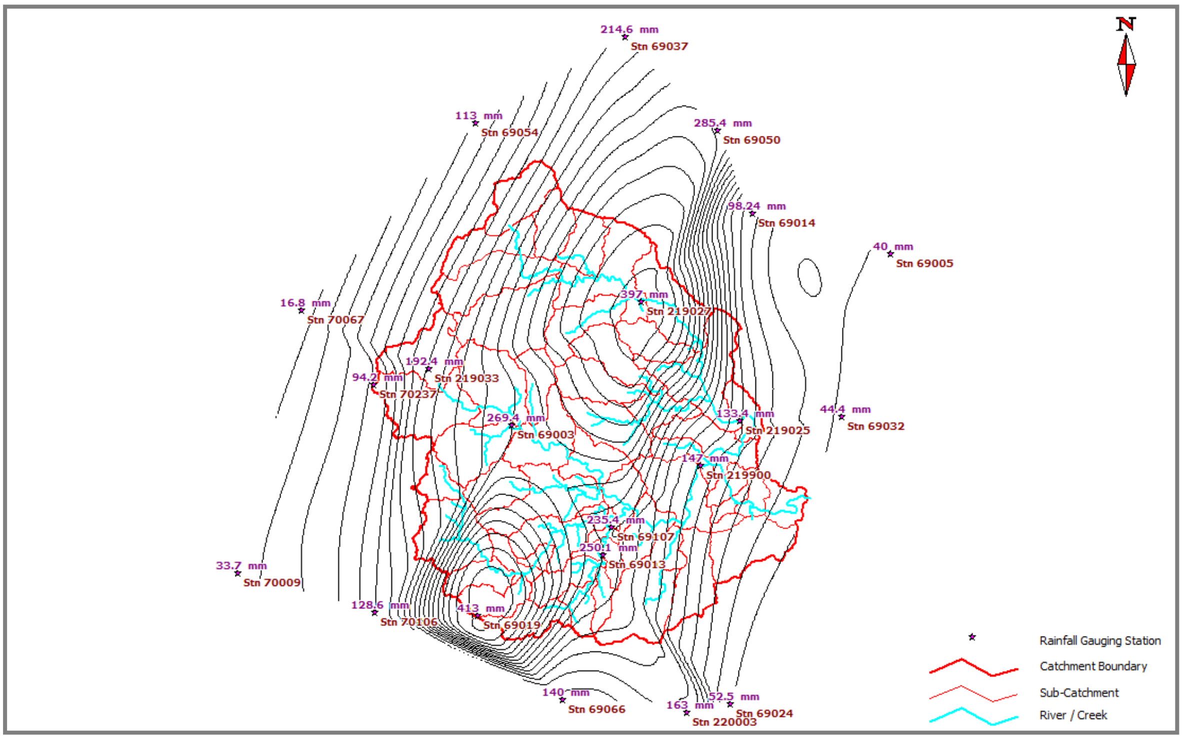
* (Total Rainfall for 6th and 7th February – 24 hours to 9am)

Figure 14.2: Isohyetal Map Showing Spatial Distribution of Rainfall for March 2011 Event – ALL DATA*



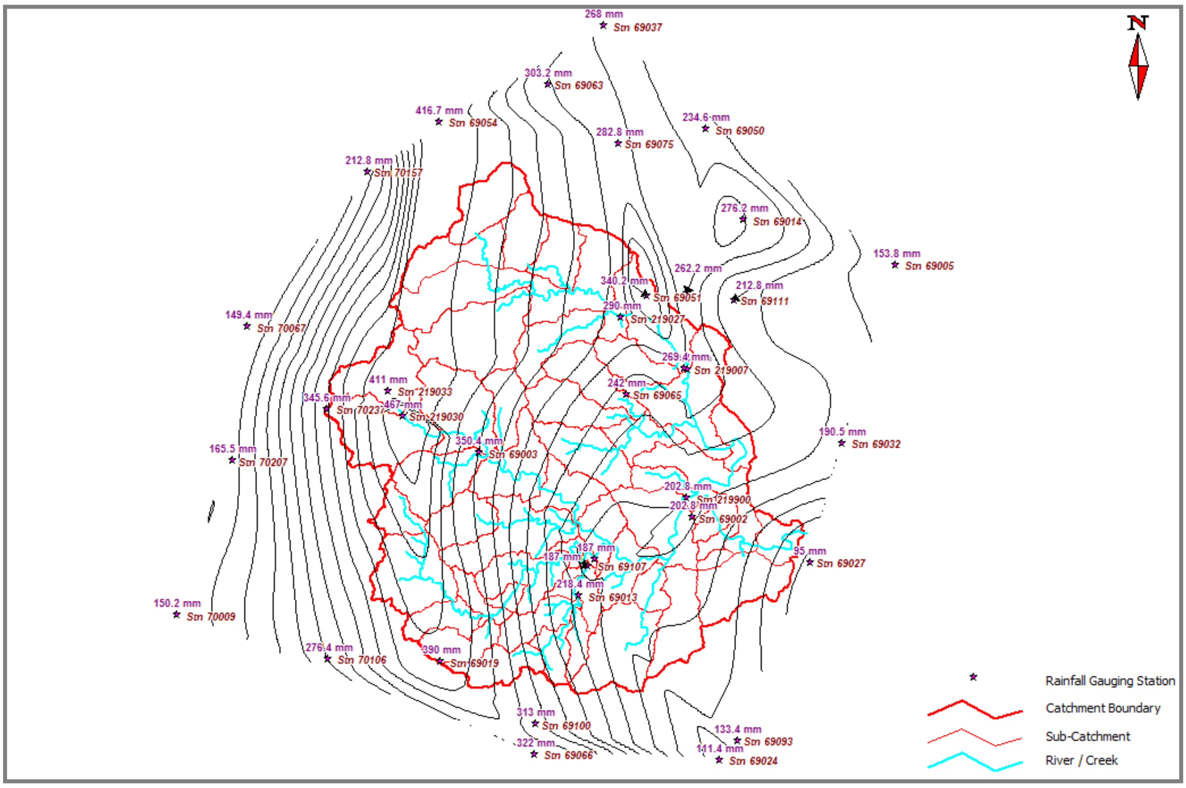
* (Total Rainfall for 21st and 22nd March – 24 hours to 9am), including Bureau of Meteorology Station 69065

*Figure 14.3: Isohyetal Map Showing Spatial Distribution of Rainfall for March 2011 Event – FOR MODELLING**



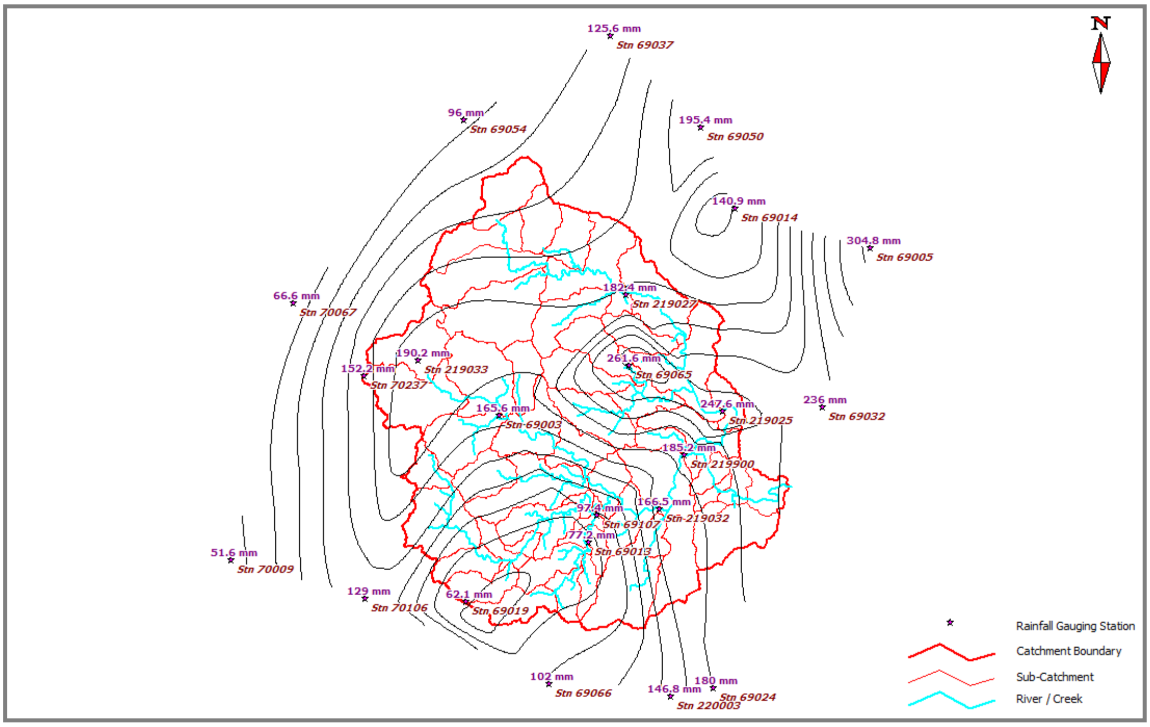
* (Total Rainfall for 21st and 22nd March – 24 hours to 9am) excluding Bureau of Meteorology Station 69065

*Figure 14.4: Isohyetal Map Showing Spatial Distribution of Rainfall for March 1983 Event**



* (Total Rainfall for 21st and 22nd March – 24 hours to 9am)

*Figure 14.5: Isohyetal Map Showing Spatial Distribution of Rainfall for February 2010 Event**



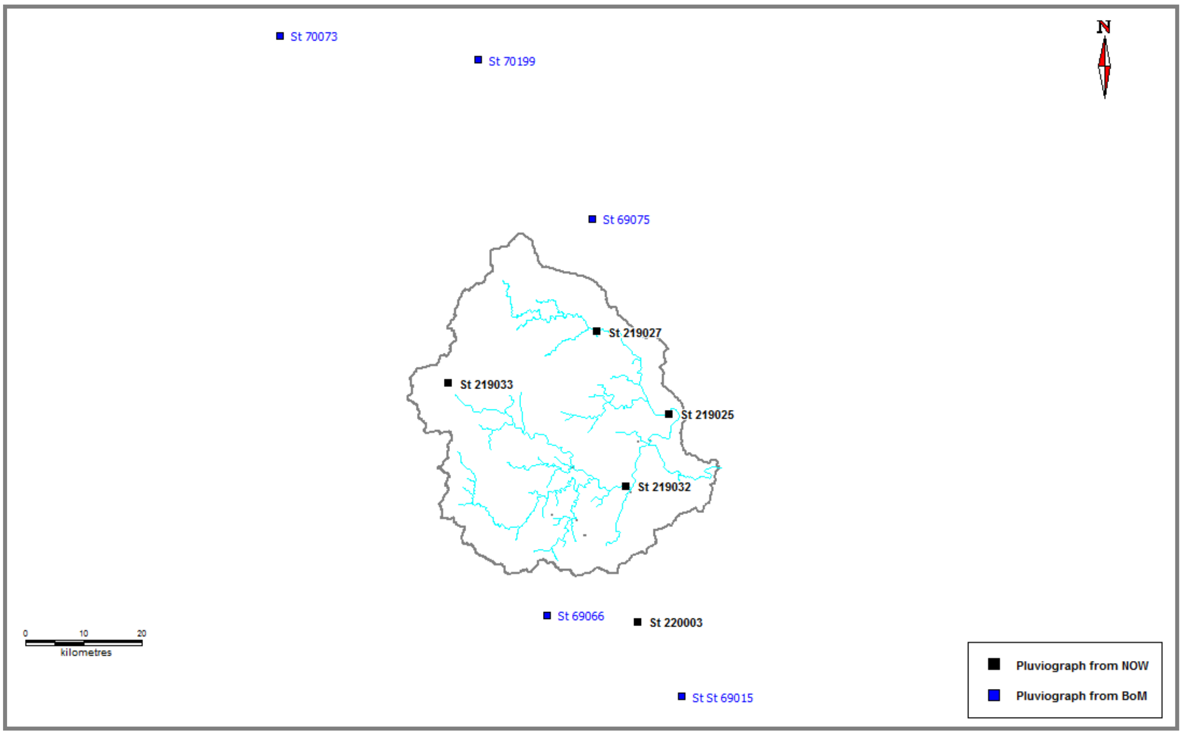
* (Total Rainfall for 15th and 16th February – 24 hours to 9am)

14.3.2 Temporal Distribution of Rainfall / Pluviographic Data

It should be noted that it is not simply the total rainfall during an event that is often quoted in newspaper articles that govern the hydrology of a catchment and resulting flood behaviour. The temporal distribution of rainfall has a major impact on flood behaviour and to calibrate hydrologic models the temporal distribution of rainfall is measured by pluviograph stations that record the timing and amount of rainfall or rainfall intensity throughout an event. Thus pluviograph stations provide an instantaneous record of rainfall over time.

A search of all available pluviograph stations was undertaken at or near the catchment for use in the modelling of historic events. This search included stations from the Bureau of Meteorology (BoM) and Pinneena DVD by the NOW. The NSW Office of Water, State Water, Council, MHL and Public Works were also contacted for additional pluviograph readings but no additional records were provided other that those obtained from the Pinneena DVD or from the BoM. Although MHL provided the location of their nearest pluviograph station at Wallaga Lake - Regatta Point, data was only available outside of the catchment from 1999 onwards and therefore could not improve the calibration or validation.

Figure 14.6: Pluviograph Stations Map



The availability of pluviograph data from these stations with respect to the rainfall events targeted for calibration is shown in Table 14.1.

Table 14.1: Availability of Pluviograph Data for Calibration/ Validation Events

Station	Feb 1971	Mar 2011	Mar 1983	Feb 2010
70199	Yes	Yes	Yes	Yes
69066	No	No	No	No
69075	No	No	No	No
219033	No	Yes	No	Yes
219027	No	Yes	No	Yes
219025	No	Yes	No	Yes
219032	No	No	No	Yes
220003	No	Yes	No	Yes

Locations of the pluviograph stations were plotted in the MapInfo GIS (Geographic Information System), and superimposed onto the catchment layout previously delineated into subareas. The pluviograph that was adopted at each sub-area was from the station closest in proximity as determined using GIS.

The closest operating station for the February 1971 event was obtained from the Bureau of Meteorology at station 70199 - Numeralla (Badja Composite) but was a significant distance from the catchment. The NSW Office of Water held no pluviograph records for the February 1971 event within the catchment. Considering that station 70199 is located a significant distance outside the catchment, it could not be confirmed if the modelling results obtained for the February 1971 event were influenced by effects such as orographic lifting or other variations in temporal rainfall patterns throughout the catchment.

A comparison of the February 1971 flows from observed streamflow records and from observed pluviograph readings indicated that the pluviograph from Numeralla had a significant difference in the timing of rainfall (approximately 13hours) compared to that experienced in the study area. The measured hydrographs began to increase in flowrate earlier during the event than rainfall measurements indicated, a phenomena that is not possible as runoff is dependent on rainfall. Since the pluviograph was obtained from outside of the catchment area, and since a number of hydrographs within the catchment showed consistent timing, the inconsistency against the rainfall pattern was understood as either incorrect time recording at Numeralla station or as a storm travel lag from the Numeralla Station to the catchment. For modelling purposes the timing of the pluviograph was adjusted to have occurred at an earlier point in time matching available hydrographs. Satisfactory results were achieved for calibrating the hydrologic model with this shift to the pluviograph readings.

A number of pluviographs from NOW were available for modelling the March 2011 and February 2010 events with no time modification necessary. Rainfall readings for the three events are presented in Figures 14.7 to 14.9. The additional pluviograph records associated with the March 2011 and February 2010 events indicate how variations in temporal patterns of rainfall can occur throughout the catchment. The different spatial patterns obtained from pluviograph records can impact on the timing, volume, peak, and shape of the hydrographs produced from the upper reaches of the catchment to the outlet. Where multiple pluviograph records were available the subareas were assigned to the nearest station's record. Note that for the February 2010 and March 2011 events, although multiple stations were used in modelling, for information only rainfall from a single rainfall station is presented below.

Figure 14.7: Pluviograph for the February 1971 Event – Station 70199

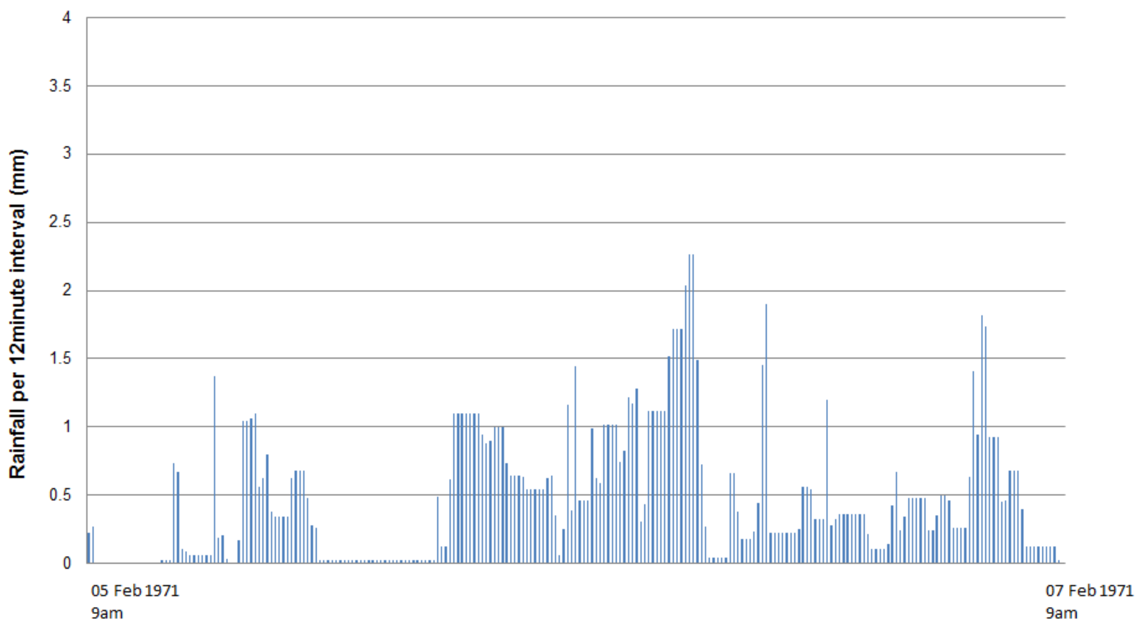


Figure 14.8: Pluviograph for the March 2011 Event – Station 219033

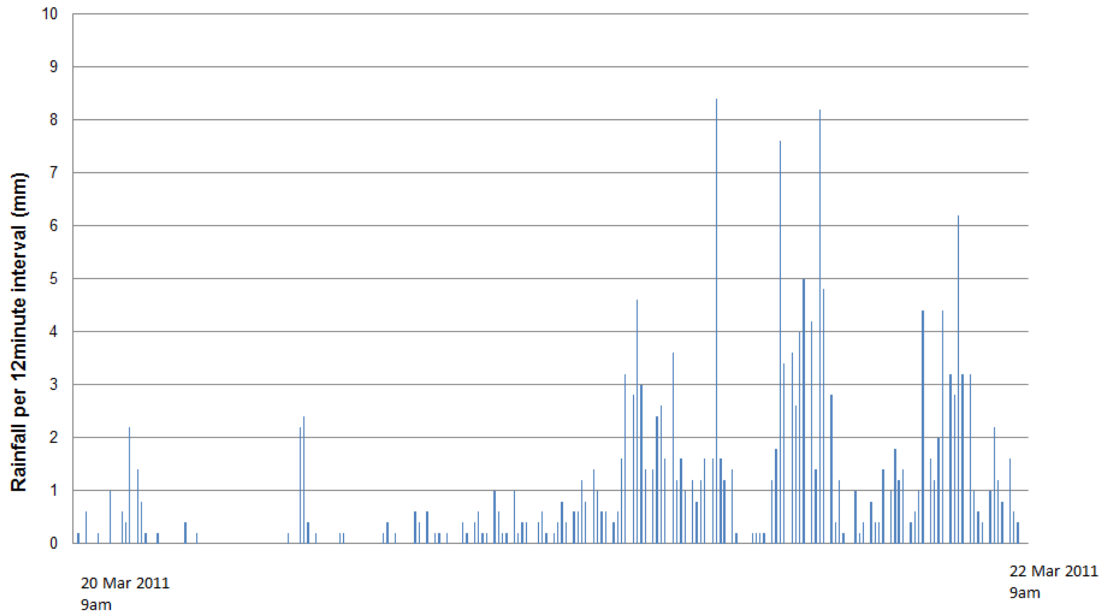
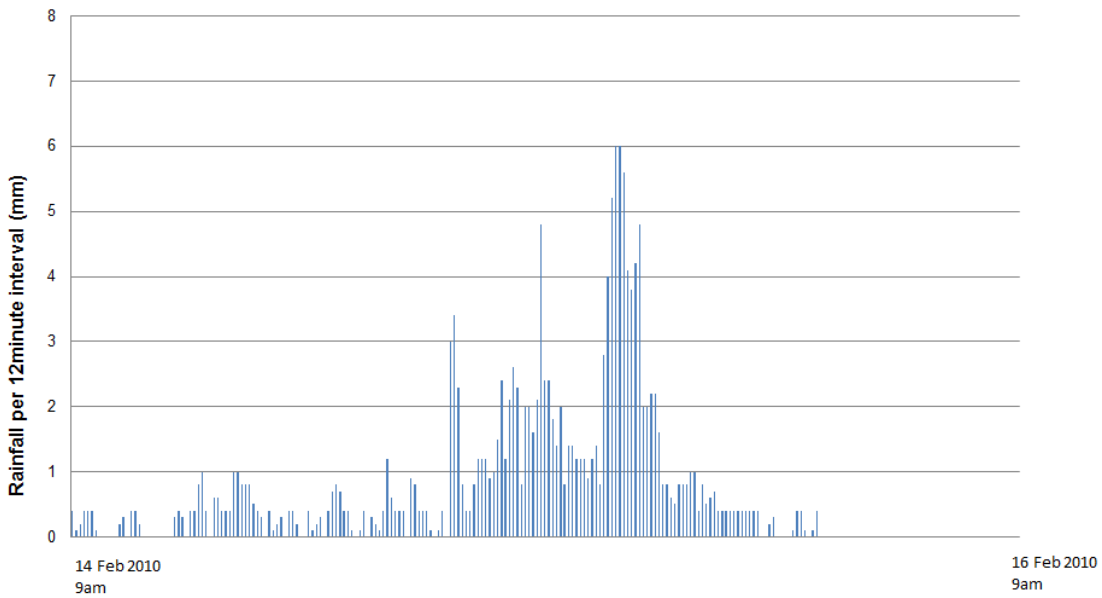


Figure 14.9: Pluviograph for the February 2010 Event – Station 219032



Despite a thorough effort to obtain pluviograph records for the March 1983 event, no records were found within the catchment. The nearest station with available data was Station 70199 at Numeralla. The unavailability of pluviograph data for this event required a number of additional considerations which were:

- Records indicated that the rainfall occurred over two days namely the 24 hours to 9am on the 21st and 22nd March 1983.
- The daily rainfall records indicated a significant difference in totals over the two days of rainfall, compared to the pluviograph records from the only available pluviograph, station 70199, situated outside of the catchment (refer Table 14.2). The initial model runs consistently overestimated observed flows at several stations throughout the catchment The difference in the original

pluviograph data was found to be the reason it significantly skewed initial modeling results to day 2, rather than distributing the temporal pattern over two days.

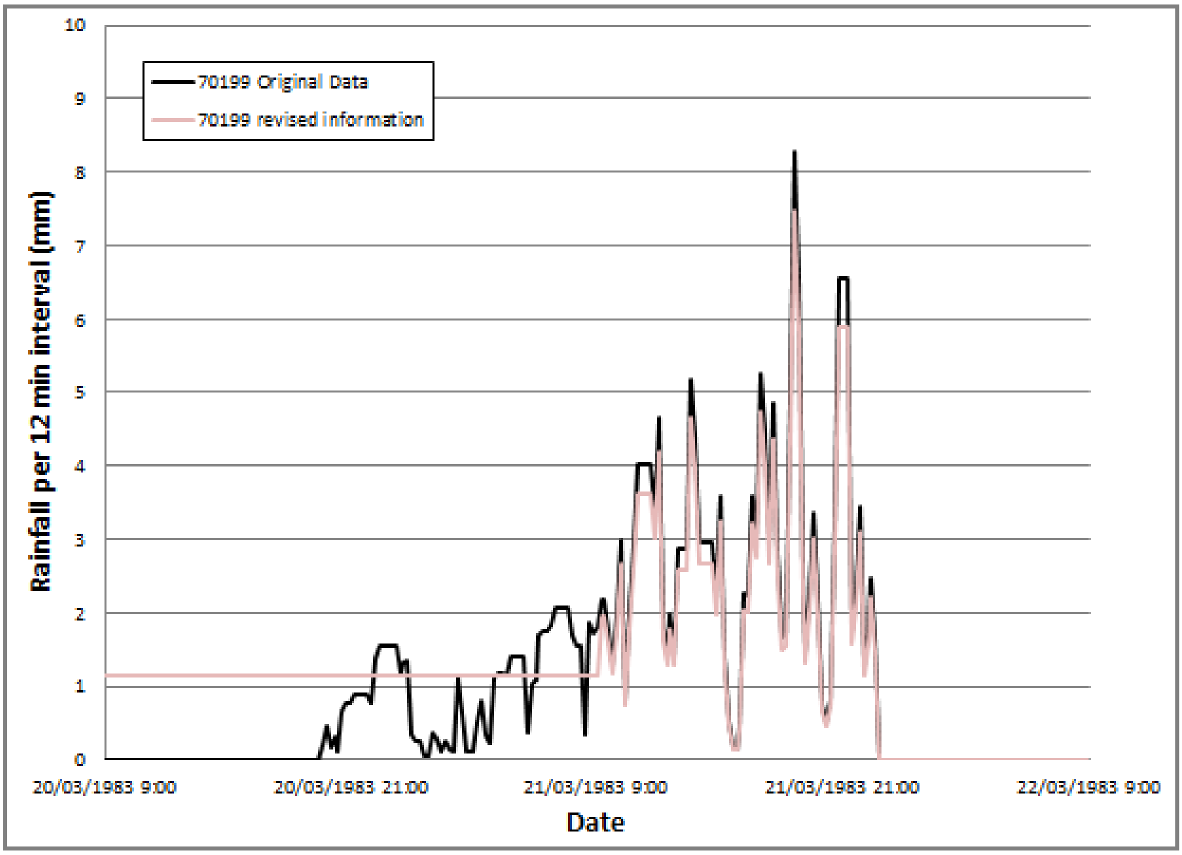
- The rainfall totals had to be adjusted using the mean value of rainfall over the catchment for each day, and adjusting the rainfall from pluviograph records at Numeralla. This could be validated as the daily rainfall totals are often better measurements of total rainfall than pluviographs. Numerous daily rainfall stations confirmed behaviour of the storm where more rainfall fell during day 1.
- Three methods were tested, where using an average rainfall intensity for the first day and prorating the totals for the second day provided the closest match in results. Later calibration results indicated that the first day's rainfall is lost from runoff due to a high continuing loss rate.
- Satisfactory results were obtained from the revised temporal pattern, however, although the approach was validated during the calibration process at later stage of the project, the results must be taken with a high degree of caution due to the revised dataset used.

Table 14.2: Revised Rainfall Totals for March 1983 Event

Station	Day 1		Day 2		Total over 2 days
Pluviograph	65.7 mm	(25%)	193.3 mm	(75%)	259.0 mm
Daily readings*	139.7 mm	(45%)	173.9 mm	(55%)	313.6 mm
Revised Temporal Pattern	139.7 mm	(45%)	173.9 mm	(55%)	313.6 mm

* Mean value over catchment

Figure 14.10: Revised Temporal Pattern for March 1983 Event



14.3.3 Flow and Water Level Gauging Data

A search of available continuous streamflow records was undertaken with records obtained from NSW Office of Water's (NOW) latest Pinneena DVD (Ver 10.1). These records included data for all four calibration and validation events. Streamflow records were available for the locations along the four main tributaries. These tributaries included Brogo River situated north of Bega, Bemboka River located west of Bega, Candelo Creek passing through the township of Candelo, and Tantawangalo Creek, a relatively large tributary arriving from the south-western part of the catchment. No streamflow records were available further downstream near Bega or at the outlet to the ocean.

Table 14.3: Availability of Data at Adopted Streamflow Gauging Stations

Station	Feb 1971	Mar 2011	Mar 1983	Feb 2010
Brogo River @ North Brogo (Station 219013)	Yes	Yes	No	Yes
Brogo River @ Angledale (Station 219025)	No	Yes	Yes	Yes
Tantawangalo Creek @ Kameruka (Station 219019)	Yes	No	No	No
Tantawangalo Creek @ Candelo Dam Site (Station 219022)	No	Yes	Yes	Yes
Candelo Creek (Station 219034/219014)	Yes	Yes	No	Yes
Bemboka @ Morans Crossing (Station 219003)	Yes	Yes	Yes	Yes
Bemboka River @ Bemboka (Station 219021)	Yes	No	No	No
Double Creek Near Brogo (Station 219017)	Yes	Yes	Yes	Yes
Bega River @ Kanoona (Station 219032)	No	Yes	No	Yes
Bega River @ Warraguburra (Station 219026) – n/a	-	-	-	-
Bega River @ Bega	No	No	No	No

Although no streamflow records were available between Bega and Mogareeka, two water level recording sites were confirmed to have data available for the historic events. The station near the ocean outlet is operated by OEH with data supplied by Manly Hydraulics Laboratory (Station 219410) while the other recording site is located upstream of the Brogo-Bega River confluence and is operated by NSW Office of Water (Station 219900).

Table 14.4: Water Level Recording Stations

Station	Feb 1971	Mar 2011	Mar 1983	Feb 2010
Bega River @ Bega (North Bye) (Station 219900)	No	Yes	No	Yes
Bega River @ Mogareeka Inlet (Station 219410)	No	Yes	No	Yes

The continuous water level records from these data sets indicate that the Station 219900 measured a peak depth of 8.47m during the March 2011 and 6.84m during the February 2010. No continuous water level records were available from either station for the Feb 1971 or Mar 1983 events however gauge values of 9.78m and 6.5m were recorded at St 219900 for these two events respectively, (and assumed to be the peak water levels for each event).

At Brogo and Cochrane Dams water level data was available for the following:

Table 14.5: Water Level Recording Stations - Dam Sites

Station	Feb 1971	Mar 2011	Mar 1983	Feb 2010
Brogo Dam	No	Yes	Yes	Yes
Cochrane Dam	No	Yes	No	Yes

14.3.4 Reliability of Gauged Rating Curves

A further investigation of observed hydrographs was undertaken to test the reliability of gauged readings and degree of extrapolation in the rating curves. Data was obtained from the Pinneena DVD that indicated the highest gauged flow at a site from available records. The difference between this reading and the largest derived flowrate indicates the degree of extrapolation from the rating curve and may indicate a level of confidence in the observed hydrographs against which the results from XP-RAFTS model were calibrated.

Table 14.6: Rating Curve Extrapolation

Station No.	Peak Gauged Flow used to develop rating curve (m^3/s)	No. Gaugings used to develop rating curve	Peak Flowrate applied from rating curve (m^3/s)				Station Name
			Feb 1971	Mar 2011	Mar 1983	Feb 2010	
219013	433	354	1643	1182	n/a	882	Brogo River @ North Brogo
219025	878	348	n/a	1556	1087	1429	Brogo River @ Angledale
219019	37	155	1548	n/a	n/a	n/a	Tantawangalo Creek @ Kameruka
219022	70	272	n/a	789	360	31	Tantawangalo Creek @ Candelo Dam Site
219034	16	55	n/a	250	n/a	43	Candelo Creek @ Greenmount Rd (Yurammie No 4)
219014	368	167	374	n/a	n/a	n/a	Candelo Creek at Yurammie No3
219003	190	341	1808	687	653	321	Bemboka @ Morans Crossing
219021	60	187	332	n/a	n/a	n/a	Bemboka River @ Bemboka
219017	159	316	1085	1036	277	646	Double Creek near Brogo
219032	52	115	n/a	2546	n/a	516	Bega River @ Kanoona
219013	433	354	1643	1182	n/a	882	Brogo River @ North Brogo
219025	878	348	n/a	1556	1087	1429	Brogo River @ Angledale

The results indicated that there was a high level of extrapolation used in the observed hydrographs obtained from Pinneena and NOW. As such, despite a significant effort to calibrate flows against observed hydrographs, there is a degree of uncertainty in calibration results, due to potential variations in the rating curve.

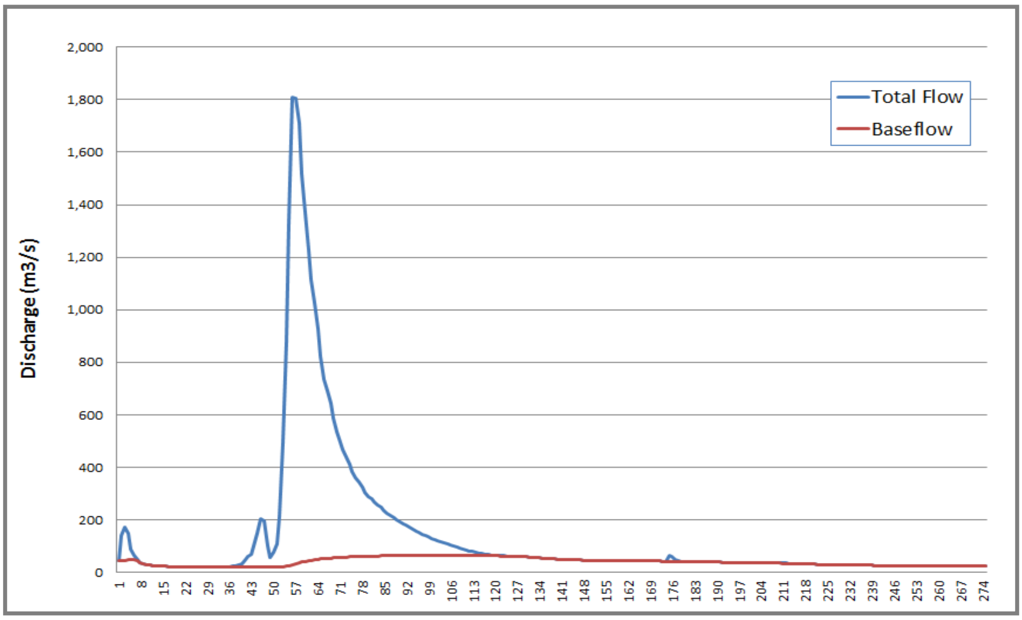
The NOW was contacted for additional information on the development of rating curves from Pinneena. NOW indicated that various methods were used to extend rating curves in the absence of high gaugings. Some methods include using Manning's, Steven, Log and the best fit to gaugings taken for extending rating tables. As opportunities to undertake higher gaugings occur, efforts may be made to carry out further gaugings and improve the quality of rating curves. The NOW indicated that wherever rating tables are extended beyond gaugings they are identified as low quality until confirmed by more reliable gaugings.

14.3.5 Separation of Baseflow

Before calibrating the hydrologic model against observed flows, the total flow measured at each gauge was separated into "quickflow" and "baseflow" components. The baseflow component is a measure of the contribution of streamflow from groundwater and is separated from the runoff generated from direct rainfall. The calibration of the hydrologic model against observed recordings was performed against the quickflow component of the total hydrograph. The method of separating the baseflow and quickflow components from the total flows was undertaken using the Chapman and Maxwell method as outlined in Grayson, Argent, et al., 2004.

An example of the separation of baseflow from the total observed hydrograph is shown in Figure 14.11 below.

Figure 14.11: Example of Separation of Baseflow from Total Observed Flow (Feb 1971 Flood Event, Station 219003)



Upon completion of the calibration, the design event baseflows were added to the quickflows, to provide total hydrographs for input into the hydraulic model. Procedures from the Stage 2 Australian Rainfall and Runoff Report – 2011 were used for estimating the design event baseflow components.

14.3.6 Modelling of Brogo Dam

The first flood passed by Brogo dam was on the 5th March 1976 indicating that the dam was constructed after 1971 and that the February 1971 flood past through the site when no dam existed. Therefore Brogo Dam was not incorporated into the hydrologic model for the February 1971 event. For the March 1983, February 2010 and March 2011 events Brogo Dam was in-place and incorporated into the hydrologic model. Initial water levels were obtained from gauged readings.

14.3.7 Modelling of Cochrane Dam

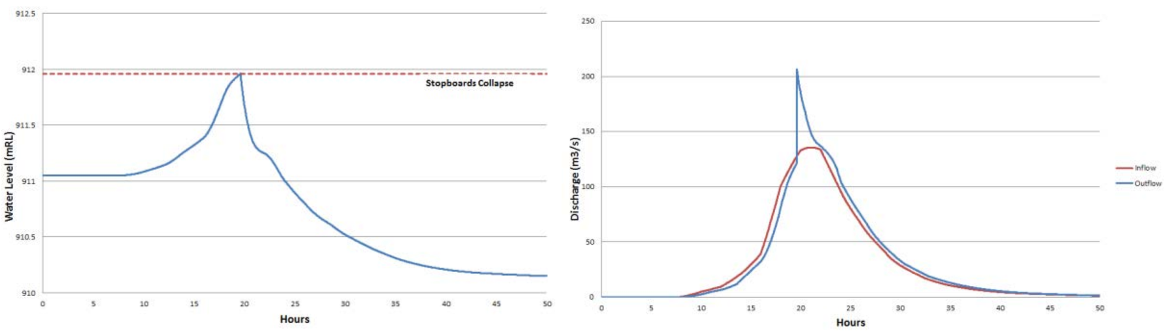
Cochrane Dam was constructed in 1958 and was in-place for all four historic events used in the calibration. Continuous water level data was available from NOW's Pinneena DVD for the March 2011 and February 2010 events, and only single monthly point data was available for March 1983. These water levels compared to the spillway rating curve indicated that the spillway did not release flows for these flood events. Although no water level data was available for the February 1971 event, anecdotal information was available indicating that the dam spilled in February 1971.

The method employed during the calibration for the March 2011, March 1983 and February 2010 events was to exclude the subarea leading to Cochrane Dam. In this way the spillway and flow releases would not add to the flows to Bega River as indicated by the Cochrane Dam gauged water levels. Where spillway releases were likely as in the case of February 1971, the dam was incorporated. The initial February 1971 storage level was assumed at 75% Full Supply Level (FSL) at a level of 907.7 mRL.

The Cochrane dam operates under two spillway rating curve regimes, depending on the water level and whether the stopboards at the top of the spillway have collapsed or not. The following flood behaviour is based on the assessment of the spillway discharge curve for Cochrane Dam, provided by Eraring Energy (refer to Appendix A).

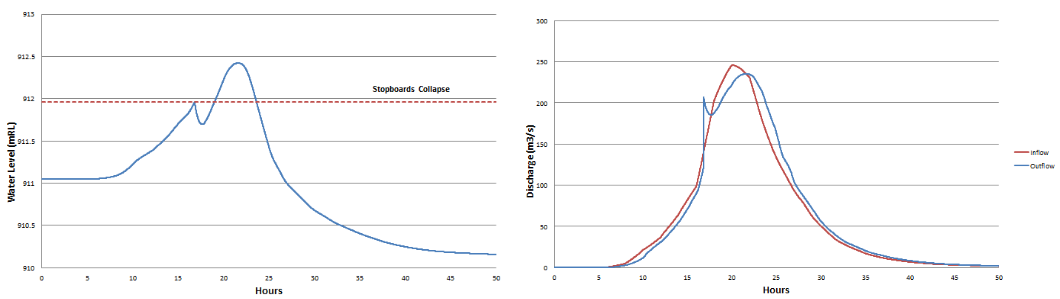
- According to the stage-discharge curve, the dam begins releasing flows at the top of the stopboards that are situated on top of the spillway, at a level of 2989 ft RL (911.05mRL).
- Above the stopboards, the spillway begins to be engaged with flows overtopping the spillway and being released to the Bemboka River.
- With water at a level of 2992 ft RL (911.96 mRL) the stopboards break and spillway invert level is lowered to the top of the concrete weir at 2986 ft RL (910.13 mRL). Due to the stopboards collapsing, the head changes from 3ft (0.914m) above the stopboard to 6ft (1.829) above the top of the concrete weir.
- If the water level does not get high enough to cause the stopboards to collapse then the stopboards are assumed to remain intact and the rating curve drops to a lower level without affecting the stopboards.
- If the stopboards do collapse then the outgoing discharge curve suddenly increases and there is a chance that the peak outflow is greater than the peak inflow associated with the hydrographs. A plot of this behavior under the 10%AEP flood event is shown in Figure 14.12.
- Similar behaviour to this occurs during dam-break conditions but to a much larger extent, as the capacity of the spillway increases as a result of the breach.

Figure 14.12: Effect of Stopboard Collapse at Cochrane Dam 10%AEP 36 hour flood event



Under the 1%AEP flood event the impact of the stopboards on flooding is much less pronounced with the stopboard collapse producing a relatively minor impact on the flood behavior (refer Figure 14.13).

Figure 14.13: Effect of Stopboard Collapse at Cochrane Dam 1%AEP 36 hour flood event



The simulation of the February 1971 event considered the stopboards but the results from the simulation indicated that the stopboards would not have collapsed in passing the February 1971 flood. The peak simulated water level at the dam reached 911.87 mRL which is less than the level of 2992 ft RL (911.96 mRL) needed to produce a collapse of the stopboards.

14.4 Hydrologic Model Calibration Summary

Three events were used to calibrate the hydrological (XP-RAFTS) model for subsequent input into XP-SWMM2D, with an additional event used in the validation run. The calibration of the hydrologic model generally provided a close match of hydrographs for all storm events selected for assessment. However for the February 1971 and March 1983 events there was an absence of sufficient pluviograph data required to accurately describe rainfall temporal distribution throughout the catchment. Sources were adopted from outside the catchment, thus to some extent reducing the level of confidence in the model results for these events.

A good pluviographic data coverage is important for determining the temporal variability of rainfall and accounting for orographic impacts. The orographic impacts occur where mountain ranges are located near the upper reaches of the catchment, causing clouds and water vapour to suddenly rise due to the topography of the mountain ranges. The rise in water vapour causes an increased potential of rainfall in the vicinity of the ranges and may significantly vary the temporal distribution of rainfall in that localised area, which is difficult to confirm without the local pluviographic data.

The nearest pluviograph station gauge that could be applied for February 1971 and March 1983 was Numeralla (BoM Station No 70199), situated 30 km outside of the catchment boundary. For the March 2011 event three pluviograph station sites were available within the catchment, while for the February 2010 event four sites were available, all from NOW's Pinneena database. Despite a significant effort to obtain additional continuous records of rainfall from pluviograph stations from organisations such as Public Works, Manly Hydraulics Laboratory (MHL), NSW Office of Water (NOW), State Water, Bureau of Meteorology (BoM), no additional sites were found within the catchment or its close proximity.

A number of flow gauging station sites were used during the calibration to maximise the confidence in the resulting flows and hydrographs. Since the closest flow gauging station was situated upstream of Bega, flows downstream of the gauging stations had a degree of uncertainty in estimating flows. In order to avoid large errors and increase the reliability of the overall calibration, it was necessary to confirm the validity of the hydrological model parameters for the areas downstream of the gauging stations, in line with the results of the calibration of the hydraulic model. This was completed by comparing gauged floodmarks obtained from the community survey with the modelled flood levels. This approach is commonly used when no gauged hydrographs are available in the area of interest and presents an assessment of the joint performance of both the hydrologic and hydraulic model (XPRAFTS and XP-SWMM2D).

The calibration of the hydrographs was an iterative process with model parameters varied in an attempt to optimise the match of flow peak, volume, timing and shape of the rising and falling limb of the hydrographs.

The hydrologic model setup that produced the best match in observed gauged and simulated flows while providing a relatively good match to floodmarks included:

- ***February 1971 event,*** where:
    - Cochrane Dam was included;
    - Brogo Dam was excluded as it was not yet constructed during the passing of the February 1971 event;

- A non-uniform set of roughness coefficients was used in the hydrologic model. This set was applied as constant across all events based on validation by a review of historic aerial photos;
- A non-uniform set of rainfall losses was used;
- Five gauging stations were used to calibrate the event including Station No. 219013, 219003, 219019, 219014, 219021.

- ***March 2011 event,*** where:
  - Cochrane Dam sub-catchment was excluded as the water levels in the dam were not high enough to cause overtopping of the spillway;
  - Brogo Dam was incorporated;
  - A non-uniform set of roughness coefficients was used in the hydrologic model;
  - A non-uniform set of losses was used, losses were calibrated with 35mm IL, 5.0mm/hr CL for gauging stations 219013, 219025, Brogo Dam levels, 219003, 219022, 219034 and 219032;
  - Additional more detailed refinement was undertaken by incorporating Station 219017 and adjusting the losses downstream of gauges to improve the calibration by reducing the errors in modelled flood levels.

- ***March 1983 event,*** where:
  - The five flow gauging stations were used in the March 1983 event including Station No. 219025, Brogo Dam levels, 219003, 219022, and 219017.
  - A relatively small quantity of runoff was observed at the flow gauging stations while a number of daily rainfall stations situated throughout the catchment indicated that a large volume of water had been recorded.
  - The data from pluviograph station (70199) was outside of the catchment and required to be adjusted to remove a bias in rainfall totals over two days (refer Section 14.3.2). Despite a significant effort to obtain a continuous record of rainfall from pluviograph stations from organisations such as Public Works, Manly Hydraulics Laboratory (MHL), NSW Office of Water (NOW), State Water, Bureau of Meteorology (BoM) the closest available station was a BoM pluviograph station (Station 70199) significantly outside of the catchment;
  - Although the rainfall losses were unusually high, the data included several locations with similar characteristics with respect to flow volumes that highlighted relatively large quantities of rainfall and relatively small quantities of runoff confirming large losses.
  - Since an adjustment to the pluviograph readings was used, the reliability of results from the March 1983 event is limited. Although a good match in flows was achieved, the use of the event in the hydraulic modelling was limited to a validation of the model.

- ***February 2010 event.***
  - The February 2010 event was used as a validation event in both the hydrology and hydraulics to test the overall robustness of the XP-RAFTS and XP-SWMM2D model combined.
  - Since the March 1983 event required unusually high losses and required adjustment to the available distant pluviograph data sets, the March 1983 event was not included in the dataset for estimating loss parameters used in the February 2010 event.
  - The February 2010 validation run highlights the large potential for variation of losses within the catchment and the impact that this variation has on flow volumes and peaks.

The resulting losses from the calibration runs are shown in the Figure 14.7. It should be noted that the initial loss was initially trialled at 10mm and adjusted for the February 1971 event. Subsequent runs indicated that an initial loss of 35mm did not need to be varied significantly to achieve satisfactory results with a relatively good time of rise, shape, peak and volume. For the current study varying continuing losses had a more beneficial effect on calibration and matching the hydrographs, while adjusting the initial losses did not produce significant improvements. The results of the calibration and validation showing simulated versus gauged hydrographs are presented in Appendix E.

Table 14.7: Rainfall Losses from Calibration and Validation Runs

Station	February 1971 Calibration Run1		March 2011 Calibration Run2		March 1983 Calibration Run3		February 2010 Validation Runs	
	IL	CL	IL	CL	IL	CL	IL	CL
Brogo River @ North Brogo (Station 219013)	35	5.0	35	5.0	35	7.0	35	5.0
Brogo River @ Angledale (Station 219025)*	35	3.0	35	5.0	35	7.0	35	4.0
Tantawangalo Creek @ Kameruka (Station 219019)**	35	5.0	35	5.0	35	10.0	35	5.0
Tantawangalo Creek @ Candelo Dam Site (Station 219022)	35	5.0	35	5.0	35	10.0	35	5.0
Candelo Creek (Station 219034/219014)	35	3.0	35	5.0	35	10.0	35	4.0
Bemboka @ Morans Crossing (Station 219003)***	35	1.5	35	5.0	35	10.0	35	3.3
Bemboka @ Bemboka (Station 219021)	35	5.0	35	5.0	35	10.0	35	5.0
Double Creek Near Brogo (Station 219017)	35	3.0	35	2.0	35	7.0	35	2.5
Bega River @ Kanoona (Station 219032)	35	3.0	35	5.0	35	10.0	35	4.0
Bega River @ Warraguburra (Station 219026) – n/a	-	-	-	-	-	-	-	-
Other	35	3.0	35	2.0	35	10.0	35	2.5

**downstream of 219013, **downstream of 219022, ***downstream of 219021*

The Manning's roughness coefficients that were obtained from the calibration are shown in Table 14.8. The adoption of these roughness coefficients were validated through the calibration of the hydrologic model, calibration of the hydraulic model against observed floodmarks, inspection of aerial photography, and by comparison with documented roughness coefficients (refer Table 14.9).

Table 14.8: Manning's Roughness Coefficients from Calibration and Validation Runs

Sub-catchments upstream of Station/ Node	Natural/Forested Land	Cleared Land
Brogo River @ North Brogo (Station 219013)	0.200	-
Brogo River @ Angledale (Station 219025)*	0.120	0.060
Tantawangalo Creek @ Kameruka (Station 219019)**	0.150	0.060
Tantawangalo Creek @ Candelo Dam Site (Station 219022)	0.150	0.060
Candelo Creek (Station 219034/219014)	0.100	0.060
Bemboka @ Morans Crossing (Station 219003)	0.100	0.050
Other	0.120	0.060

**downstream of 219013, **downstream of 219022*

Table 14.9: Comparison with Documented Roughnesses

Documented Values HECRAS Manual	Natural/Forested Land	Cleared Land
Scattered Brush-heavy weeds		0.035-0.070
Pasture-no brush-high grass		0.030-0.050
Dense trees-summer-straight	0.110-0.200	
Heavy stand of timber-few down trees- little undergrowth Flow into branches	0.100-0.160	
Range of Values from Calibration and recommended for use in Design Runs (see above)	0.100-0.200	0.050-0.060

Channel routing employed the Muskingum Method where a mean velocity of 2m/s was used to provide an appropriate level of channel routing based on the results of the calibration. The timing of peak flowrates at the upstream and downstream end of individual channels confirmed the appropriateness of 2m/s as a flow velocity.

The February 1971 calibration provided a good match of hydrographs for the entire range of gauging locations including Brogo River, Bemboka River, Tantawangalo Creek, and Candelo Creek. The volume was underestimated at the Brogo River gauge but provided a close match in peak discharge. Volumes were well represented at Bemboka River, Tantawangalo Creek, and Candelo Creek. Peak flows were closely matched at Brogo River, Bemboka River, Tantawangalo Creek, and Candelo Creek. The simulation achieved a good match to the shape of the hydrograph in the rising and falling limb of the hydrographs, indicating that storage parameters such as imperviousness and roughness coefficients were appropriate.

The calibration using the March 2011 event produced relatively good fits to the water level at Brogo Dam, slightly overestimated the peak at Bemboka River at Morans Crossing (St 219003), but provided a close match in the lower reaches of the same river at Kanoona (St 219032),. A good fit was provided to the hydrographs at Brogo River, Tantawangalo Creek and Candelo Creek. During the March 2011 event the gauge on Brogo River at Angledale did not record the flowrate for a significant part of the hydrograph including the peak flow, therefore it was difficult to confirm the accuracy of the hydrographs at this gauge. An additional gauge along the Brogo River, situated upstream of Angledale, was compared that provided a close match in volume and peak flow.

The March 1983 hydrologic calibration produced a good match of volumes, peak flows, shape of the hydrographs and timing of peaks for the entire range of locations, including water levels at Brogo Dam, and flows at Brogo River, Bemboka River, Tantawangalo Creek and Double Creek.

The February 2010 event was used to validate the hydrologic model. The validation run applied the mean value of losses, developed from the two hydrologic calibration events (February 1971, March 2011). All other parameters unchanged other than the temporal and spatial pattern of rainfall applicable for the February 2010 event.

The validation run 3A (refer to Appendix E) did simulate storage effects satisfactorily. The shape of the hydrographs and the rising and falling limbs of the hydrograph were in good agreement. There was, however an irregularity noted in peak flow estimation, with overestimates and underestimates of flows in various parts of the catchment. Flows were underestimated at Brogo River, Brogo Dam, and Candelo Creek and overestimated at Bemboka/Bega River and Tantawangalo Creek. A close match resulted at Double Creek.

Two further validation runs were undertaken whereby the continuing losses were set uniformly at 3mm/hour and 5mm/hour for runs 3B and 3C respectively to provide a wider range of expected rainfall losses. These additional runs still highlighted significant differences between observed and simulated hydrographs.

The validation in run 3B, showed reasonably good results near the downstream end of Brogo River (St 219025). This validation was also in close agreement to the peak water level at Brogo Dam and in close agreement with the gauged hydrograph at Candelo Creek (Station 219034). Downstream of Brogo Dam, between the dam and Station 219025, the simulated hydrograph underestimated the peak water levels and flow volumes at Station 219013. At Bemboka River (Station 219003) and Tantawangalo Creek (Station 219022) flows were again overestimated. The validation based on a continuing loss of 5mm/hour (Run 3C) showed improvements to the gauges at Bemboka River and Tantawangalo Creek by reducing overestimation but produced underestimates of flows for the other stations. This may indicate that in the areas of Brogo River and Candelo Creek the losses used for the February 2010 event (derived from the calibration runs) might have been overestimated in comparison to the real event losses. As previously stated the losses can vary between events and also spatially, varying between different areas of the catchment as a result of localised pre-bursts leading into the main event.

Further improvements could only be made to the February 2010 event results by changing the spatial distribution of losses in this scenario. If the February 2010 event was used as a calibration event this approach may be appropriate, but since this event was used as a validation event to test the robustness of the model, the losses have been based on the previously calibrated events. Of importance for validation is that the shape of hydrographs is very similar to the shape of the recorded hydrographs, which indicates that for adjusted losses the hydrographs would be matching more closely.

It was concluded that the hydrologic model with the modelling parameters established in the process of calibration, was a good representation of the catchment and the hydrologic processes within it, and as such could be used for estimation of design floods with a reasonably high level of confidence. Further truthing of the model performance was carried out as part of hydraulic model calibration to confirm that the modelled flowrates accurately reproduced observed flood levels during historic events.

14.5 Adoption of Hydrologic Model Parameters for Design Events

14.5.1 Rainfall Loss Parameters

To help determine appropriate design losses for use in modelling design storms two sets of losses were run through the XP-RAFTS model including cases with and without aerial reduction factors.

The peak flowrates were compared to the flood frequency curves at three stations, namely:

- BROGO RIVER AT ANGLEDALE (Station 219025);
- TANTAWANGALO CREEK AT CANDELO DAM SITE (Station 209022); and
- BEMBOKA RIVER AT MORANS CROSSING (Station 219003).

The rating curve from Pinneena developed for the Brogo River gauge included 36 gaugings, while the Tantawangalo Creek rating curve used 40 gaugings, and the Bemboka River rating curve used 69 gaugings.

The first set of losses applied an initial loss of 10mm and continuing loss of 2.5mm/hr uniformly throughout the catchment (based on Table 3.2 AR&R), and the second set of losses applied an initial loss of 10mm and mean value for the continuing loss (AR&R) based on the February 1971 and Mar 2011 events. The design peak flowrates were compared to the flood frequency curves from the annual series flood frequency analyses with the following results:

- Based on Station 219025, the best fit to the flood frequency curve was obtained when applying the mean value of continuing losses (from the current study's calibration) in conjunction with an aerial reduction factor.
- Based on Station 219022, the fitted curve overestimated the peak flows compared to the plotting positions, and again the case with the mean value of continuing losses (from the current study's calibration) in conjunction with an aerial reduction factor provided the best fit to the frequency curve; and
- Based on Station 219003, all sets of losses overestimated flows more than at other two stations.

Figure 14.14: Flood Frequency Curve - Station 219025 Brogo River

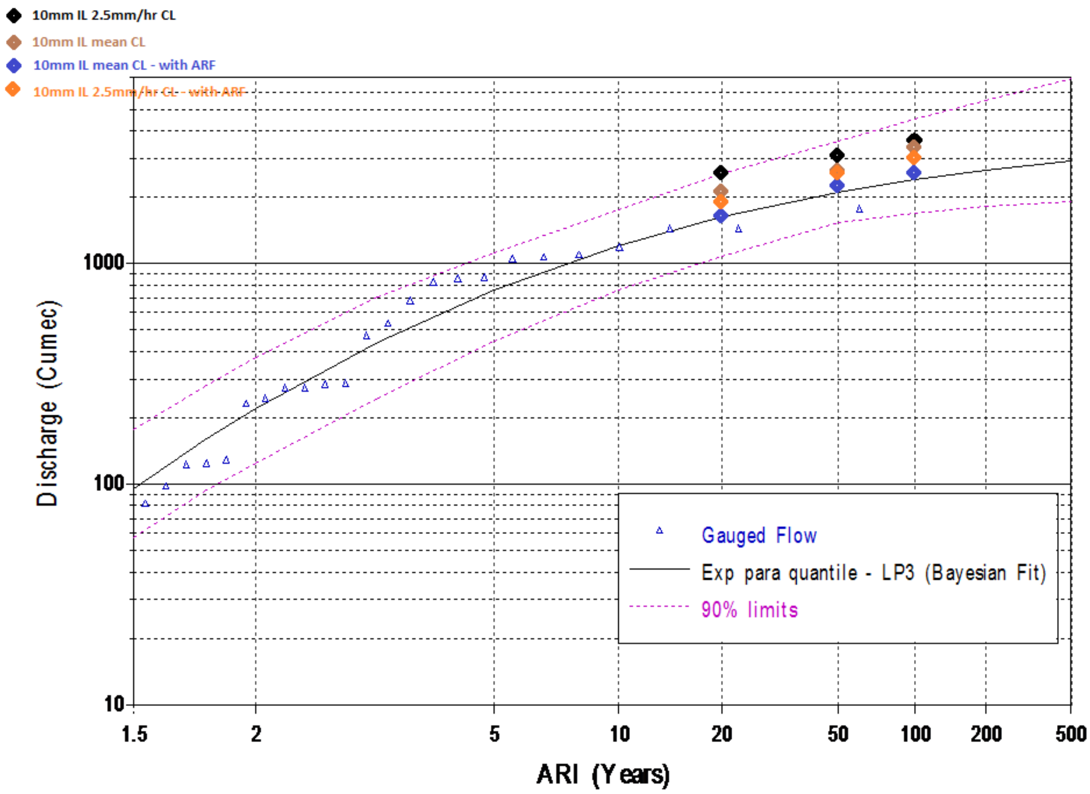


Figure 14:15: Flood Frequency Curve - Station 219022 Tantawangalo Creek

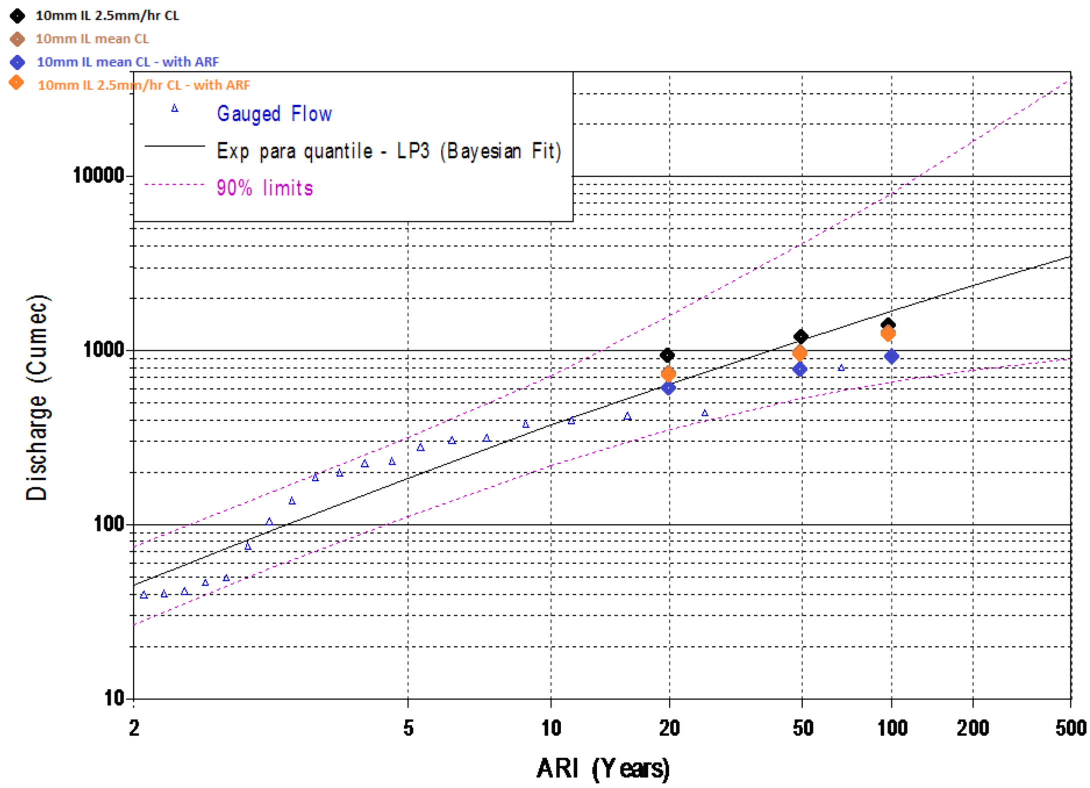
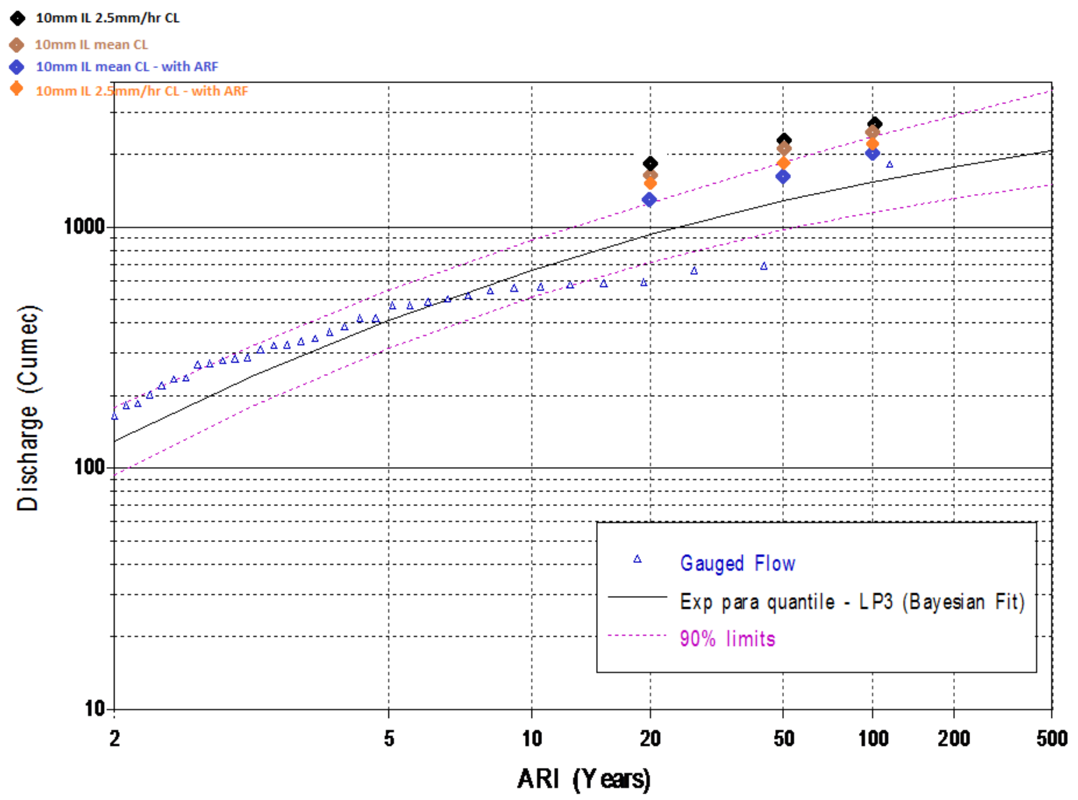


Figure 14:16: Flood Frequency Curve - Station 219003 Bemboka/ Bega River

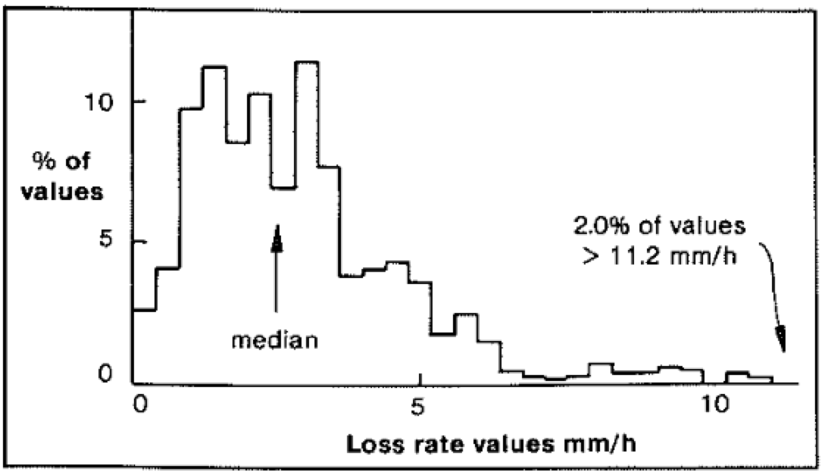


Based on the above analysis, some variation in results may occur from the flood frequency analyses, depending on which set of loss factors is applied, while the application of aerial reduction factors improved results for both sets of losses. A value of 10mm is recommended for initial loss in line with recommendations of AR&R, Table 3.2 as a lower range (more conservative) value. The testing of the model sensitivity to changes of the initial loss in the range recommended by AR&R (10-35mm) has confirmed that the difference for the 36hr storm duration (critical for the catchment) is minor.

The continuing losses used in the two abovementioned methods are based on recommendations in AR&R. This indicates that initial losses derived from historic events are not necessarily applicable to design events, while median value of continuing losses derived from historic events are likely to be more appropriate for use in modelling design events. The first set off losses (using 2.5mm/hr) is from a larger dataset base for application at locations in NSW east of the western slopes –, while the second set of losses was taken as mean values from the current study's calibration that vary spatially throughout the catchment and is more site specific.

After consultation with Council and OEH representatives, for the purpose of this study the uniform approach with 2.5mm/hr continuing loss was adopted for application in modelling the design events. This approach provided an acceptable level of conservatism compared to the mean loss values derived from calibration. As a comparison, AR&R provides a chart (shown in Figure 14.17) indicating the variation in continuing loss rates from across Australia, where loss rates vary from 0mm/hr to over 11mm/hr. The chart also indicates the potential distribution and where a median value (approx. 2.5mm/hr) may be positioned.

Figure 14:17: Frequency Distribution of Individual Loss Rates from Values Across Australia (Source AR&R)



Accordingly, the initial loss value of 10mm was adopted as a lower, more conservative, limit of the design range recommended by AR&R (10-35mm). Although the calibration yielded the higher initial loss figure (i.e. 35mm), testing confirmed that this difference does not have impact on larger events, however the lower initial loss may result in more conservative, higher flows and water levels in more frequent flood events.

Table 14.10: Recommended Rainfall Loss Parameters for use in Design Events up to 1%AEP Event

Parameter	Recommended Design Value	Basis for Recommendation
Initial Rainfall Loss	10mm	The lower (conservative) limit of the range (10-35mm) recommended by AR&R, Book 2, Table 3.2
Continuous Rainfall Loss	2.5 mm/hr	Value recommended by AR&R, Book 2, Table 3.2 and in agreement with (but slightly more conservative than) the mean loss value obtained in calibration for major storm events
Design Aerial Reduction Factors	XP-RAFTS methods Varies with ARI and storm duration	ARF's from AR&R Book 2 Sect 1.7 Conversion of point rainfall to aerial rainfall

The parameters for estimation of the Probable Maximum Flood (PMF), were calculated using procedures in AR&R with an initial loss of 0mm and continuing loss of 1.0mm/hr. The Probable Maximum Flood is defined as the limiting value of flood that could reasonably be expected to occur. In this case the PMF has been computed as the Probable Maximum Precipitation Defined Flood (PMPDF) i.e. using smoothed temporal patterns from the BoM's GSDM and GSAM approaches. The losses for the 0.2%AEP have been interpolated between the 1%AEP and PMF events as recommended in AR&R99.

14.5.2 Adopted Basic Model Parameters

Basis model parameters recommended for adoption in the design flood events are shown in Table 14.11 below.

Table 14:11: Recommended Basic Model Parameters

Parameter	Recommended Design Value	Basis for Recommendation
Imperviousness	Spatially variable	Imperviousness ratio based on Land Use Categories (draft LEP 2012)
Baseflow Separation	Time variable	As per AR&R using techniques in revised AR&R Stage 2 report on Baseflow. Baseflow to be added to quickflow for running of design storms in XP-SWMM2D
Modelling Brogo Dam	Initial Level at FSL (102.60mAHD)	The higher (conservative) starting level of the spillway level
Modelling Cochrane Dam	Initial Level at Spillway crest (911.05mRL)/ Stopboard incorporated	The higher (conservative) starting level of the spillway level
Catchment wide Storage Multiplier, Bx	Bx = 1	As per results of calibration of hydrologic model
Roughness Coefficient	See below	As per results of calibration of hydrologic model
Channel routing	Muskingum Method 2m/s	As per results of calibration of hydrologic model

14.5.3 Adopted Hydrologic Roughness Coefficients

The roughness coefficients developed during the modelling of historic events were recommended and adopted in the modelling of design flood events.

Table 14.12: Manning's Roughness Coefficients for Modelling of Design Events

Sub-catchments upstream of Station/ Node	Natural/Forested Land	Cleared Land
Brogo River @ North Brogo (St 219013)	0.200	-
Brogo River @ Angledale (St 219025)*	0.120	0.060
Tantawangalo Creek @ Kameruka (St 219019)**	0.150	0.060
Tantawangalo Creek @ Candelo Dam Site (St 219022)	0.150	0.060
Candelo Creek (St 219034/219014)	0.100	0.060
Bemboka @ Morans Crossing (St 219003)	0.100	0.050
Other	0.120	0.060

**downstream of 219013, **downstream of 219022*

14.6 Hydraulic Model Calibration and Validation

14.6.1 Model Establishment

The two historic events used to calibrate the hydraulic model included the February 1971 and March 2011 events. The hydraulic model in XP-SWMM2D included two basic setups, depending on the event being modelled to reflect historic changes.

The Princes Highway bridge crossing over the Bega River was originally a relatively small timber truss bridge and was associated with the February 1971 event. The March 2011, March 1983 and February 2010 events incorporated the current geometry at Princes Highway with an upgraded large span bridge that is currently in use today.

Near Mogareeka, the Tathra-Bermagui bridge over Bega River was severely damaged during the February 1971 event with 9 out of the 15 spans being washed away by the flood. For the other events the Tathra-Bermagui bridge over Bega River was modelled as per the present day rebuilt conditions.

Other differences between events included changes to cross sections at bridges, blockages at bridges, changes to the roughness coefficients along Bega River from variations in vegetation and debris, changes to ground levels near the outlet and changes to the initial water levels based on observed readings.

As part of the model establishment, cross-sections were obtained from the ground/bathymetric survey undertaken during the course of the current study. In the downstream reaches of the Bega River, sections were interpolated between the surveyed locations, and adjusted to match the width of the channel as indicated by LIDAR data. In the upstream reaches of the river, LIDAR was used for extraction of modelling cross sections as it showed a good match with the surveyed sections.

14.6.2 Approach

In order to calibrate/validate the hydraulic model performance, an iterative process was undertaken, during which the model was modified to represent floodplain conditions at the time of the event and provide a reasonable correlation between modelled and observed flood behaviour. Calibration of the hydraulic model used the February 1971 and March 2011 events against floodmarks identified during the community consultation and data collection process. The March 1983 and February 2010 events were used for validation of the model. Initial values for Manning's roughness coefficients used in the calibration were obtained from literature sourced from the HEC-RAS manual and in line with site observations and assessment of the relevant aerial photos (where available). Blockage was represented using an increased roughness coefficient at bridge sites and along the river.

The observed floodmarks were mostly situated near Princes Highway bridge, Tarraganda bridge, Tathra bridge, the Bega township, and Jellat Flats. The surveyed flood levels were assessed, with due consideration of the nature/source of the level and then assigned a level of confidence rating based on the established accuracy or reliability. The low confidence marks were generally associated with floodmarks where a comparison of levels against surrounding floodmarks indicated high variability in observed water levels. Some of these flood levels were rejected because they were considered to not provide a fair or proper representation of the flood level. The rejections were based on a comparison with the adjacent floodmarks of the high level of confidence, or because only approximate depths were quoted without a firm flood level. In some cases flood marks were rejected as they were surveyed to a Reduced Level (RL) and the link to Australian Height Datum (AHD) could not be established. Existing floodmarks outside of the modelling area were not relevant for calibration and as such could not be used.

Ocean tide data for modelled events was obtained from Manly Hydraulic Laboratory (data owned by OEH), where available. The March 2011 event included tide data from Bermagui and Eden. No tide data was available for the February 1971 event and an assumed level of 1mAHD was applied for the tailwater condition. The only data available for the March 1983 event was from Eden (Snug Cover) where the original dataset did not include metadata defining the datum as the original source of the data is unknown. For the March 1983 event a datum shift of -0.924m was applied based on the local datum currently in use (Twofold Bay Hydro Datum). The application of this assumption could not be confirmed without the metadata reference.

Near the outlet at Mogareeka the XP-SWMM2D model was adjusted during the calibration by lowering the invert of the channel (sandbar) to a level that drains away flow by matching historic flood mark information near Tathra Bridge, for each historic event.

For the February 1971 calibration, surface roughnesses had to be slightly adjusted from the initial values to obtain a good match between the observed and modelled water levels throughout. Initial runs for the March 2011 event underestimated flood levels using the initial flowrates and February 1971 roughness coefficients. A better March 2011 calibration was achieved by including more detail into the hydrologic model (adding an additional flow gauge at Double Creek) and by adjusting the rainfall losses downstream of the flow gauging stations to better match the historic floodmarks. Additional blockage was applied to both the Bega River and Anabranch bridges at Tarraganda Lane and the roughnesses were increased along the main Bega River channel upstream of Tarraganda Lane, to allow for trees and debris. Anecdotal evidence including photos of debris at Tarraganda Lane after the March 2011 event indicates that a significant amount of debris was identified at Tarraganda Lane Bridges confirming the validity of the modelling approach employed.

Figure 14.18: March 2011 Event Flood Debris Tarraganda Lane, (Source BWSC)

An inspection of aerial photography from the 1980 orthophoto indicated that the old timber bridge across Bega River that existed in 1971 had been replaced by the current Princes Highway Bridge about 200m upstream of the old site. In addition, the Tathra bridge that had been partially washed away in 1971 was rebuilt. Hence, for the March 1983 event the configuration with the larger Princes Highway Bridge and rebuilt Tathra bridge from the March 2011 model was used being more appropriate for application.

The model for the March 1983 event also applied the March 2011 roughnesses trialled using the calibrated February 1971 and March 2011 events. It was found that the roughnesses from the February 1971 were more appropriate for use in March 1983 model with closer matching of floodmark data as a calibration/validation run.

Variations between the roughnesses used in the model setups (from the two calibration events) can be attributed to changes in the growth, transport and collection of vegetation and debris along channels and at bridges.

14.6.3 Results

Results of the calibration and validation runs are presented in Figures 14.19-14.22 and Tables 14.13-14.16 below.

February 1971 Event

The February 1971 event included 26 floodmarks with survey data, of which 14 were of high confidence, 4 of medium confidence, and 2 of low confidence while 6 were disregarded due to low reliability. The difference between observed and simulated water levels for all high confidence February 1971 floodmarks ranged from -0.17m to 0.18m with an average of -0.04m. This indicated a very close match with observed flood behaviour. Selective sites with February 1971 results include:

- The Bega River (North Bye) flood gauge: +0.01m difference;
- 274 Carp Street, Bega:-0.17m difference;
- 5 Canning Street, Bega:-0.12m difference;
- East end Tarraganda Bridge:-0.08m difference;
- Warragaburra flood gauge:-0.07m difference;
- Jellat Jellat Flats:-0.03m difference; and
- North End Tathra Bridge:-0.03m difference;

The four additional high confidence floodmarks were sourced from Council documents relevant to the February 1971 and assessed after the initial calibration of the hydraulic mode, resulting in a final average difference between observed and simulated levels of -0.05m.

March 2011 Event

The March 2011 event registered a larger number of readings with 43 floodmarks, where 27 were of high confidence, 3 of medium confidence, 4 of low confidence and 9 disregarded. Levels at Princes Highway bridge matched well along with levels at Tarraganda Lane, Tathra bridge and Jellat Jellat Flats with levels at the Bega township, also providing a reasonable match. For the March 2011 event, the average difference between observed and simulated flood levels was +0.06m. Selective sites with March 2011 results include:

- Upstream of Princes Hwy: : 0.02m difference;
- The Bega River (North Bye) flood gauge: -0.09m difference;
- 130 Upper Street:-0.23m difference;
- Lot 1 Gibbs Street, Bega: -0.16m difference;
- East end Tarraganda Bridge: -0.06m difference;
- Lot 5 Tathra Road, Bega: -0.03m difference;
- Jellat Jellat Flats:+0.12m difference; and
- OEH Bega (Live) flood gauge at Tathra bridge: -0.08m difference;

March 1983 Event

The March 1983 event included 23 surveyed floodmarks of which 4 were of high confidence, 6 were of medium confidence, 3 were of low confidence, and 10 were disregarded (mainly due to an unavailability of AHD level information). The difference between observed and simulated water levels for all medium and high confidence floodmarks ranged from -1.25m to +2.20m with an average of +0.21m. This indicated an overly good match, but a significant variation in some individual results. Selective sites with March 1983 results include:

- The Bega River (North Bye) flood gauge: +0.51m difference;
- Bega STW: +1.07m difference;
- Warragaburra flood gauge: +0.06m difference;
- Daisy Bank: -0.81m difference; and
- Flood Level near Tathra bridge: -1.25m difference.

The March 1983 validation run showed a lower level of matching, compared with the 1971 and 2011 events, with levels generally being underestimated near Tathra Bridge and overestimated near Bega. Of the observed flood levels with high confidence rating, the mark at Tathra Bridge was underestimated by 1.25m. The level upstream of Jellat Jellat Flats was in good agreement with a difference of +0.06m.At Gauging Station 219900 near Princes Highway bridge, there was an overestimate of +0.51m.

An additional nine floodmarks relevant for the March 1983 event were later sourced from Council's documents with model results showing some level of overestimation at most of these sites. Including the additional floodmarks, the analysis produced an average difference from all medium to high confidence floodmarks of +0.49m. At Jellat Jellat Flats levels were overestimated near the Jellat Jellat Weir by 1.84m and by 2.2m further upstream indicating conservatively high flood estimates.

The March 1983 results highlight the potential variation in rainfall behaviour within the catchment (which could not be confirmed due to the absence of pluviograph stations within the catchment boundaries) and consequent variation in hydraulic results governing flood levels. Local changes in surface roughness and debris load could also have a significant impact on the results and, considering that this event was of lower magnitude than the February 1971 or March 2011 event, be much more susceptible to change to these conditions. The observed irregularity of differences between the levels (i.e. absence of either uniform under or over estimation) confirms that this could be a potential reason for the observed localised variations.

Although the modelling of the March 1983 event is subject to some uncertainty due to lack of pluviograph data, the information used resulted in a reasonably close match in average simulated and gauge levels for a validation event.

February 2010 Event

The February 2010 event included 10 floodmarks of which 3 were of high confidence, 3 were of medium confidence, and 4 were disregarded. The difference between observed and simulated water levels for all high confidence February 2010 floodmarks ranged from -0.87m to 0.29m with an average of -0.33m indicating a relatively good match with observed flood behaviour for the validation run. At the two sites with the highest confidence of observed data i.e. the two gauging stations (219900 and 219410) the results were within 0.5m difference which is considered to be a reasonable fit for a validation run. However, given that only three high confidence flood marks were available, the deviation in results (sometimes quoted as standard deviation or variance) is likely to be high. Selective sites with February 2010 results include:

- Gillcrest Rd, Buckajo (the upstream end of the model): : -0.87m difference;
- The Bega River (North Bye) flood gauge: +0.29m difference;
- Stafford Dr Kalaru: +1.29m difference; and
- OEH Bega (Live) flood gauge at Tathra bridge: -0.40m difference;

Candelo Locality

For the isolated Candelo locality only one relevant floodmark was available for calibrating the XP-SWMM model. This floodmark was from the February 1971 event, while no floodmarks were available for either of the other historic events used for modelling.

An additional floodmark was initially noted as relevant for the March 2011 event but after contacting the resident for more information this floodmark was confirmed to relate to local flooding, and was therefore disregarded in calibrating the hydraulic model which related to mainstream flooding of Candelo Creek.

The February 1971 calibration for the Candelo Creek model achieved a close match with a difference of +0.01m between simulated and observed flood levels. Since no validation could be carried out using the modelled historic events the use of the Candelo Creek model for design flood events would be heavily dependent on the modelling parameters for the February 1971 flood event.

Figure 14.19: February 1971 Event - Flood Map with Locations of Floodmarks

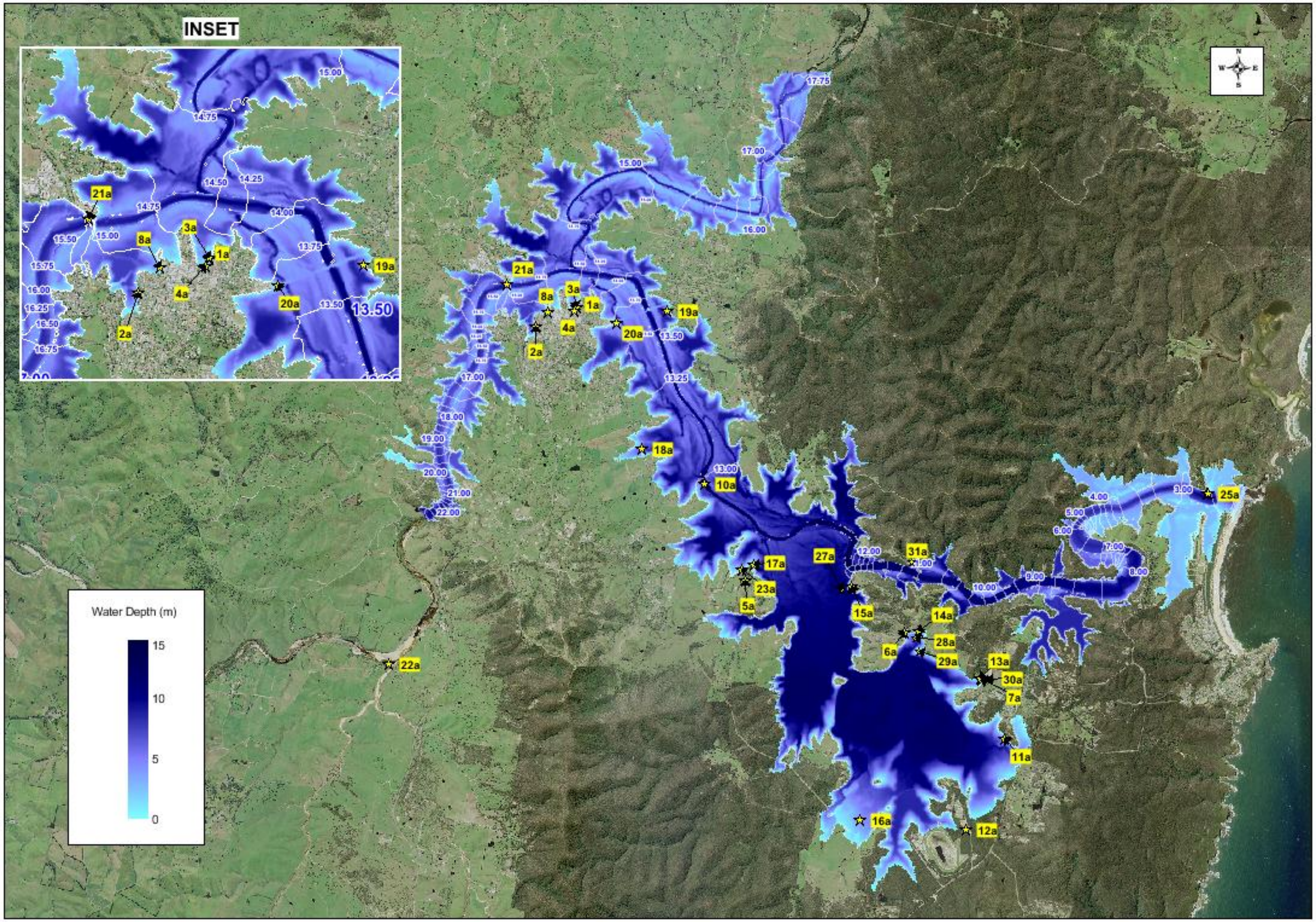


Table 14.13a: Calibration Results – February 1971 Event

Flood Mark ID	Floodmark Description	Confidence Rating	Observed Level (mAHD)	Modelled Level (mAHD)	Difference (m)
1a	Lot 1 Canning St BEGA	High	14.59	14.50	-0.09
2a	130 Upper St BEGA	Low/ Disregarded No level	-9999	15.05	-9999
3a	5 Canning St BEGA (mark on wall)	High	14.62	14.50	-0.12
4a	19 Canning St BEGA	Low/ Disregarded No level	-9999	14.50	-9999
5a	1116 Tathra Rd Jellat Jellat	Low/ Disregarded No level	-9999	12.84	-9999
6a	20 Ike Game Rd Kalaru	Low/ Disregarded No level	-9999	12.84	-9999
7a	564 Tathra Rd Kalaru (concrete block marker)	High	12.93	12.84	-0.09
8a	274 Carp St BEGA	High	15.23	15.05	-0.17
9a	21 Sharpe St Candelo (over window sills)	Medium (outside Bega Flood model, part of Candelo Creek Model)	100.90	100.91	+0.01
10a	Bega River at WAR&Ragaburra Gauging Station No. 219026	Medium	13.06	12.99	-0.07
11a	North end Wallagoot Rd nr Armstrong's N.bdy	High	12.87	12.84	-0.03
12a	South end Wallagoot Rd nr Armstrong's S.bdy	Medium	12.87	12.84	-0.03
13a	Lot Staffords gate (nr Brickworks)	High	12.89	12.84	-0.05
14a	Reg. Taylors W.B Garage Door	High	12.93	12.84	-0.09
15a	Russells Fibro Grage E. end Jellat Flat	High	12.88	12.82	-0.06
16a	Sliprail nr Alf. Watersons cottage at Benookd	Low (Compared to nearby floodmarks)	12.67	12.84	0.17
17a	Jelgowry Homestead	High	12.87	12.84	-0.03
18a	Parberry Creek	Medium	13.20	13.05	-0.15
19a	East end Tarraganda Bridge	High	13.70	13.62	-0.08
20a	Bega Readycut, Tallaganda Rd	HIgh	13.73	13.55	0.18
21a	Gauging Station NSW Office of Water, BEGA (Station No. 219900) (datum at 5.70m)	High	15.48	15.49	0.01
22a	Upstream of Wolumla Creek	Low/ Disregarded (no level, (outside Bega Flood model)	-9999	-9999	-9999
23a	1129 Tathra Rd BEGA	High	12.81	12.84	0.03
24a	North End Hancocks Bridge	High	2.85	2.88	0.03
25a	North End Hancocks Bridge	Low (adjacent floodmark higher)	2.38	2.88	0.50
26a	Bridge in Candelo Creek	Low/Disregarded (out by order of magnitude)	49.29 RL	-9999	-9999

Table 14.13b: Additional Calibration Results – February 1971 Event*

Flood Mark ID	Floodmark Description	Confidence Rating	Observed Level (mAHD)	Modelled Level (mAHD)	Difference (m)
27a	Tathra Road JELLAT JELLAT	High	12.80	12.83	0.03
28a	Tathra Road JELLAT JELLAT	High	12.98	12.84	-0.14
29a	Tathra Road JELLAT JELLAT	Medium	12.70	12.84	0.14
30a	Tathra Road JELLAT JELLAT	High	12.90	12.84	-0.06
31a	Bega River D/S Jellat Jellat Flats	High	11.30	11.13	-0.17

**Floodmarks provided by Council after completion of calibration and additionally assessed*

Figure 14.20: March 2011 Event – Flood Map with Locations of Floodmarks

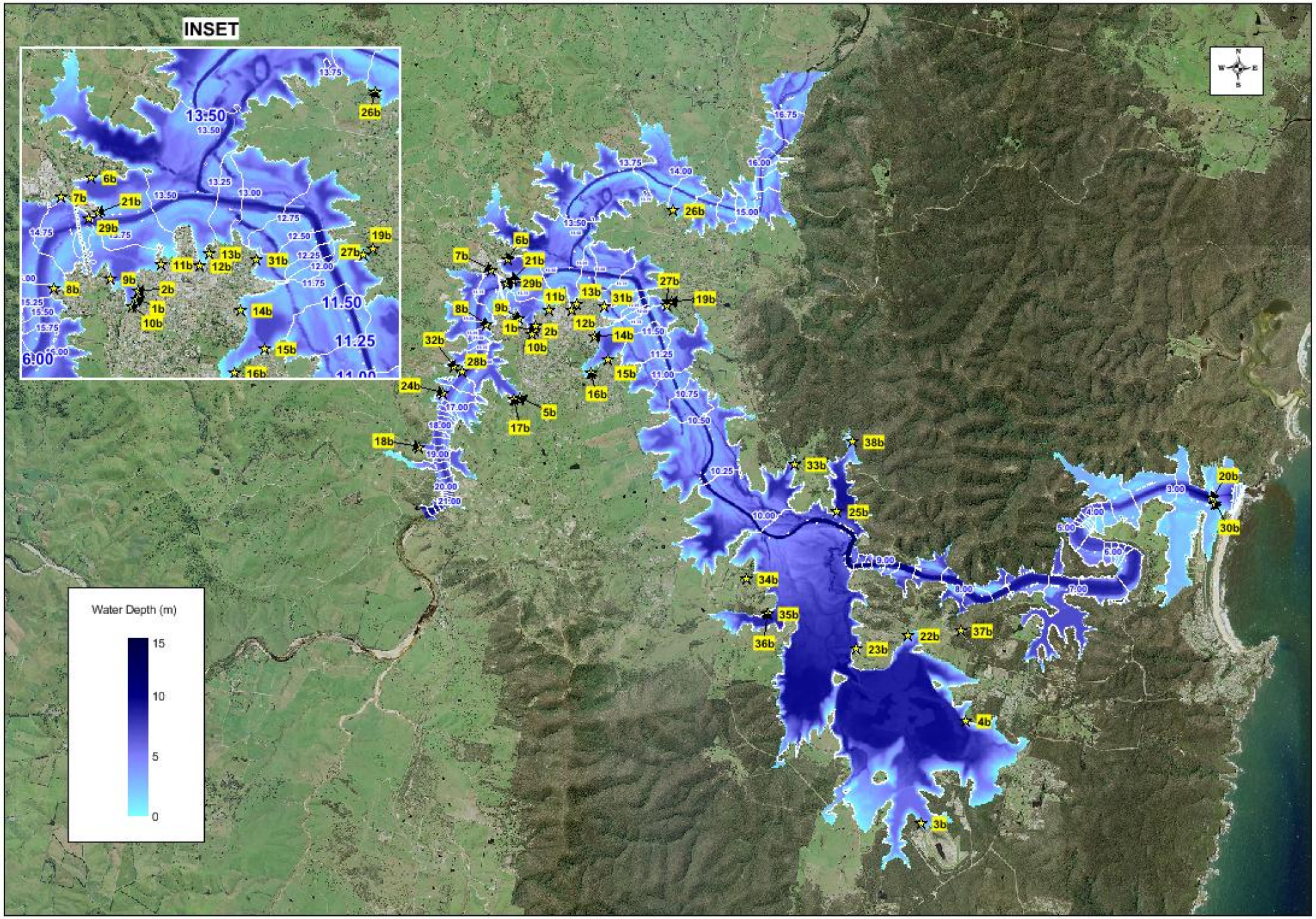


Table 14.14: Calibration Results – March 2011 Event

Flood Mark ID	Floodmark Description	Confidence Rating	Observed Level (mAHD)	Modelled Level (mAHD)	Difference (m)
1b	26 Nelson Street, BEGA (water mark on garage)	High	14.15	13.91	-0.23
2b	130 Upper St, BEGA (water mark brick corner)	High	14.15	13.91	-0.23
3b	1695 Sapphire Coast Dr, KALARU (top electrical box in photo)	High (confirmed by nearby floodmarks – Jellat Flats)	9.82	9.97	0.15
4b	74 Old Wallago Rd, KALARU (at post)	High (confirmed by nearby floodmarks – Jellat Flats)	9.85	9.97	0.12
5b	131 Ravenswood St Bega, (water mark brick corner)	High	16.16	16.10	-0.06
6b	Lot 2 Bridge St BEGA	High	13.83	13.54	-0.29
7b	Lot 23 Buckajo Rd BEGA	High	14.73	14.75	0.02
8b	Lot 1 Angle St BEGA	High	14.75	15.02	0.28
9b	Lot 7 Kirkland Ave BEGA	High	14.09	13.91	-0.18
10b	Lot 10 Nelson St BEGA	High	14.11	13.91	-0.20
11b	Lot 2 Carp St/Princes Hwy	High	14.09	13.92	-0.17
12b	Lot 1 Gipps St BEGA	High	13.43	13.27	-0.16
13b	Lot E Bega St BEGA	High	13.42	13.27	-0.15
14b	Lot 13 Upper St BEGA	High	11.54	11.52	-0.02
15b	Lot 5 Tathra Rd BEGA	High	11.55	11.52	-0.03
16b	Lot 1 East St BEGA	High	11.57	11.52	-0.05
17b	No 7 Charlotte St BEGA	High	16.13	16.10	-0.03
18b	Grosse Creek Rd upstream (approximate location)	Low	17.89	18.97	1.08
19b	Tarraganda Rd TARRAGANDA	High	11.82	11.75	-0.07
20b	Bridge at MOGAREEKA	High	3.07	2.88	-0.19
21b	Lot 2 West St BEGA	High	13.85	13.77	-0.08
22b	20 Ike Game Rd, KALARU (nail in bitumen)	High (confirmed by nearby floodmarks – Jellat Flats)	9.89	9.97	0.09
23b	857 Tathra Rd, KALARU (on dam wall)	Med	9.70	9.97	0.27
24b	Daisy Hill Rd, BUKAJO (top of rock)	High	16.81	16.66	-0.15
25b	PO BOX 185 (at gate in photo)	Med (Lower than downstream levels)	9.66	9.95	0.29
26b	98 Corridgeree Ln, TARRAGANDA (water mark pump shed)	Med	14.22	14.07	-0.15
27b	Tarraganda Lane (nail in footpath)	High (confirmed by level 19b)	11.81	11.75	-0.06
28b	West of Buckajo Road (nail in bitumen)	High	16.09	16.21	0.12
29b	Gauging Station NSW Office of Water, BEGA (Station No. 219900) (datum at 5.70m)	High	14.18	14.09	-0.09
30b	Gauging Station Manly Hydraulics Laboratory, BEGA(LIVE) (Station No. 219410)	High	2.98	2.90	-0.08
31b	Lot 3 East St, BEGA	High	12.35	12.48	0.13
32b	26 Springvale Cl,BEGA (at fence)	Low/ Disregarded Surveyor's remark - incorrect date	13.33	16.06	2.73
33b	19 Emma Rd, REEDY SWAMP (fence post in photo)	Low Compared to adjacent floodmarks	9.06	10.02	0.96

Flood Mark ID	Floodmark Description	Confidence Rating	Observed Level (mAHD)	Modelled Level (mAHD)	Difference (m)
34b	1116 Tathra Rd, JELLAT JELLAT	Low/ Disregarded No level	-9999	9.97	-9999
35b	78 Darcy Ln, JELLAT JELLAT (on fence in photo)	Low Compared to nearby floodmarks	9.34	9.97	0.63
36b	80 Darcy Ln, JELLAT JELLAT (at tree)	Low Compared to nearby floodmarks	9.34	9.97	0.63
37b	130 Lot Stafford Drive KALARU	Low/ Disregarded No level	-9999	-9999	-9999
38b	539 Reedy Swamp Rd REEDY	Low/ Disregarded No level	-9999	9.95	-9999
39b	1089 Greendale Rd, ANGLEDALE (water mark on bitumen)	Low (outside Bega Flood model)	23.25	-9999	-9999
40b	Greendale Bridge BROGO	Low (outside Bega Flood model)	29.00	-9999	-9999
41b	12622 Princes Hwy Brogo	Low (outside Bega Flood model)	49.81	-9999	-9999
42b	2025 Snowy Mountains Hwy,MORANS CROSSING (at fence post)	Low (outside Bega Flood model)	102.50	-9999	-9999
43b	1270 Bega RD, CANDELO (water mark on pump shed)	High (outside Candelo Flood model)	89.54	-9999	-9999
9d	21 Sharpe St, CANDELO (on steps)	Disregarded (local flooding)	99.76	-9999	-9999

Figure 14.21: March 1983 Event – Flood Map with Locations of Floodmarks

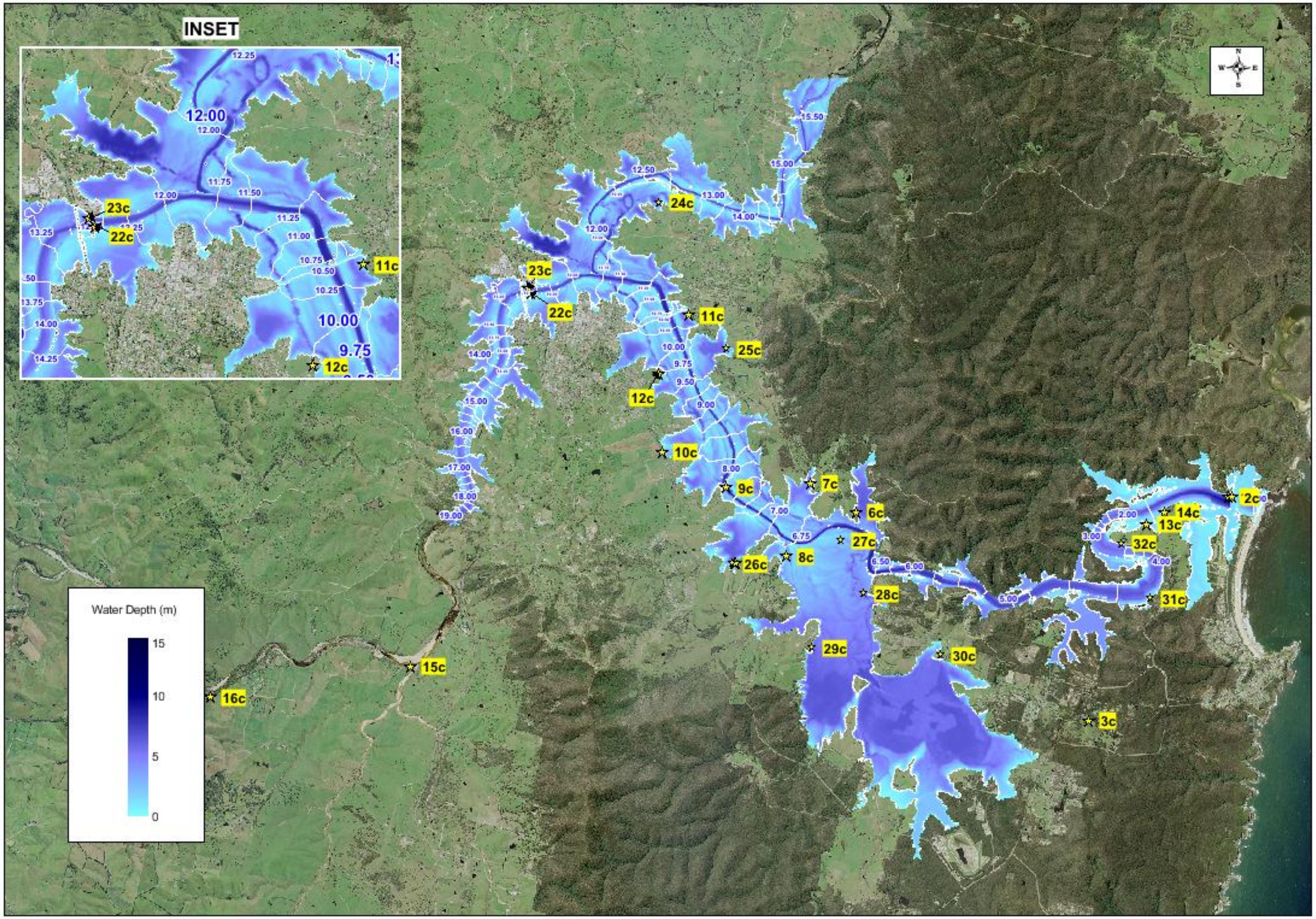


Table 14.15a: Validation Results – March 1983 Event

Flood Mark ID	Floodmark Description	Confidence Rating	Observed Level (mAHD)	Modelled Level (mAHD)	Difference (m)
1c	North End Hancocks Bridge	High	2.83	1.58	-1.25
2c	East end Nth abutment Hancocks Bridge	Med	2.76	1.57	-1.19
3c	Buena Vista Entrance, East end Jellat Jellat Flats	Low (outside Bega Flood model)	4.82	-9999	-9999
4c	Bargo Lagoon SE side	Low (Compared to nearby floodmarks)	5.93	7.15	1.23
5c	Bargo Lagoon SE side	Med	6.15	7.15	1.01
6c	Reedy Swamp Farm	Low	3.99	6.66	2.67
7c	Daisy Bank	High	7.58	6.77	-0.81
8c	Kevin Russell's house "Jelgowry"	Med	4.52	6.71	2.20
9c	WAR&Ragaburra GS 219026	High	7.90	7.96	0.06
10c	Parberry Creek	Med	7.83	8.56	0.73
11c	East end Tarraganda Bdge	Low/Disregarded (Compared to nearby floodmarks)	6.92	10.34	3.42
12c	Bega STW	Med	8.71	9.78	1.07
13c	Old Boatshed (ruin)	Low/Disregarded (Compared to nearby floodmarks)	1.82	1.79	-0.03
14c	Headland South Side of Bega River	Med (Date unclear)	2.75	1.7	-1.05
15c	Upstream of Wolumla Creek	Low/Disregarded (out by order of magnitude)	46.63 RL	-9999	-9999
16c	Tylers Creek Bridge	Low/Disregarded (out by order of magnitude)	47.42 RL	-9999	-9999
17c	Ryan D'Arcy Road	Low/Disregarded (out by order of magnitude)	49.19 RL	-9999	-9999
18c	Colombo Creek Confluence	Low/Disregarded (out by order of magnitude)	47.52 RL	-9999	-9999
19c	Greens Crossing	Low/Disregarded (out by order of magnitude)	51.57 RL	-9999	-9999
20c	Nobby Park Road	Low/Disregarded (out by order of magnitude)	47.26 RL	-9999	-9999
21c	Bemboka R & Nunnock R Confluence	Low/Disregarded (out by order of magnitude)	70.35 RL	-9999	-9999
22c	Old Bega Bridge Line, south side	Low (Compared to nearby floodmarks)	11.32	12.71	1.39
23c	Gauging Station NSW Office of Water, BEGA (Station No. 219900) (datum at 5.70m)	High	12.30	12.81	0.51

*Table 14.15b: Additional Validation Results – March 1983 Event**

Flood Mark ID	Floodmark Description	Confidence Rating	Observed Level (mAHD)	Modelled Level (mAHD)	Difference (m)
24c	Tathra Road BROGO RIVER	Low/ Disregarded No level	-9999	12.14	-9999
25c	Reedy Swamp Road, BEGA RIVER	High	7.58	9.69	2.11
26c	Tathra Road, west of JELLAT JELLAT	High	6.42	7.15	0.73
27c	Bega River, JELLAT JELLAT FLATS	High	5.39	6.66	1.27
28c	Tathra Road, near JELLAT JELLAT WEIR	High	4.82	6.66	1.84
29c	PWD Gauge Board JELLAT JELLAT FLATS	Low/ Disregarded No Level	-9999	6.66	-9999
30c	Tathra Road, JELLAT JELLAT FLATS	Low (Compared to nearby floodmarks)	3.80	6.66	2.86
31c	Bega River Upstream of Tathra Bridge	High	2.56	4.17	1.61
32c	Bega River Upstream of Tathra Bridge	High	2.19	3.20	1.01

**Floodmarks provided by Council after completion of calibration and additionally assessed*

Figure 14.22: February 2010 Event – Flood Map with Locations of Floodmarks

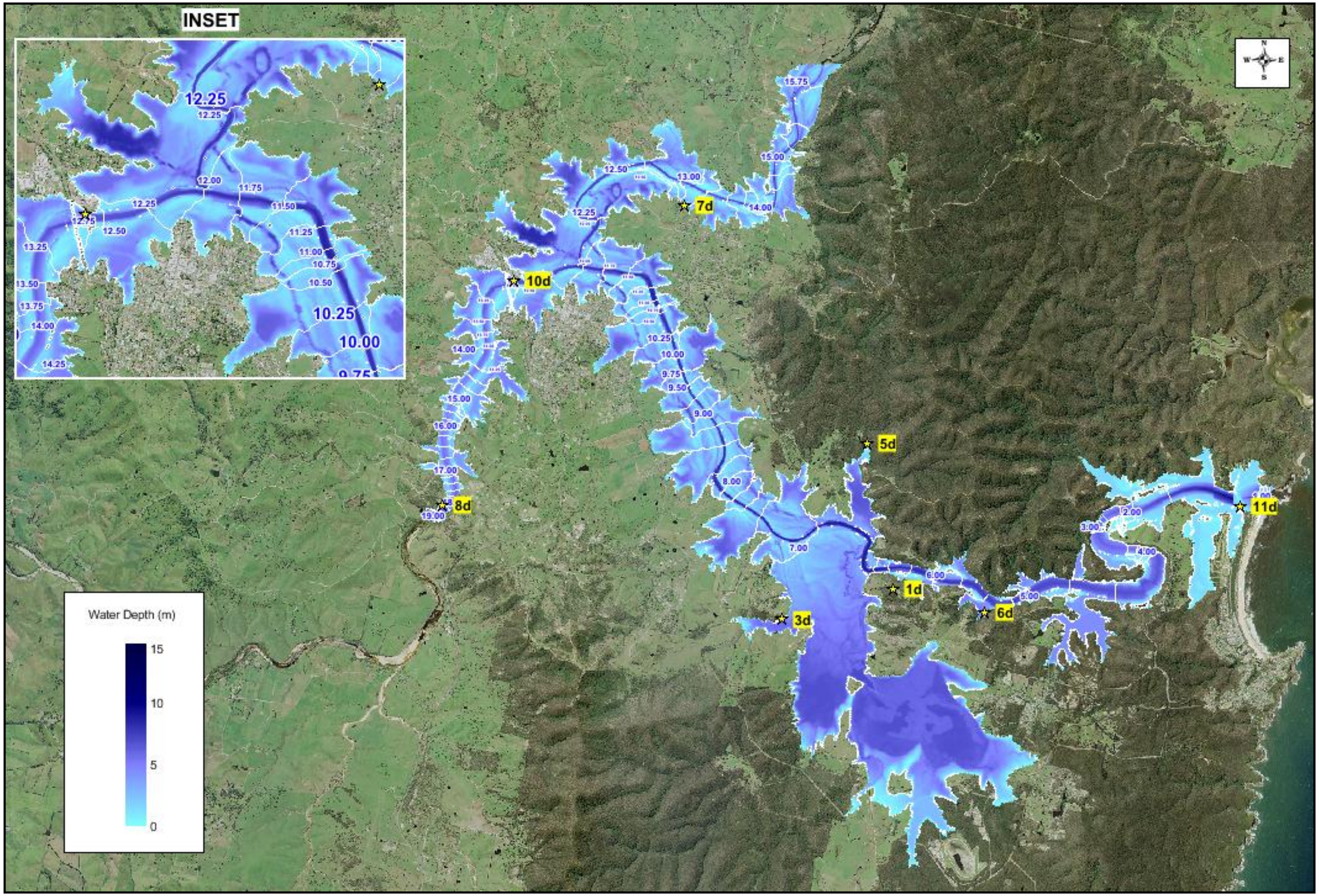


Table 14.16: Validation Results – February 2010 Event

Flood Mark ID	Floodmark Description	Confidence Rating	Observed Level (mAHD)	Modelled Level (mAHD)	Difference (m)
1d	50 Russell Lane Kalaru	Low/ Disregarded No level	-9999	-9999	-9999
2d	132 Glen Oaks Rd Brogo	Low/ Disregarded No level	-9999	-9999	-9999
3d	78 Darcy Ln Jellat Jellat (flood debris in photo)	Med	5.28	6.98	1.70
4d	12622 Princes Hwy Brogo	Low/ Disregarded No level	-9999	-9999	-9999
5d	539 Reedy Swamp Rd Reedy Swamp	Low/ Disregarded No level	-9999	6.97	-9999
6d	130 Lot Stafford Dr Kalaru (nail in tree)	Med	4.20	5.49	1.29
7d	98 Corridgeree Ln, Tarraganda (watermark pump shed)	Med	13.32	13.02	-0.29
8d	52 Gillcrest Rd, Buckajo	High	19.48	18.61	-0.87
10d	Gauging Station NSW Office of Water, Bega (Station No. 219900) (datum at 5.70m)	High	12.54	12.83	0.29
11d	Gauging Station Manly Hydraulics Laboratory, Bega(LIVE) (Station No. 219410)	High	2.04	1.64	-0.40

14.7 Hydraulic Model Calibration Summary

Generally the calibration and validation indicated a good performance of the hydraulic model with the overall average difference from all floodmarks used, excluding those disregarded, and for all modelled events was 0.25m. Of the two calibration runs the average difference for all the floodmarks was 0.03m.

The two validation events produced a higher variation in results compared to the calibration events. This highlighted the dependence of results on selected calibration events and the reliance that modelled flood levels and subsequent flood planning have on large events such as February 1971 and March 2011. Observed water levels at gauging station St 219900 indicate the relative difference to the size of these historic floods with the calibrated floods recording levels of 15.48 and 14.18 mAHD, and the validation floods recording levels of 12.30 and 12.54 mAHD.

Growth of vegetation and debris causing blockages can vary significantly between events resulting in a change of applicable parameters and variations in flood levels or flow distributions. These variations are most likely the cause of differences in flood levels noted during the validation runs. The events used in validation were of much smaller magnitude than calibration events and as such more sensitive to variations of local flow conditions.

The results also indicate that Jellat Jellat Flats area has a significant effect on flows and flood levels in downstream parts of the river by providing offline storage that significantly impact levels during flood events.

The final set of hydraulic modelling parameters obtained from the calibration and validation runs is presented in the following tables.

Table 14.17: 2D Modelling Surface Roughness Coefficients from Calibration and Validation Runs

Area/Location	Roughness Coefficients (Manning 'n')		
	February 1971 Calibration	March 2011 Calibration	March 1983/ February 2010 Validation**
2d AREA			
- Roads	0.016	0.016	0.016
- Pasture	0.045	0.045	0.045
- Trees	0.180	0.180	0.180
- Urban	0.080	0.080	0.080
1d AREA			
- BEG57 to outlet	0.025	0.025	0.025
- BEG56 to BEG57	0.030	0.030	0.030
- BEG46 to BEG56	0.045	0.045	0.045
- BEG40 to BEG46	0.045	0.033	0.045
- Tarraganda to BEG40	0.050	0.050	0.050
- Tarraganda Bridge Main	0.060	0.200	0.060
- Tarraganda Anabranch	0.045	0.200	0.045
- BEG01 (US) to Tarraganda	0.045	0.120	0.045
- Brogo	0.045	0.045	0.045
	Losses		
BRIDGES			
- Tathra Bridge/Mogareeka	0.1/0.1	0.1/0.1	0.1/0.1
- Tarraganda Bridge Main	0.4/0.4	0.4/0.4	0.4/0.4
- Tarraganda Anabranch	0.4/0.4	0.4/0.4	0.4/0.4
- Princes Hwy	0.2/0.2	0.1/0.1	0.2/0.2
	Adjusted Elevation at Outlet (m)		
SANDBANK LEVEL at outlet	-1.7	-0.6	-0.6

** Mar 1983 hydrologic model calibration run, hydraulic model validation run

** Feb 2010 hydrologic model validation run, hydraulic model validation run

Overall, the model shows a good performance and can be used for modelling of design storm events with a reasonably high level of confidence, including events of a magnitude close to 1%AEP relevant for establishing the interim Flood Planning Levels (FPL) and development controls within the modelling area. This also confirmed appropriateness of parameters adopted for the hydrologic model and overall robustness of the modelling suite utilised for the project.

14.8 Adoption of Hydraulic Modelling Parameters for Design Events

The calibration of the hydrologic/hydraulic models against the historic flood events confirmed the appropriateness of the final modelling parameters. The results of the assessment were presented to Council and OEH and the following parameters were adopted as representative of the catchment for further modelling of design flood events.

14.8.1 Modelling Surface Roughness Coefficients

Table 14.18: Modelling Surface Roughness Coefficients for Design Event Runs

Modelling Area	Roughness Coefficients (Manning 'n')	Basis for Recommendation
2d DOMAIN		
- Roads	0.016	Adopted maximum value from all calibration runs
- Pasture	0.045	
- Trees	0.180	
- Urban	0.080	
1d DOMAIN		
- BEG57 to outlet	0.025	Adopted maximum value from all calibration runs
- BEG56 to BEG57	0.030	
- BEG46 to BEG56	0.045	
- BEG40 to BEG46	0.045	
- Tarraganda to BEG40	0.050	
- Tarraganda Bridge Main	0.060	Adopted maximum value from all calibration runs ignoring high losses (0.2) representing 2011 blockage as it will be represented by a separate blockage factor
- Tarraganda Anabranch	0.045	
- BEG01 (US) to Tarraganda	0.045	From Feb 1971 event
- Brogo	0.045	Adopted maximum value from all calibration runs

** Refer to Appendix E – Figure E3 for Identifiers

14.8.2 Modelling Bridge Entry/Exit Losses

Table 14.19: Modelling Bridge Entry/Exit Losses for Design Event Runs

Bridge location	Entry/Exit Loss	Basis for Recommendation
- Tathra Bridge/Mogareeka	0.1/0.1	Adopted maximum value from all calibration runs
- Tarraganda Bridge Main	0.4/0.4	
- Tarraganda Anabranch	0.4/0.4	
- Princes Hwy	0.1/0.1	Adopted present configuration.
- Candelo Creek	0.5/1.0	Adopted value from calibration run

14.8.3 Sandbar/ Berm Geometry

The entrance condition adopted for design events was established with the following setup:

- An entrance initially closed at the onset of the flood;
- The initial berm height determined based on the adjacent top of the berm, as obtained from the LIDAR data;
- The use of a dynamically or unsteady opening that changes over time based on trigger levels;
- When the water level reaches the trigger levels, the berm will dynamically change, making an opening to the berm that produces an exchange of flows between the catchment and the ocean;
- Provided the water level at the trigger point (upstream of the berm) is higher than the tailwater level, flows will drain away into the ocean;
- The limits to the opening were based on historic events (-0.6m AHD in March 2011) and aerial photography with managed/scoured condition based on invert levels near the inlet calibrated from the historic events. The invert from the March 2011 event was chosen for application of design events as it was considered to be a better representation of the present day configuration of the site than the February 1971 calibration event.
- The management intervention level of 1.36mAHD is based on current lagoon management practice by Council.
- Two trigger levels are used where the first stage simulates the initial management intervention to open the berm in conjunction with scouring that opens the waterway to the ocean during stage 1. During this stage the trigger level was taken as 1.36mAHD based on current management practice used by Council (i.e. the water level within the lagoon at which the berm gets opened). The opening of the stage 1 scouring is taken as 150m based on aerial photography with an estimated time of 3 hours between the initial management intervention and the scoured level of -0.6mAHD, giving a lateral erosion rate of about 1m/min.
- A second stage trigger point is also added when the water level behind the berm overtops the berm and significantly opens the channel to an additional width of 350m. The opening of the Stage 2 scouring was taken as 5 hours to open the 350m wide berm from a level of 2.9mAHD to -0.6mAHD.

A summary of the entrance conditions adopted for the design events is shown in Table 14.20 below.

Table 14:20: Entrance Conditions for use in Design Events

Condition	Width / Level	Basis for Recommendation
Initial sandbar opening width	0m (fully closed)	Assessed critical condition after prolonged dry period
Initial sandbar opening height	2.9 mAHD	Estimated from LiDAR survey /DTM
Eroded sandbank level	-0.6 mAHD	Adopted maximum (most critical) value from all calibration runs
First Stage Initial Management Intervention – trigger water level	1.36 mAHD	Trigger level provided by Council. Meeting 26 June 2012
First Stage Initial Management Intervention and Scour - width	150m	Adopted as per the existing aerial photography
First Stage Final Management Intervention – final level	-0.6 mAHD	Adopted maximum (most critical) value from all calibration runs
First Stage Initial Management Intervention – time to erode	3 hr	Assumed (based on estimated time for 0.5m flood rise at the outlet and approx. 1m/min lateral erosion rate)
Second Stage Scouring of overall berm	2.9 mAHD	Top of Berm Estimated from LiDAR survey /DTM

Condition	Width / Level	Basis for Recommendation
–trigger water level		
Second Stage Scouring of overall berm - width	350m	Estimated from Aerial Photos (remaining length of berm after First Stage erosion)
Second Stage Scouring of overall berm - final level	-0.6 mAHD	Adopted maximum (most critical) value from all calibration runs
Second Stage Scouring of overall berm – time to erode	5 hrs	Assumed (based on similarity with erosion rate at First Stage)
Initial Water Level throughout model	0.86 mAHD	Based on spring tide peak value

In the case of 1%AEP ocean flooding in conjunction with 5%AEP catchment flooding (required for establishing of Flood Planning Levels) the berm was initially set open to allow water levels along Bega River to build up, as this condition is more critical with an open berm rather than initially closed. In the 1%AEP catchment flooding with 5%AEP ocean flooding scenario the berm was initially set closed, in which case a closed entrance was considered to be more critical to peak water levels.

An option of providing no intervention was also assessed as part of the sensitivity analysis where the opening of the berm is initiated by erosion, once the water level reaches the crest level overtopping the berm. A scenario with no management intervention was used in developing the preliminary flood planning levels in conjunction with other relevant scenarios including the base case, sea level rise to year 2050 and sea level rise to year 2100, as presented Appendix H.