Upper Murray River URBS Model Enhancement

August 2016

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Don Carroll Project Management

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01/08/2016	Terry Malone				
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Contents

List of Figures

List of Tables

Executive Summary

Don Carroll Project Management Pty Ltd was commissioned by Murray Darling Basin Authority to develop and calibrate an URBS model for the Upper Murray River to Albury.

It is understood that the purpose of the model is for flood forecasting and dam operations and will be incorporated into the FEWS flood modelling platform for use in real time. As such, it was necessary to calibrate the model on a large range of events.

URBS is a semi-distributed non-linear network model which has been adopted in flood forecasting system in Australia by the Bureau of Meteorology, Seqwater and Melbourne Water Corporation and also in the Yangtze and Mekong Rivers.

The Upper Murray URBS model consists of three linked models;

- Mitta Mitta River to Tallandoon
- Upper Murray River to Hume Dam, and
- Upper Murray River below Hume Dam to Albury.

The model was calibrated on sixteen events between January 1974 and March 2012.

Rating ratios at gauging stations within the study area were assessed to determine the most reliable stations for calibration. Besides Dartmouth and Hume Dams, the next most reliable stations were considered to be the Murray River at Jingellic and the Mitta Mitta River at Tallandoon. Subsequent investigations found some inconsistency with the ratings at stations in the lower Mitta Mitta River which requires further investigation.

Model results of simulated heights and flows are output at over 25 locations in the Upper Murray River to Albury.

The models were well calibrated with respect to inflow volume and water level at Dartmouth and Hume Dams and at most of the primary calibration locations. Calibration at some gauging stations with relatively small catchment areas suffered from poor definition of spatial and temporal rainfall.

Practical guidance for the application of the model is given in the report with the regard to initial baseflow and starting level of Dartmouth and Hume Dams. Catchment wetness or dryness (and associated estimate of initial loss) is considered of high importance for real time operations and further work is required in this area to fully operationalise the model.

In its current form, the model is considered ready for application within a flood forecasting system. For operational purposes, it is recommended that the recorded outflow from Khancoban Pondage be matched as gate operations are not simulated within the URBS model.

The models are highly sensitive to losses and flow into the dams at the start of the flood event. Real time users of the models should be aware of the range of these parameters and should undertake some sensitivity analysis during floods to assess a possible range of outcomes.

The recommended loss and routing parameters to be applied to the model are shown in the table below.

Table 0-1: Recommended model parameters

Model	Typical continuing loss (mm/hr)	Channel Routing Alpha	Subarea Routing Beta	Subarea Routing Exponent m
Mitta Mitta River to Tallandoon	3.3	0.27	4.0	0.8
Upper Murray River to Hume Dam	3.8	0.30	4.0	0.8
Murray River below Hume Dam to Albury	3.2	0.35	4.3	0.8

However, as with all flood forecasting models, further improvements and enhancements are recommended:

- An investigation as to whether the BoM AWRA-L real time root zone soil moisture modelling can be used to estimate initial losses
- Review the existing real time rainfall station network to improve spatial and temporal rainfall event definition
- On an annual basis, the model should be revisited and adjusted if necessary to ensure that the rainfall runoff parameters consistently replicate recorded rainfall runoff behaviour.
- Over time, calibration and ratings of some of the water level stations should be refined.
- The model should be re-calibrated after significant flood events.
- As additional rainfall and rated river stations become available in real time, they should be added to the model.

1 Introduction

1.1 Context

This report describes the development and calibration of a flood hydrology model of Upper Murray River to Albury. It builds upon preliminary work undertaken by Terry Malone in developing a proof-of-concept flood forecasting model in 2014.

A map of the catchment showing the main locations within the Upper Murray River is shown in Figure 1-1.

It is understood that the primary use of the model will be for forecasting flood flows into Dartmouth and Hume Dams. It is also understood that the calibrated model will be incorporated into the MDBA's FEWS flood modelling platform for use in real time.

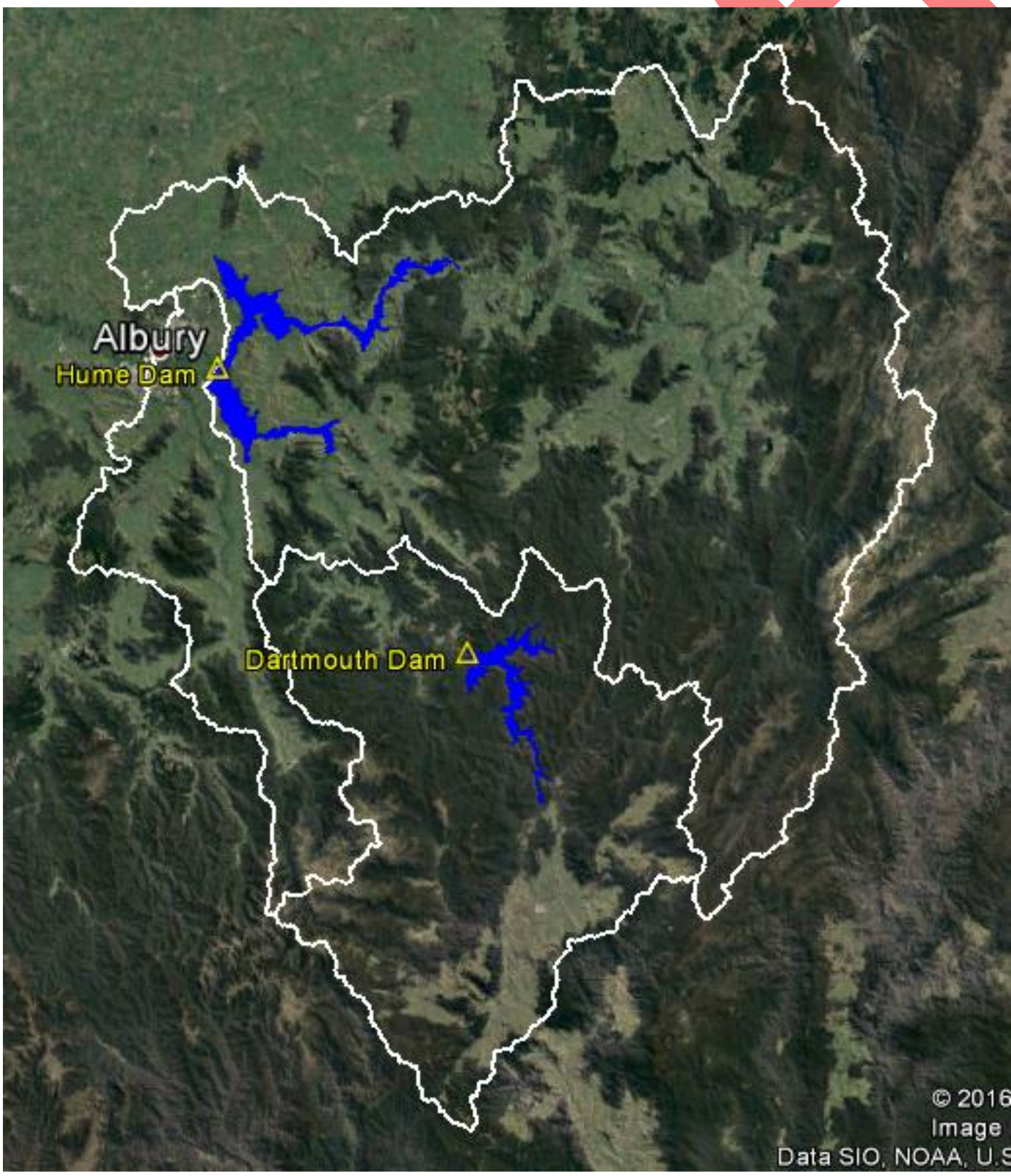

Figure 1-1~~1-1~~: Catchment Plan

1.2 Terminology

The primary inputs to the model are recorded rainfall and water level data.

Flow at gauging stations is not observed but estimated from recorded water levels by use of a rating to convert height to flow at a particular location. Flow derived in this way is termed rated flow.

Similarly, flow into dams is not observed but inflow estimated by reverse routing. Flow derived in this way is termed rated flow. The volume of inflow to dams is termed rated volume.

Model results may be reported as simulated or modelled flow or height or volume.

2 Event Data

2.1 Hydrometric Data

The collection and interpretation of rainfall and water level data is an integral part of the flood modelling process.

This section of the report is compiled with the intention of outlining the fundamental concepts behind the collection of rainfall and water level data for use in the Upper Murray model calibration study. Its purpose is as a source containing relevant information concerning rainfall and water level data collection, as well as a documentation of the availability of this data historically.

For this study, rainfall, water level and rating data from collected and collated from a number of different sources including the Bureau of Meteorology (BOM), Goulburn-Murray Water (GMW), Murray-Darling Basin Authority (MDBA), NSW Department of Primary Industries Water (NOW) and Victorian Department of Environment, Land, Water and Planning (DELWP).

2.1.1 Rainfall Data

Rainfall data is the primary input to hydrologic models. Rainfall data can be collected either manually (by volunteers or contractors), or automatically (using a computer system setup) and both methods are utilised in the collection of rainfall data. In terms of reliability, manual recordings are more favourable in that the gauge is inspected daily – thus enabling sources of error to be quickly identified and fixed. Automated systems on the other hand are able to provide detailed times series of rainfall readings, and are hence also widely used.

The definition of rainfall in space and time are essential elements that are required for robust hydrologic modelling.

Data collected for this study includes:
- Manual data - Traditionally, rainfall data was measured by a standard 8” (203mm) rain gauge at 9am each day, and manually recorded by volunteers and contractors.
- Pluviograph data - A variety of automated precipitation measuring devices are used to provide times series of rainfall data which is generally required for hydrologic models. Data was recorded via chart but now is usually logged on site.

The daily rainfall stations considered in this study are shown in Figure 2-1 and listed in Appendix A. In Figure 2-1, currently closed stations are shown as filled in squares while open stations are shown as open squares.

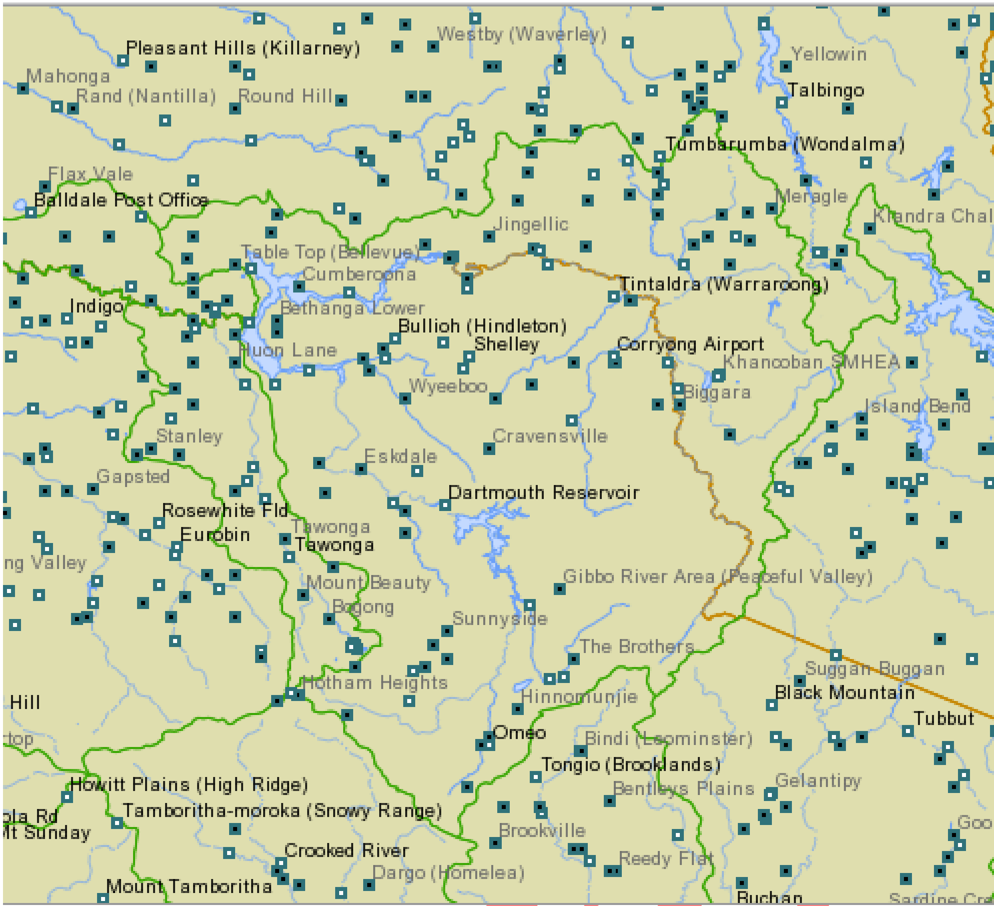

Figure 2-12~~-1~~: Daily Rainfall Stations   Source: Bureau of Meteorology

Table 2-1: Pluviograph Stations

BoM No	Name	Longitude dddmmss	Latitude ddmmss
070217	COOMA AIRPORT AWS	1485821	-361739
071010	KIANDRA CHALET	1483000	-355300
071029	SPENCERS CREEK	1482100	-362600
071032	THREDBO AWS	1481709	-362929
071034	GUTHEGA POWER STATION	1482445	-362106
071035	MOONBAH (RIVERVIEW)	1483300	-362900
071042	INGEBYRA (GROSSES PLAINS)	1482804	-363608
072023	HUME RESERVOIR	1470158	-360614
072056	BLOWERING DAM	1481449	-352341
072060	KHANCOBAN SMHEA	1480835	-361331
072091	CABRAMURRA SMHEA	1482303	-355618
072099	TOOMA (UPPINGHAM)	1481300	-355440
072156	JINGELLIC	1474300	-355600
072159	ADELONG (ETHAM PARK)	1475625	-351807
072160	ALBURY AIRPORT AWS	1465703	-360407

BoM No	Name	Longitude dddmmss	Latitude ddmmss
072161	CABRAMURRA SMHEA AWS	1482240	-355613
072162	KHANCOBAN AWS	1480826	-361348
072163	TOOMA (EUDLO)	1481056	-355356
073007	BURRINJUCK DAM	1483554	-345959
082011	CORRYONG (PARISH LANE)	1475344	-361201
082034	MYRTLEFORD POST OFFICE	1464400	-363400
082039	RUTHERGLEN RESEARCH	1463034	-360617
082076	DARTMOUTH RESERVOIR	1472954	-363207
082139	HUNTERS HILL	1473219	-361254
082169	CORRYONG AIRPORT	1475338	-361058
083003	BENAMBRA (EVANDALE)	1474427	-365644
083025	OMEO COMPARISON	1473553	-370604
083055	MT HOTHAM AIRPORT	1472000	-370306
083067	BRIGHT	1465741	-364353
083071	FALLS CREEK	1471700	-365200
083084	FALLS CREEK AWS	1471628	-365221
083085	MT HOTHAM AWS	1470758	-365843
083090	OMEO AWS	1473601	-370605
084142	GELANTIPY AWS	1481544	-371319
572005	PINEGROVE	1480304	-360231
572006	JINGELLIC CK	1474145	-355336
582009	BERRINGAMA	1474030	-361248
582012	MONGANS BRIDGE	1470560	-363600
582015	BIGGARA	1480301	-361916
582016	GIBBO PARK	1474248	-364512
582018	GRANITE FLAT	1472442	-363412
582020	OSBORNES FLAT	1465412	-361824
582022	MCCALLUMS	1472000	-361230
583004	JOKERS CK	1472816	-365604
583005	HINNOMUNJIE	1473618	-365654
401012	BIGGARA	1480307	-361909
401549	BRINENBONG	1480134	-361004
401013	JINGELLIC	1474134	-355345
401027	HUME_DAM	1470154	-360627
401009	MARAGLE	1480600	-355532
401014	PINEGROVE	1480312	-360227
401015	YAMBLA	1465830	-355503

BoM No	Name	Longitude ddmmss	Latitude ddmmss
401203	HINNOMUNJIE	1473621	-365645
401800	ANGLERS REST	1472921	-365937
401823	VICTORIA FALLS	1472729	-370517
401824	UPLANDS	1474205	-365205
401825	UPPER NARIEL	1474940	-362658

2.1.2 Water Level Data

Staff gauges remain the primary method for measurement of water levels in the Upper Murray catchment and are located at every stream gauge and dam site where water level is monitored.

Typically stream staff gauges were installed at local datum with zero on the gauge (GZ) being the cease to flow level. Over time, gauge zeroes have been related to Australian Height Datum (AHD). Staff gauges at dams are typically set to AHD.

Water level stations in the Upper Murray catchment are owned and operated by different authorities such as GMW, MDBA, NSW Office of Water and DELWP. Water level sensing at stream gauges mostly utilise gas bubbler systems while float wells or radars are utilised at dams.

During the data collection phase, it was noted that different authorities use a different AWRC number for the same station. For example, DELWP adopted an AWRC number of 409011 for Hume dam headwater levels while NSW Office of Water adopt 401027 for the same site. Additionally, the same data may be available on multiple sites.

In this study, the gauging stations considered in the Upper Murray catchment are listed in Table 2-2 and shown in Figure 2-2.

Table 2-2: Upper Murray River Water Level Stations

AWRC	Stream	Station	Catchment Area	Source	Open	Affected by Regulation
			km^2			
401216	Big R	Jokers Ck	356	DELWP	01/01/1934	No
401203	Mitta Mitta R	Hinnomunjie	1,533	DELWP	01/01/1984	No
401217	Gibbo R	Gibbo Park	389	DELWP	01/01/1971	No
401224	Mitta Mitta R	Dartmouth Dam	3,561	DELWP	01/01/1977	
401211	Mitta Mitta R	Colemans	3,634	DELWP	01/01/1968	Yes
401204	Mitta Mitta R	Tallandoon	4,716	DELWP	01/01/1934	Yes
401012	Murray R	Biggara	1,165	NOW	01/01/1948	
401549	Murray R	Bringenbong	2,323	NOW	01/01/1956	Yes
401009	Maragle Ck	Maragle	215	NOW	01/01/1947	No

AWRC	Stream	Station	Catchment Area km^2	Source	Open	Affected by Regulation
401014	Tooma R	Pinegrove	1,845	NOW	01/01/1955	Yes
401208	Cudgewa Ck	Berringama	350	DELWP	01/01/1967	No
401229	Cudgewa Ck	Cudgewa North	837	DELWP	01/01/1993	No
401201	Murray R	Jingellic	6,527	DELWP	01/01/1965	Yes
401013	Jingellic Ck	Jingellic	390	NOW	27/08/1993	No
401220	Tallangatta Ck	McCallums	464	DELWP	10/06/1975	No
401015	Bowna Ck	Yambla	280	NOW	01/01/1973	No
401011	Murray R	Hume Dam	15,300	NOW	01/01/1929	
409027					16/08/2002	
409016	Murray R	Heywoods	15,300	NOW	01/01/1929	Yes
402222	Kiewa R	Kiewa	1,145	DELWP	01/01/1987	No
402205	Kiewa R	Bandiana	1,655	DELWP	01/01/1965	No
409017	Murray R	Doctors Pt	16,750	NOW	01/01/1929	Yes
409001	Murray R	Albury	17,200	NOW	14/04/1892	Yes

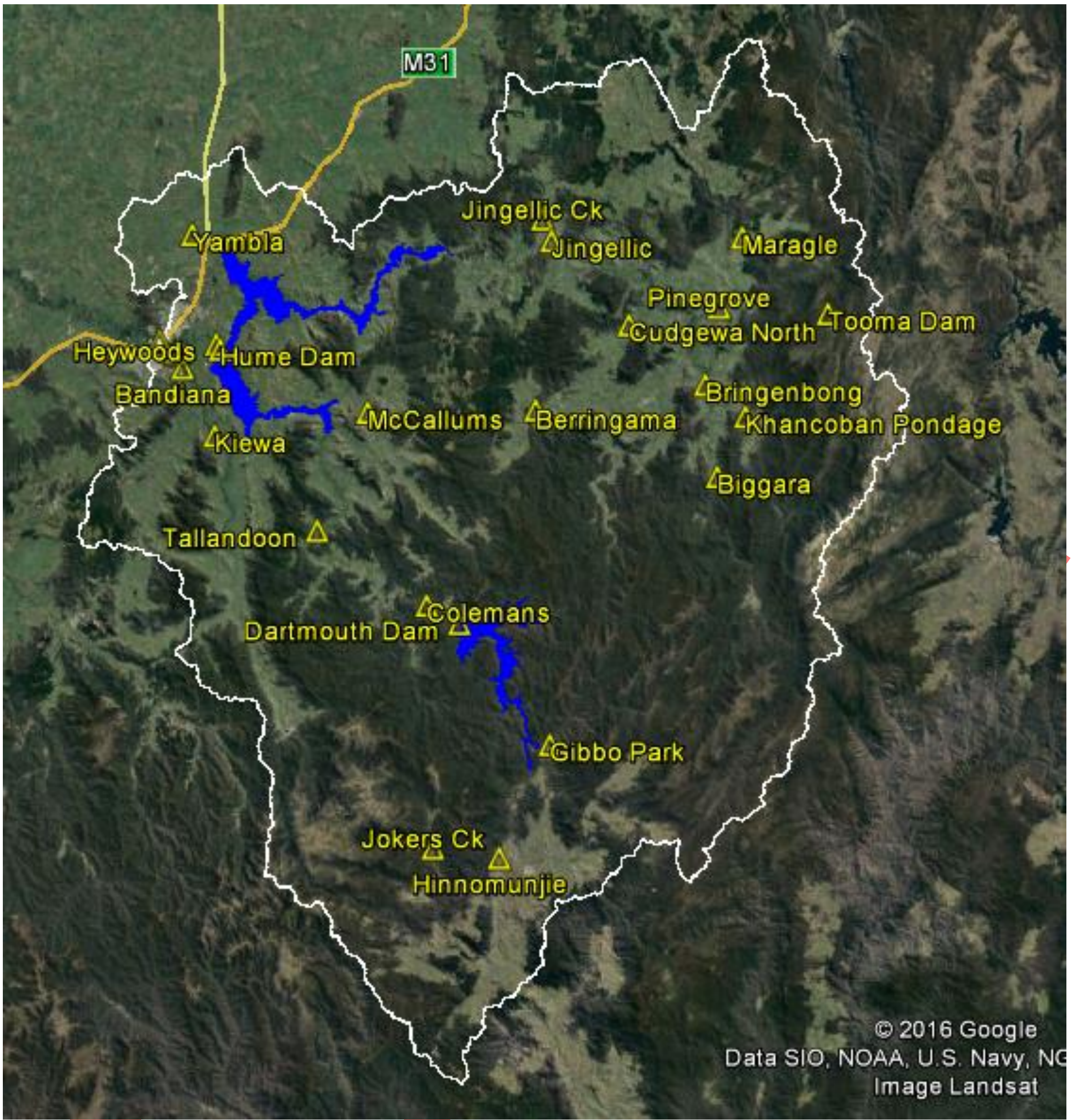

Figure 2-2~~2-2~~: Water Level Gauges

Figure 2-3~~2-3~~: Water Level Gauges below Hume Dam

Whether a station is affected by releases from upstream storages determines if that station may be used for baseflow analysis. Stations which are affected is this way are unsuitable to determine baseflow parameters to be used in models.

2.2 Event Selection

Flood forecasting models need to replicate flood behaviour over a wide range of event magnitudes, not just large floods. Thus, the selection of the calibration events to be investigated as part of this assessment was based on a range of events, including recent significant historical floods in the Upper Murray.

A large number of flood events is considered necessary for calibration of models to be used for flood forecasting for several reasons including:

- better opportunity to assess the potential range of routing & loss parameters
  some specific flood events can be used to identify unique routing behaviour in parts of the catchment
- support for review of rating consistency across the catchment and across a period of flood event records
- models need to be able to replicate a range of events from small to very large.

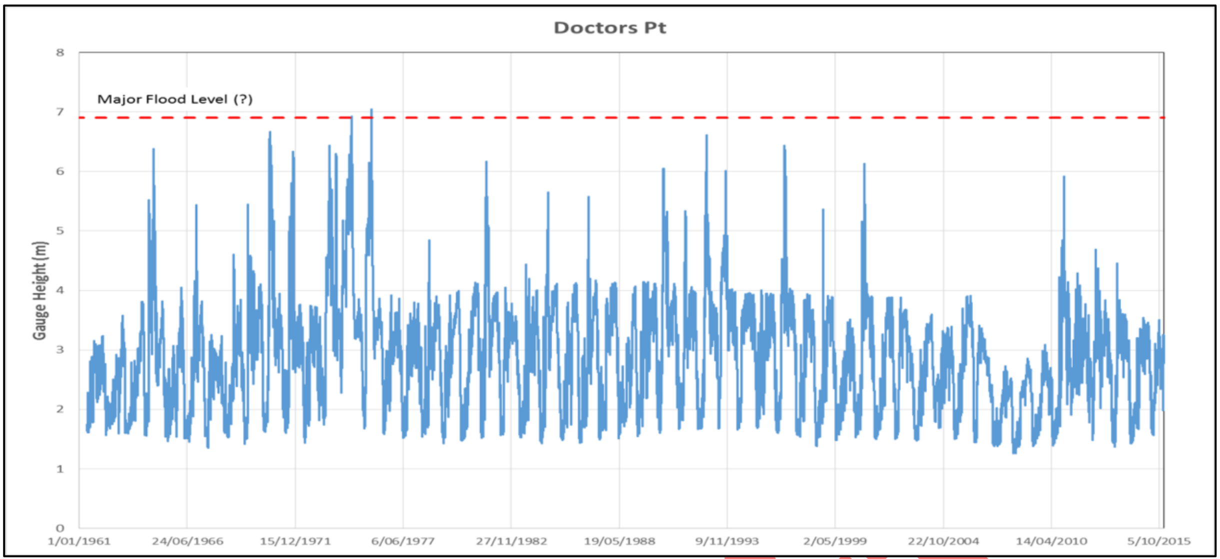

Figure 2-42~~-4~~: Flood Heights Doctors Point

The flood height records at Doctors Point in Figure 2-4 provides a basis for the identification and selection of suitable flood events for model calibration. The major flood level for Doctors Point is based on the corresponding level at Albury.

Significant floods in the system were identified by an analysis of peak heights at key stations as shown in Table 2-3.

Table 2-3: Historical Peak Heights – Post 1970

Year	JINGELLIC m	HEYWOODS m	DOCTORS PT M	ALBURY m
1970	6.77		5.45	
1971	4.05	6.74	6.67	
1972	2.63	6.15	6.34	
1973	4.78	3.96	3.76	
1974	7.51	6.37	6.44	
1975	7.32	7.15	6.93	
1976	6.02	7.25	7.05	
1977	3.35	3.79	3.92	
1978	4.58	3.83	3.87	2.93
1979	3.72	4.25	4.85	4.02
1980	3.00		3.93	3.00
1981	5.76		4.00	3.06
1982	2.24	5.94	6.17	5.05
1983	5.62	3.91	4.05	3.05
1984	5.10	3.78	4.44	3.51
1985	3.61	4.93	5.65	4.64
1986	4.65		4.12	3.17
1987	3.26	4.96	5.58	4.50

Year	JINGELLIC m	HEYWOODS m	DOCTORS PT M	ALBURY m
1988	3.99	4.01	4.17	3.10
1989	3.21	4.05	4.14	3.11
1990	5.71	3.98	4.15	3.12
1991	4.17	5.77	6.05	4.97
1992	6.71	4.74	5.34	4.37
1993	6.44	6.62	6.61	5.40
1994	2.65	5.60	6.01	5.00
1995	5.34	3.83	4.02	3.09
1996	5.43	3.85	4.00	3.09
1997	2.71	6.15	6.44	5.31
1998	5.81	3.75	4.04	3.06
1999	3.36	3.72	5.36	4.34
2000	5.07	3.74	3.90	3.03
2001	2.94	5.42	6.13	5.13
2002	2.80	3.74	3.91	3.00
2003	4.97	3.73	3.89	3.02
2004	3.39	3.20	3.44	2.54
2005	5.15	3.48	3.59	2.67
2006	2.29	3.51	3.70	2.80
2007	2.40	3.79	3.91	3.01
2008	3.16	2.82	2.89	1.86
2009	2.76	2.55	2.65	1.62
2010	7.64	2.98		
2011	4.60	4.65	5.92	4.95
2012	7.91		4.30	3.48
2013	3.77	4.16	4.69	3.89
2014	3.06	4.02	4.46	3.61
2015	2.70	3.65	3.60	2.69

Table 2-4 summarises the historical flood events selected for calibration and investigation. For convenience in storing the events electronically in chronological order, they are labelled by the event start date in terms of *yyyymmdd*. Start and end times of events were set to 9:00am so that daily rainfall gauge data could be used to assist in defining the event total rainfall for the models.

Table 2-4: Historical Floods

Event Label	Start Date	End Date	Duration (days)
197401	02-01-74	23-01-74	21
197410	01-10-74	31-10-74	30
197510	18-10-75	10-11-75	23
198107	19-07-81	03-08-81	15
198308	25-08-83	03-09-83	9
199210	15-10-92	25-10-92	10
199310	01-10-93	16-10-93	15
199607	16-07-96	01-09-96	47
199610	13-09-96	01-11-96	49
199809	19-09-98	30-09-98	11
201009	27-08-10	27-09-10	31
201010	03-10-10	31-10-10	28
201012	05-12-10	19-12-10	14
201102	01-02-11	07-03-11	34
201109	28-09-11	08-10-11	10
201203	27-02-12	13-03-12	15

In addition to the events included in our proposal, the events in October 1975, July 1981, August 1983, October 1992 and October 1996 were added as they were used in the 2009 assessment (StateWater 2009).

3 Dams

This section describes characteristics of the dams which are of significance for potential influence flood behaviour.

3.1 Hume Dam

Hume Dam is located on the Upper Murray River about 11.5 km east of Albury. The dam's key characteristics are outlined in Table 3-1.

Figure 3-1~~3-1~~: Hume Dam

Table 3-1: Key Characteristics Hume Dam

Criteria	Start Date
Type	Concrete gravity dam with four earth embankments
Commissioned	1936
Purpose	Flood mitigation, hydro-power, irrigation and water supply
Catchment Area	15,300 km^2
Full Supply Level	192.0 m AHD
Full Supply Volume	3,036,500 ML
Surface Area at FSL	
Primary Outlet Structures	29 vertical undershot gated concrete overflow spillways
Record Peak Height (Post 1969) Pre Dartmouth Dam Post Dartmouth Dam	 192.26 m AHD 11/01/1974 192.15 m AHD 25/10/2000

The stage-storage curve shown in Figure 3-2 is based on data provided to Terry Malone during the proof-of-concept modelling.

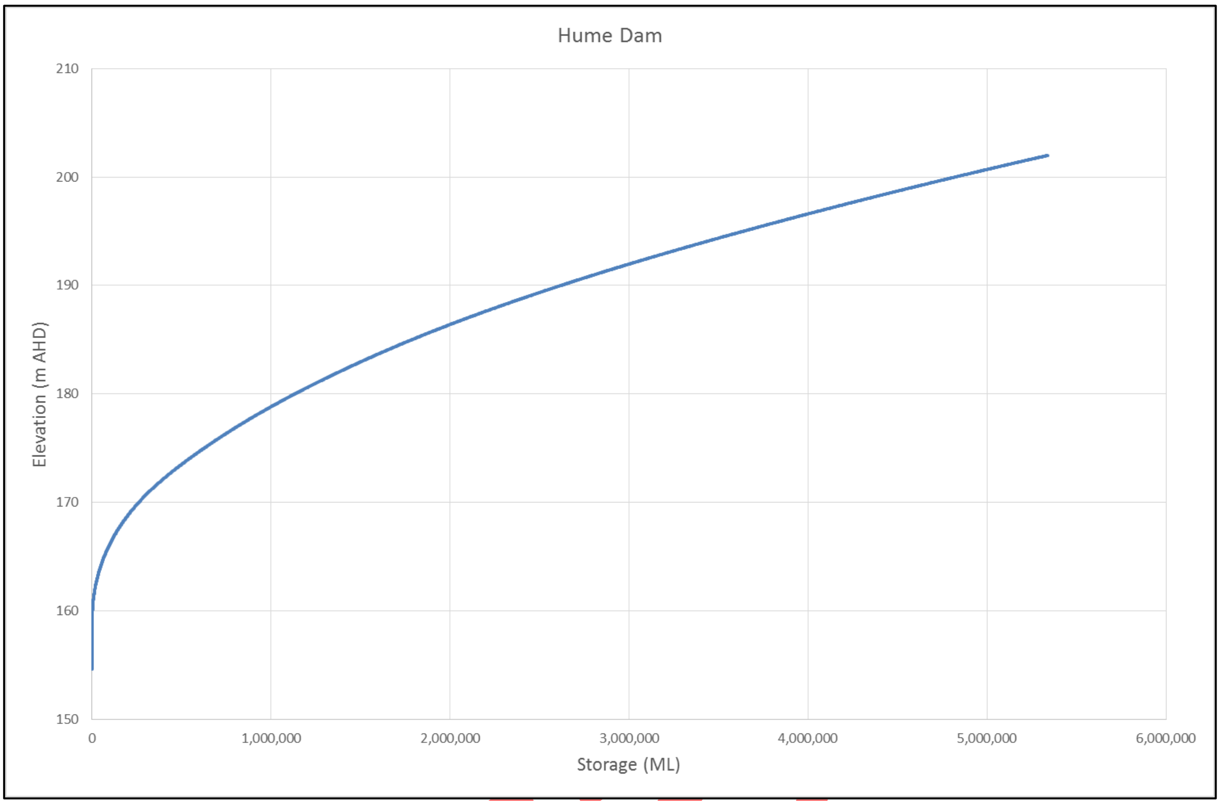

Figure 3-2~~3-2~~: Stage Storage Curve Hume Dam

Because it is a gated structure, Hume Dam does not have a fixed stage-discharge relationship. Outflow depends upon headwater level and the number and status (percentage open) of each vertical undershot gate. However, outflow from the dam can be inferred from the rated flow at Heywoods gauging station located about one kilometre downstream of the dam.

3.2 Dartmouth Dam

Dartmouth Dam is located near Mount Bogong in the north-east Victoria across the Mitta Mitta, Gibbo and Dart rivers, the Morass Creek and a number of small tributaries. The spillway of the dam, shown in the right hand side of Figure 3-3, consists of an uncontrolled concrete shute about 80 metres long, starting at 92 metres at the crest and widening to 300 metres at river level.

Figure 3-3~~3-3~~: Dartmouth Dam

Table 3-2: Key Characteristics Dartmouth Dam

Criteria	Start Date
Type	Rock-fill embankment dam
Commissioned	1979
Purpose	Irrigation, hydro-electric power and water supply
Catchment Area	3,600 km^2
Full Supply Level	486.0 m AHD
Full Supply Volume	3,856 ,000 ML
Surface Area at FSL	
Primary Outlet Structures	Uncontrolled chute spillway
Record Peak Height	487.20 m AHD 05/10/1996

The representation of Dartmouth Dam was explicitly included in the model using the characteristics, provided by MDA, in Figure 3-4 and Figure 3-5.

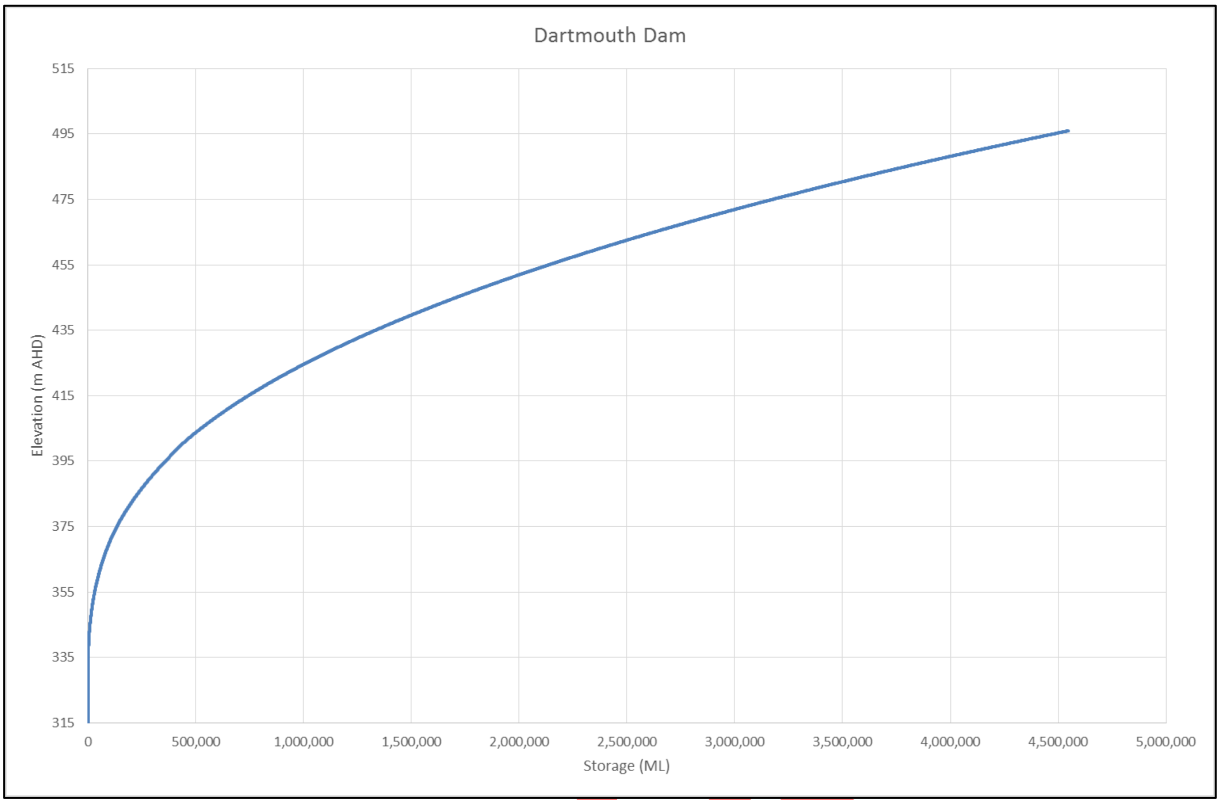

Figure 3-4~~3-4~~: Stage Storage Curve Dartmouth Dam

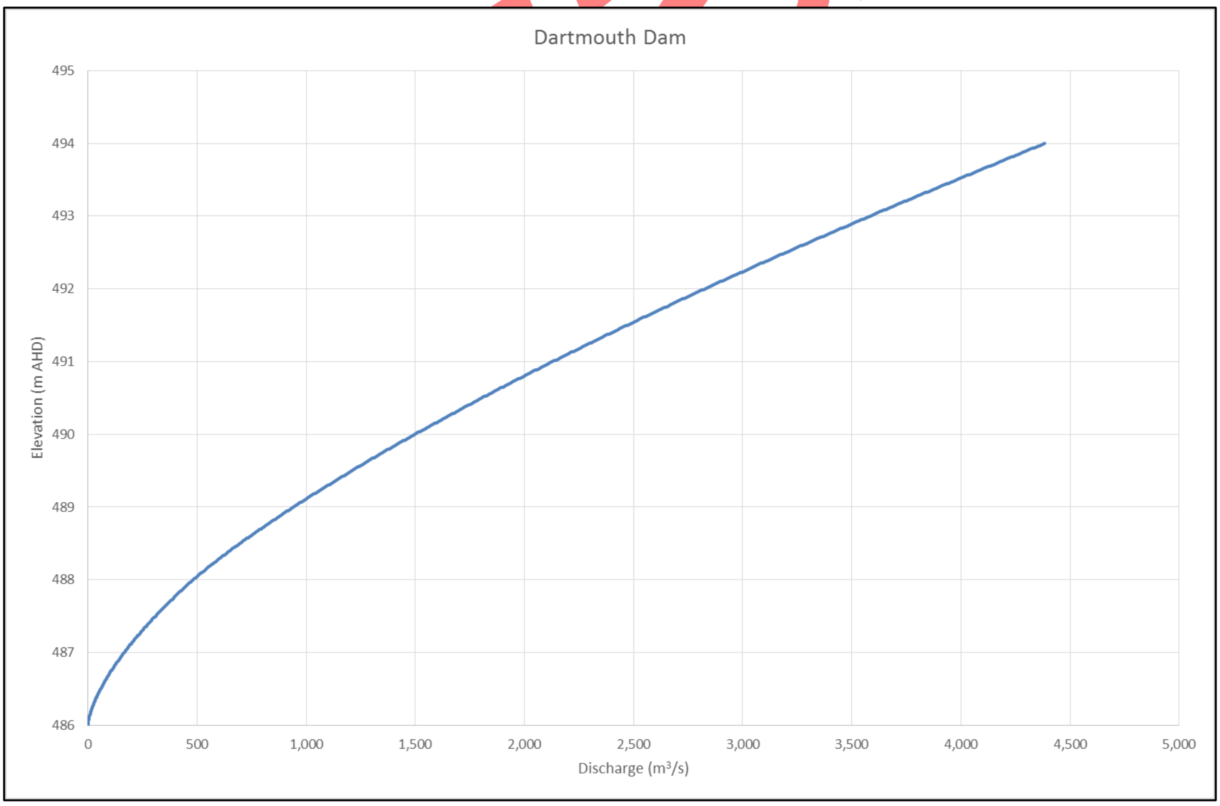

Figure 3-5~~3-5~~: Stage Discharge Curve Dartmouth Dam

3.3 Dam Starting Levels

The available data for dam starting for each flood event is summarised in Table 3-3.

Table 3-3: Dam event start levels (m AHD)

Event	Starting Level	
	Dartmouth Dam (FSL 486.0m AHD)	Hume Dam (FSL 192.0m AHD)
197401	Na	191.58
197410	Na	191.68
197510	Na	191.85
198107	445.07	183.27
198308	411.02	182.24
199210	486.23	191.85
199310	485.60	190.93
199607	480.57	186.09
199610	483.84	190.77
199809	445.09	181.63
201009	438.32	182.88
201010	445.85	189.06
201012	453.46	191.84
201102	456.65	189.87
201109	467.86	191.59
201203	471.31	185.77

4 Review of Ratings

Rating tables or curves are the relationship between a recorded water level at a particular gauging station and the estimated flow at the site.

A key aspect that must be understood is that water levels are routinely measured and ratings are used to convert a water level measurement to an estimate of flow. Flow gauging measurements are not a direct measure of flow, but rather produce an estimate of flow. Flow gauging provides measurements of the water velocity and waterway area which can be combined to estimate flow.

The development and calibration flood hydrology models undertaken has placed substantial attention on a review of the rating relationships in the scale of flows of interest to flood assessment.

The review of ratings required a holistic approach to make best use of available data from multiple sources and to consider different methods to estimate flow. The review and subsequent rating relationships adopted and documented in this report are not yet considered definitive or final. Investigations which may be undertaken in the future may yield further results suitable for more detailed review to either confirm or revise key rating relationships.

The following terminology was applied:

- Highest gauged flow - an estimate of flow from measured velocities and area
- Highest rated flow - an estimate of flow from highest recorded height and the rating relationship
- Rating ratio - highest gauged flow / highest rated flow

The rating ratio can be a good indication of rating reliability but it is dependent on quality of rating extrapolation and should be used with caution. It is important to note that the definition of rating ratio applied herein is the inverse of the rating ratio concept published as part of the Australian Rainfall and Runoff revision projects. The 'rating ratio' definition used in this study was preferred as it offers a more intuitive indicator in that a higher rating ratio would indicate probable higher confidence in the rating relationship.

Table 4-1: Ratings Review

AWRC Number	Station	Owner	Latest Table	Highest						Rating Ratio
				Gauged			Recorded			
				Date	Height	Gauged Flow	Date	Height	Rated Flow	
					m	m^3/s		m	m^3/s	%
401216	Jokers Ck	DELWP	14	24/07/1981	2.93	99	23/09/1998	4.49	288	34%
401203	Hinnomunjie	DELWP	9.01	17/03/1933	0.46	1	23/09/1998	4.04	486	0%
401217	Gibbo Park	DELWP	18	18/09/1975	2.29	55	05/09/2010	3.07	111	49%
401224	Dartmouth Dam	DELWP								
401211	Colemans	DELWP	12.03	03/10/1996	3.92	234	18/07/1974	6.69	679	35%
401204	Tallandoon	DELWP	37	19/07/1974	5.76	686	25/08/1955	6.10	1030	67%
401012	Biggara	NOW	214.02	16/10/2010	2.75	177	04/03/2012	3.53	304	58%
401549	Bringenbong	NOW	30.01	07/06/2016	2.48	133	04/03/2012	3.68	565	24%

AWRC Number	Station	Owner	Latest Table	Highest						Rating Ratio
				Gauged			Recorded			
				Date	Height	Gauged Flow	Date	Height	Rated Flow	
					m	m³/s		m	m³/s	%
401009	Maragle	NOW	385	24/07/1981	1.39	26	21/10/1955	3.33	218	12%
401014	Pinegrove	NOW	319	02/03/2012	3.39	146	15/10/2010	4.11	604	24%
401208	Berringama	DELWP	29	13/07/1975	2.92	75	08/12/2010	4.52	264	28%
401229	Cudgewa North	DELWP	20.01	08/10/1993	1.22	24	04/03/2012	2.89	182	13%
401201	Jingellic	DELWP	905.05	05/03/2012	7.75	1551	05/03/2012	7.91	1625	95%
401013	Jingellic	NOW	204.00	17/07/1995	3.38	121	15/10/2010	7.82	843	14%
401220	McCallums	DELWP	16	27/10/1975	2.76	171	13/07/1975	3.45	286	60%
401015	Yambla	NOW	185.01	15/08/2000	3.06	25	10/01/1974	6.02	110	23%
401011	Hume Dam	NOW								
409016	Heywoods	NOW	220.02	27/06/1931	7.30	2135	26/10/1975	7.25	2048	104%
402222	Kiewa	DELWP	47	24/09/1998	3.71	108	24/09/1998	3.76	130	83%
402205	Bandiana	DELWP	19.01	24/09/1998	3.47	579	24/09/1998	3.58	715	81%
409017	Doctors Pt	NOW	450	27/10/1975	7.05	2043	27/10/1975	7.05	2043	100%
409001	Albury	NOW	100				20/10/1992	5.40		

Outside of the dam spillway ratings, the ratings review concluded that the most reliable ratings are at Gibbo Park and Tallandoon in the mitta model and at Jingellic (Murray River) in the upper model. In the below model, the mainstream ratings at Heywoods, Doctors Point and Albury are considered reliable up to the maximum estimated historical flow.

5 Rainfall Analysis

The rainfall data collected as part of the data collection phase was characterised as either:

- Daily rainfall data recorded at 9am each, or
- Pluviograph rainfall data at non-uniform time intervals.

The daily rainfall station data represents a total rainfall for one day, usually measured and recorded as the depth of rainfall in the 24 hours to 9 am on the date of the record. The aggregation of daily rainfall station data provided a good estimate of the spatial variability of the total event rainfall.

Pluviograph rain station data records rainfall as it falls over time. This type of rainfall record describes the temporal pattern of rainfall.

Rainfall analysis was undertaken to efficiently remove obvious errors or suspect data in the rainfall dataset.

The rainfall analysis was generally undertaken in the following sequence:

- Total rainfall depths for each event were visually inspected using a Google Earth map generated from point rainfall values at stations in the rainfall network. A typical example of this type of map is shown in Figure 5-1,
- Pluviograph data was verified against neighbouring stations,
- Tabulated daily rainfall totals for the each event were compared to neighbouring stations for validation.
- Rainfall stations were omitted throughout the calibration process when other data such as simulated stream level/flow data indicated that the data might be erroneous.

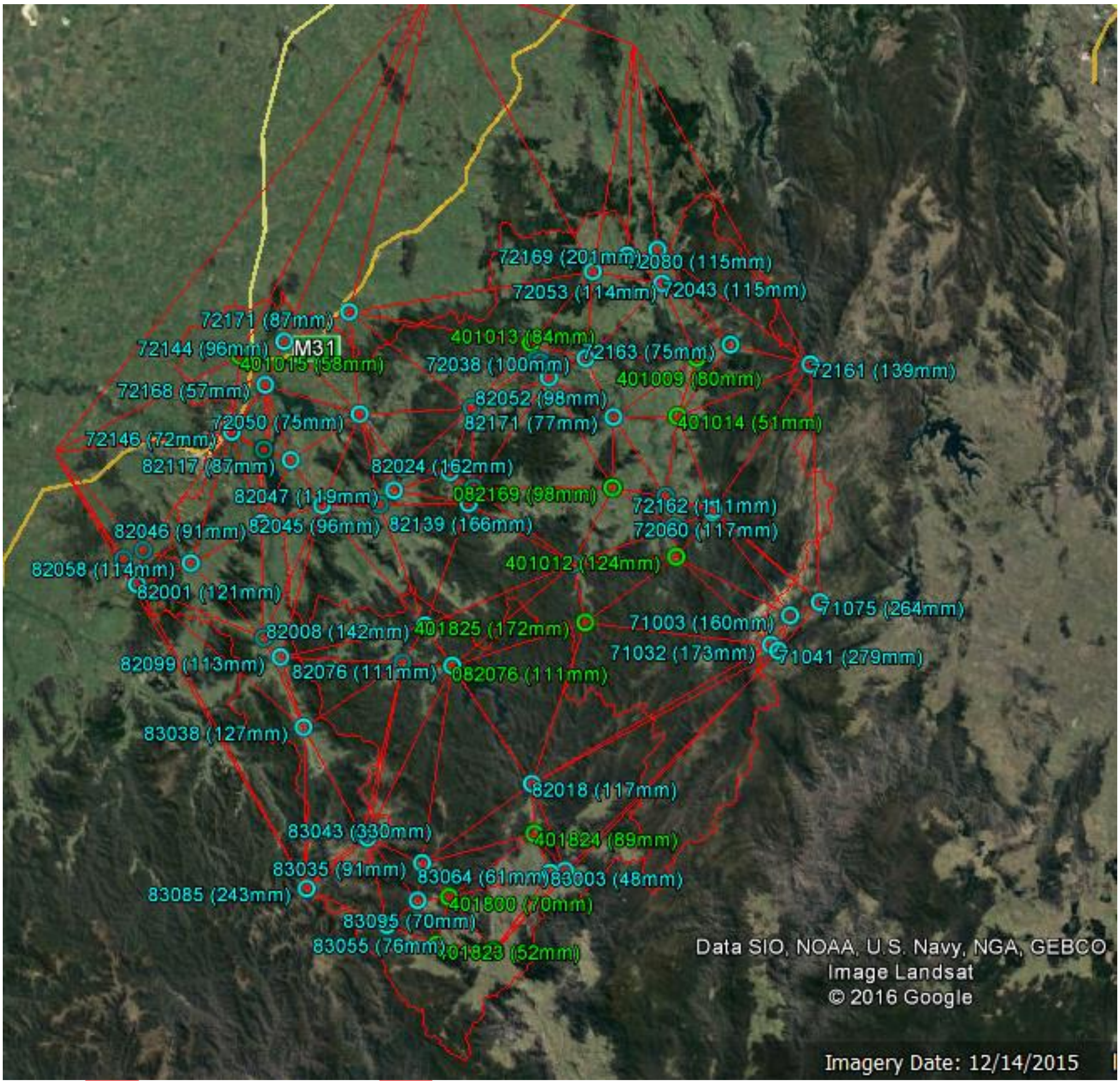

Figure 5-1~~5-1~~: Rainfall Network 201009 Event

Once the user was satisfied that rainfall depths were realistic, the depth of rainfall at each sub-catchment in the model was derived and the temporal pattern of the nearest pluviograph assigned to this depth. A method of triangulation, similar to Thiessen polygons, was used to determine sub-catchment depth.

This process results in a "virtual" pluviograph being derived at the centroid of each sub-catchment in the model. An example of the results of the rainfall analysis is shown in Figure 5-2.

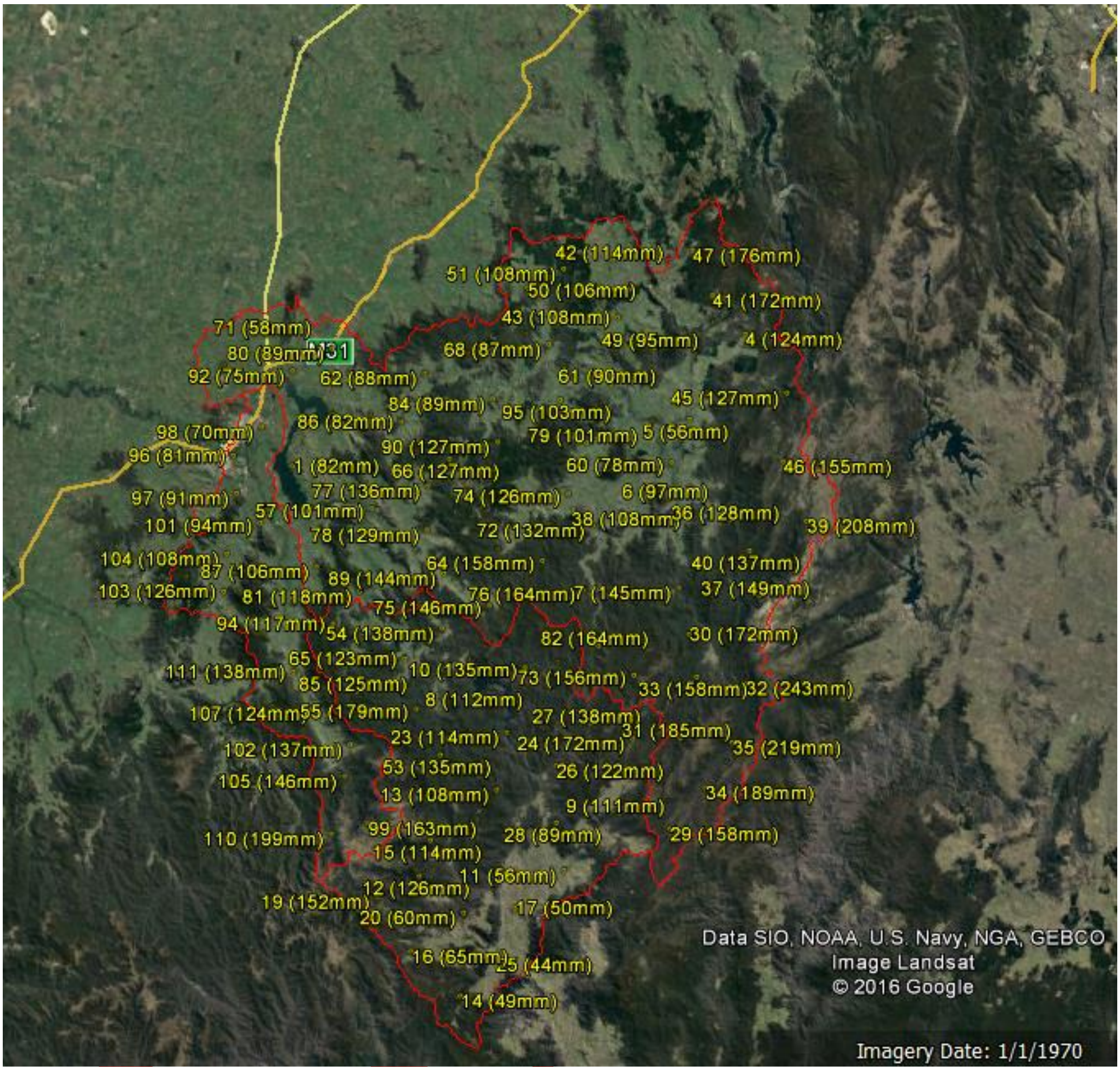

Figure 5-2~~5-2~~. Rainfall Distribution 201009 Event

Maps of the total rainfall in each event totals are shown in Appendix B.

6 Model Development

6.1 Basin Representation

The Upper Murray catchment, defined in this study is, shown in Figure 6-1, represents the main contributing tributaries and the mainstream of the creek. When considering the sub-division to adopt in this investigation, the following factors were considered:

- Scale/definition of models
- Efficiencies of model run times
- Uncertainties in rainfall and ratings
- Operational requirements for derivation of inflows to dams and flows in catchments below dams and time efficiency to run and analyse results

It was recognised that decreased scale (increased number of models) could provide an opportunity for applying locally specific loss and routing parameters. However increased division and number of models would add greater complexity (hence potential for errors) also decreases the potential to make best use of available gauge data with consideration of rating uncertainties. The final adopted basin sub-division was considered an optimal trade-off between the factors above.

6.2 Model Development

The hydrologic models were developed using 3-second SRTM data downloaded from NASA. CatchmentSIM (Ryan 2004) was used to delineate the Upper Murray River to Albury catchment.

As shown in Figure 6-1, this catchment was further subdivided into 3 sub-catchments for modelling purposes based on the location of key points of interest:

- Mitta Mitta River to Tallandoon (mitta model);
- Upper Murray River to Hume Dam (upper model); and
- Murray River below Hume Dam to Albury (below model).

Besides generating vectors for the URBS models, CatchmentSIM also produced shape files for use within a flood modelling platform such as FEWS and kmz files so that users can examine model setup within Google Earth.

A time increment of one hour was adopted for all model calibration. It should be noted that altering the time increment may require have an effect on some model parameters, particularly the continuing loss rate (lower loss rate with increasing time increment).

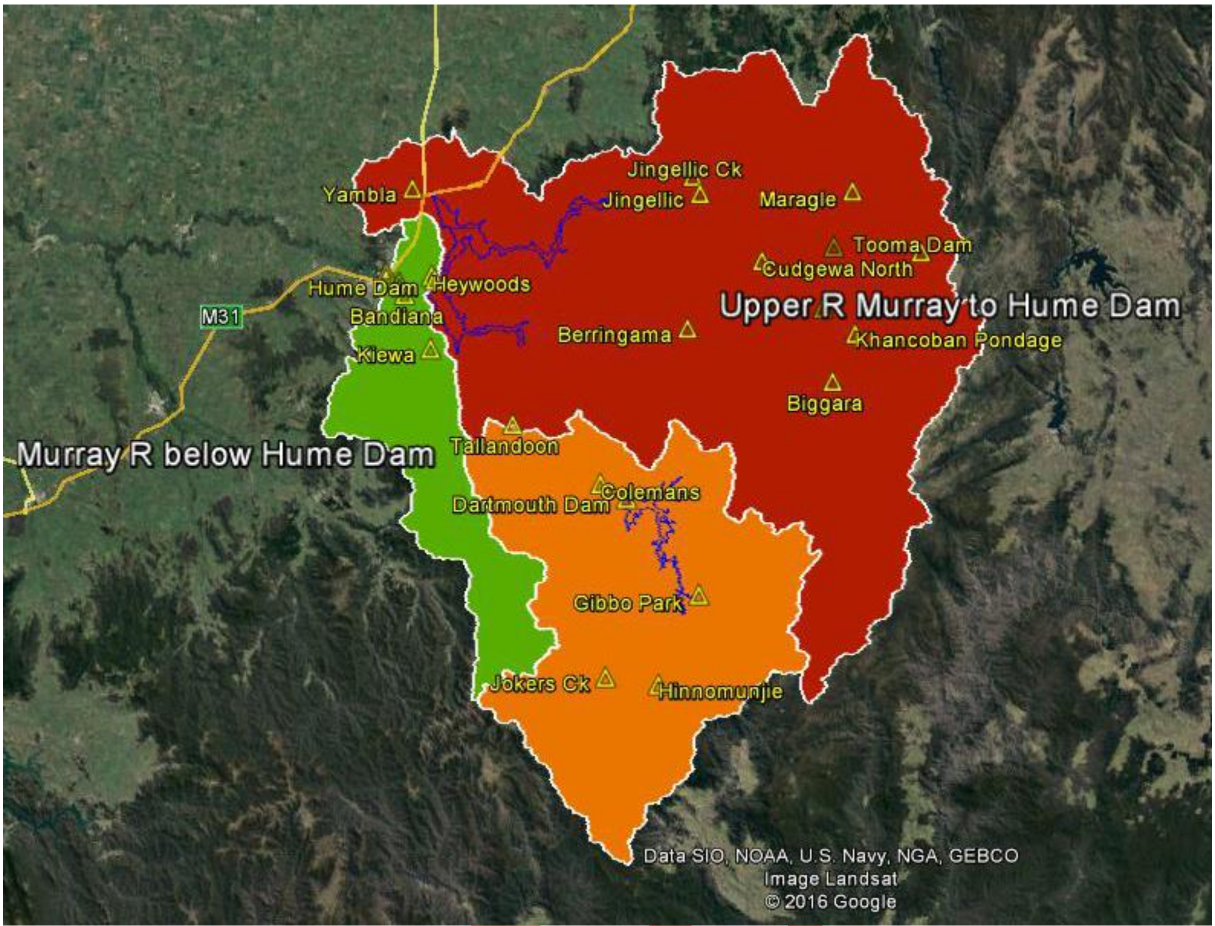

Figure 6-16~~6-1~~: Upper Murray R URBS Models

6.2.1 Mitta Mitta River to Tallandoon

The Mitta Mitta River to Tallandoon URBS model (mitta model) consists of 51 subareas representing a catchment area of 4,741 km^2 with height and flow output at:

- JOKERS_CK
- HINNOMUNJIE
- GIBBO_PK
- DARTMOUTH_DAM
- COLEMANS
- TALLANDOON

There are two versions of the mitta model; a pre Dartmouth Dam version for events prior to 1979 and a post Dartmouth Dam version for events post 1979.

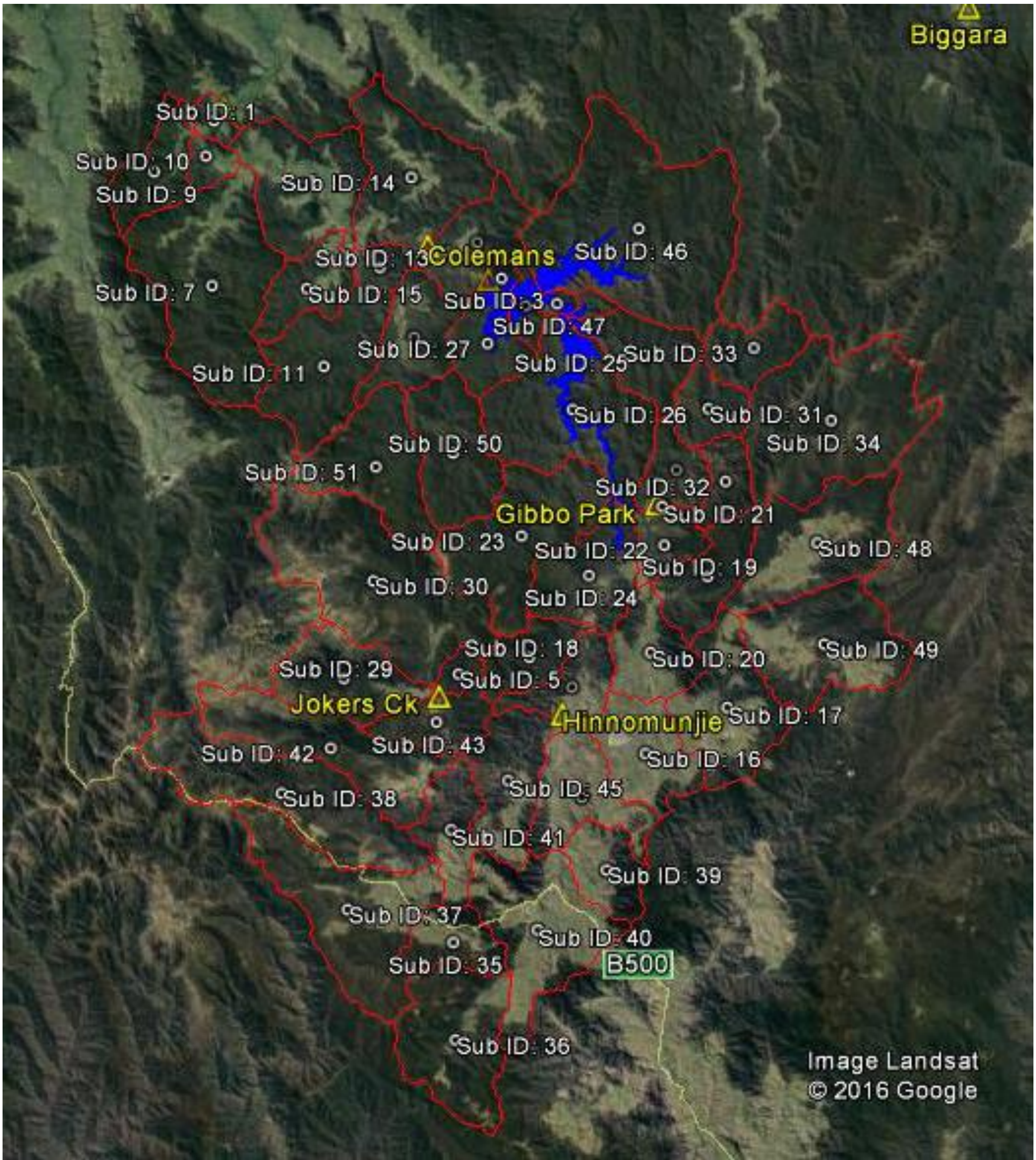

Figure 6-26~~-2~~: Mitta Mitta River to Tallandoon URBS Model

6.2.2 Upper Murray River to Hume Dam

The Upper Murray River to Hume Dam URBS model (upper model) consists of 95 subareas representing a catchment area of 10,592 km^2 (excluding the Mitta Mitta River to Tallandoon} with height and flow output at:

- BIGGARA
- KHANCOBAN
- BRINGENBON
- MARAGLE
- PINEGROVE
- BERRINGAMA
- CUDGEWA_NORTH
- R_JINGELLIC
- CK_JINGELLIC
- YAMBLA
- MCCALLUMS
- HUME DAM

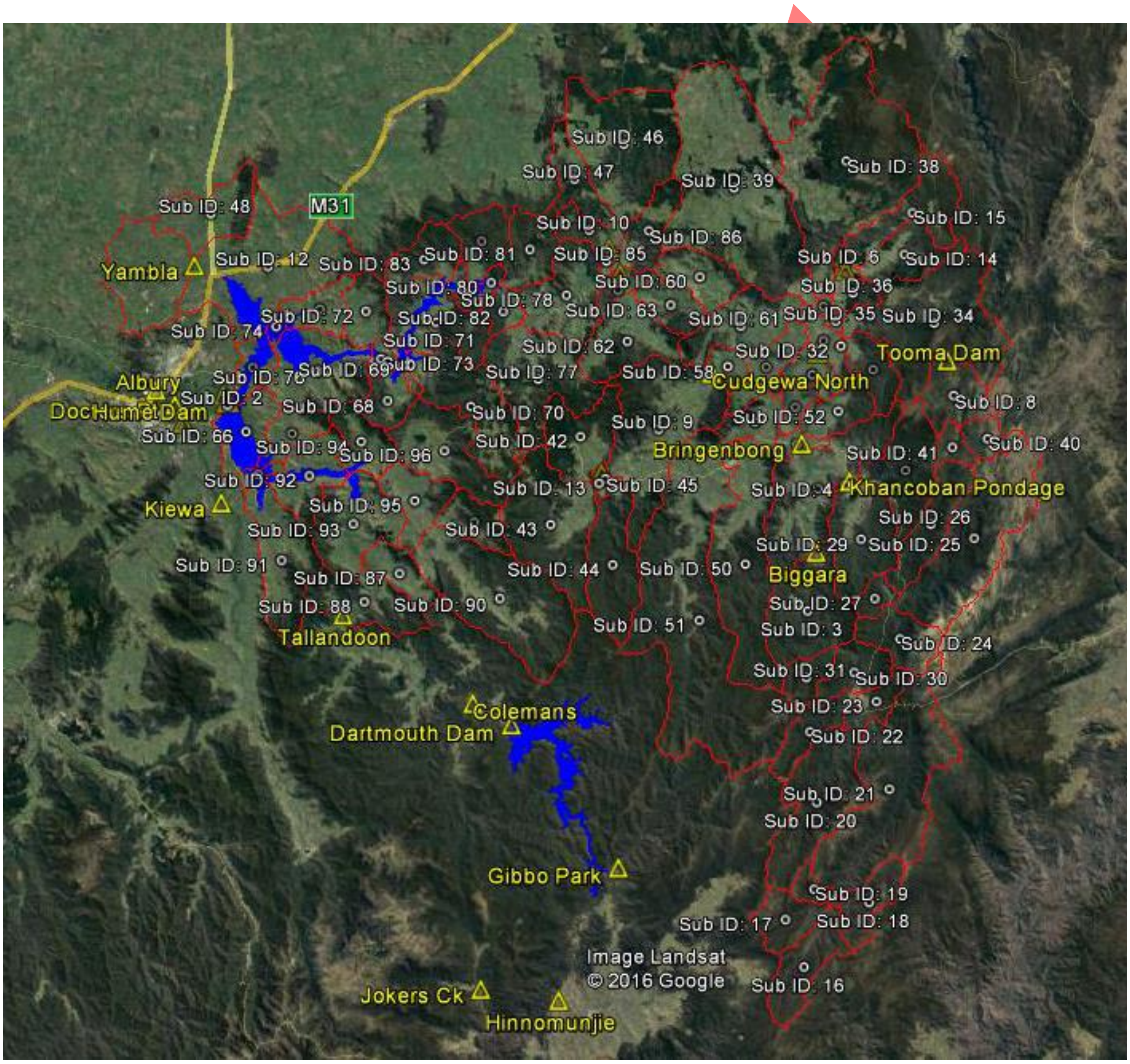

Figure 6-36~~-3~~: Upper Murray River to Hume Dam URBS Model

The upper model takes the modelled output from the mitta model as input at Tallandoon.

Even though it simulates the inflow to Khancoban, the upper model cannot simulate the outflow as Khancoban is a gated storage. The model matches the recorded outflow from Khancoban Pondage in estimating downstream flows.

To account for an apparent longer travel time, a reach length factor of 2.0 as adopted for the mainstream downstream of the junction of Cudgewa Creek to Murray River at Jingellic.

6.2.3 Murray River below Hume Dam to Albury

The Murray River below Hume Dam to Albury URBS model (lower model) consists of 13 subareas, representing a catchment area of 2,009 km^2 mostly the Kiewa River catchment, with height and flow output at:

- HEYWOODS
- KIEWA
- BANDIANA
- DOCTORS_PT
- ALBURY

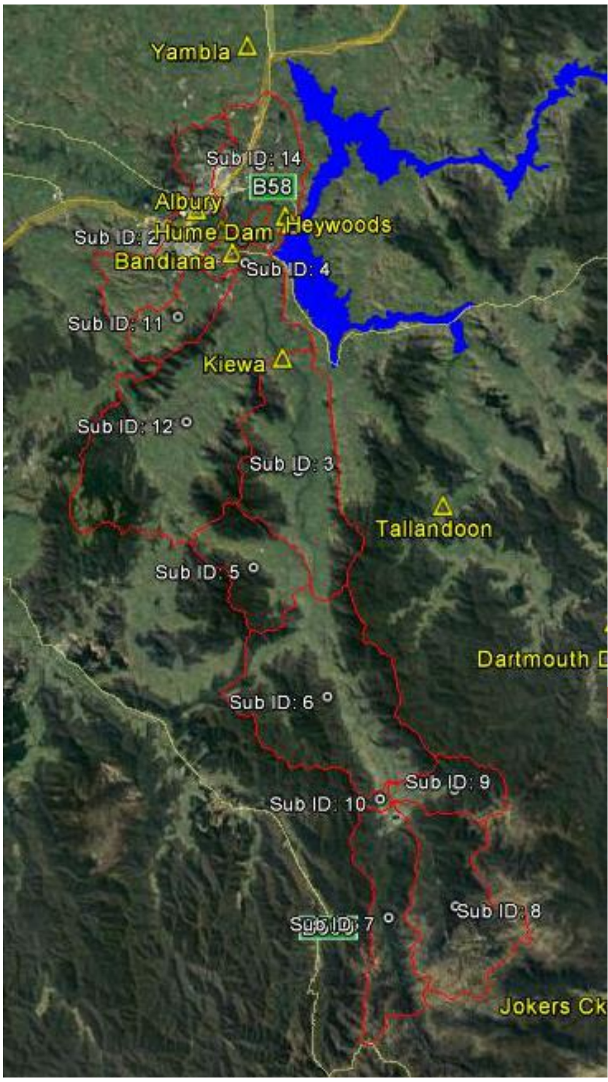

Figure 6-4~~6-4~~: Murray River below Hume Dam to Albury URBS Model

The model matches the rated flows at Heywoods in estimating downstream flows.

In some events, minor flood levels at can occur at Albury solely from runoff from the Kiewa River without any significant contribution from Hume Dam.

6.3 Model Features

Semi-distributed network models are commonly used in Australian flood hydrology and are recommended in Australian Rainfall and Runoff (IEA 2003) for use in large catchment flood hydrology studies.

URBS (Carroll 2012) combines a rainfall-runoff model with a runoff routing model and is tailored for use as a flood forecasting model. The model is used nationally by BoM for flood forecasting. URBS was selected as the preferred software for the flood hydrology models for the following reasons:

- To be consistent with BoM flood forecasting model software
- It supports calendar time inputs for real time application & elapsed time simulations for design applications
- It is easily linked to hydrometric inputs for real time use (Enviromon & FEWS)
- It can be readily setup cascade model catchments
- It can be used as a continuous simulation model or as an event model.
- It has several useful features for improved flood routing calibration
  - Range of rainfall loss models and has capability towards continuous simulation
  - Can incorporate baseflow
  - Inclusion of ratings and dependent ratings to enable input and comparison with recorded water levels
  - Matching – for better use of water level forecasts
  - Loss and bypass functions can be used for unique flood routing situations
  - Inflows to dam can be estimated by reverse routing to aid calibration
- It can be used for calibration, forecasting, deterministic & Monte-Carlo design flood estimation

The version of the model used in this study was 6.27 which is licenced for the Murray Darling Basin Authority.

6.3.1 Loss Model

In this study, an initial loss/continuing loss (IL-CL) type rainfall loss model was selected for the rainfall runoff component of the model. The IL-CL type model is a simplistic yet effective representation of the rainfall-runoff process and is commonly used in flood modelling. Essentially, the initial loss absorbs the depth of rain that occurs between the event start time and the commencement of runoff which is typically defined by the initial rise in water levels at gauging stations. The continuing loss rate lumps together on-going losses such as infiltration, interception, evapo-transpiration which occur during a storm.

Spatially varying initial and continuing loss rate can be accounted in the URBS model but typically requires comprehensive detail in rainfall data and a dense network of gauging stations with good quality rating relationships to obtain value for this level of complexity. In this study, initial loss and continuing loss rate were applied uniformly over each catchment model.

To calibrate the rainfall-runoff component of the model, two parameters are required:

- Initial loss (IL) in mm which is selected to match recorded rising limb at gauging stations, and;
- Continuing loss (CL) in mm/hr which is selected to match the rated peak flow and volume at gauging stations and dams.

6.3.2 Snow Melt

The StateWater report of 2009 states that: *“Although the higher elevations of the Hume catchment receive snow falls during winter, snow melt was not found to be a significant factor in the calibration events due to the very small percentage of the catchment that is affected by snow fall.“*

Based on this assessment snow melt was ignored in the calibration events.

6.3.3 Routing concepts

URBS simulates catchment routing by a network of conceptual storages representing the sub catchment routing, channel (stream network) routing and reservoirs.

The URBS split model mode, used in this study, separates the catchment and channel routing for each sub-catchment. First, the excess rainfall on a sub-catchment is routed to the creek channel. The lag of the sub-catchment storage is assumed proportional to the square root of the sub-catchment area. The inflow from the sub-catchment into the channel is assumed to occur at the centroid of the sub-catchment. The sub-catchment ‘outflow’ is then routed along a channel reach using linear (or non-linear) Muskingum method. The channel reach lag time is assumed proportional to the length (or derivative) of the reach.

The sub-catchment routing is defined by:

$$S_{catch} = \beta.\sqrt{A}.Q^{m}$$

S_{catch} = catchment storage
β = catchment lag parameter
A = area of sub-catchment [km^2]
m = catchment non-linearity parameter

Channel routing is defined by:

$$S_{chnl} = \alpha.f.L(xQ_u + (1-x)Q_d)^n$$

S_{chnl} = channel storage
α = channel lag parameter
f = reach length factor
L = length of reach [km]
Q_u = inflow at upstream end of reach (includes catchment inflow)
Q_d = outflow at downstream end of the channel reach [m3/s]
x = Muskingum translation parameter (normally 0.2 to 0.3)
n (exponent) = non-linearity exponent (normally use n = 1)

The sub-catchment routing exponent (m) is typically adopted to be 0.8. For channel routing, linear Muskingum routing is typically adopted (exponent n=1). To calibrate the routing behaviour of the model, the main two parameters that are varied to be catchment specific are:

- Alpha (α) which is a measure of channel travel time
- Beta (β) which is a measure of sub-catchment storage

For linear Muskingum channel routing, the value of alpha is close to the inverse of travel time in km/hr and may be initially estimated from recorded data. A larger beta value simulates more sub-catchment storage and produces a longer, slower hydrograph recession.

6.3.4 Impervious Areas

Impervious areas such as large urbanised areas or water surfaces generate 100% runoff during floods. In the URBS model, the reservoir areas of Dartmouth and Hume Dam were included in the model as impervious areas.

6.3.5 Dam Inflows

Version 6.27 of the URBS model may be configured to calculate the inflow to a dam assuming reverse level pool routing. This feature was used to derive an estimated or rated inflow to both Dartmouth and Hume Dams.

Inflow = Outflow + Rate of Change of Storage

The rate of change of storage is calculated by converting the time series of water levels into storage volumes and estimating the rate of change of storage per time increment. Because recorded water level cannot be recorded with great accuracy of precision and because of the slope of the water surface in long reservoirs, small changes in water level can be converted to large inflow rates. Additionally, the calculation is inherently unstable and some smoothing of the rate of change of storage component of the inflow is required.

For an ungated storage like Dartmouth Dam, the outflow is simply related to the height over the fixed crest spillway and is determined in URBS by reference to the spillway rating. For a gated dam like Hume Dam, the outflow must be derived external to the model. In the case of Hume Dam, the outflow is assumed to be the rated flow at Heywoods.

The smoothing factor (FS) and the time increment (T) used to derive the reverse routed inflow hydrograph.

Figure 6-5 shows that for a time increment of 6 hours, varying the smoothing factor from 0 to 1 produces a much smoother reverse routed inflow hydrograph without affecting timing of the peak which often occurs when too much smoothing is adopted.

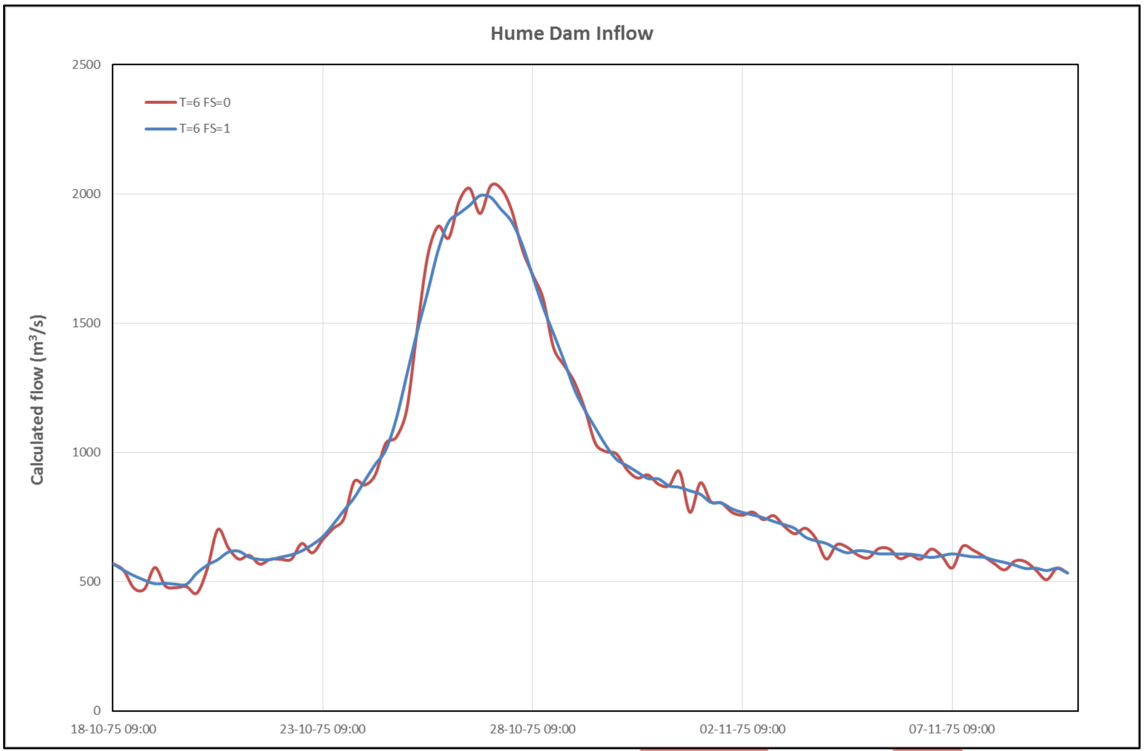

Figure 6-5~~6-5~~: Effect of Smoothing on Derived Inflow

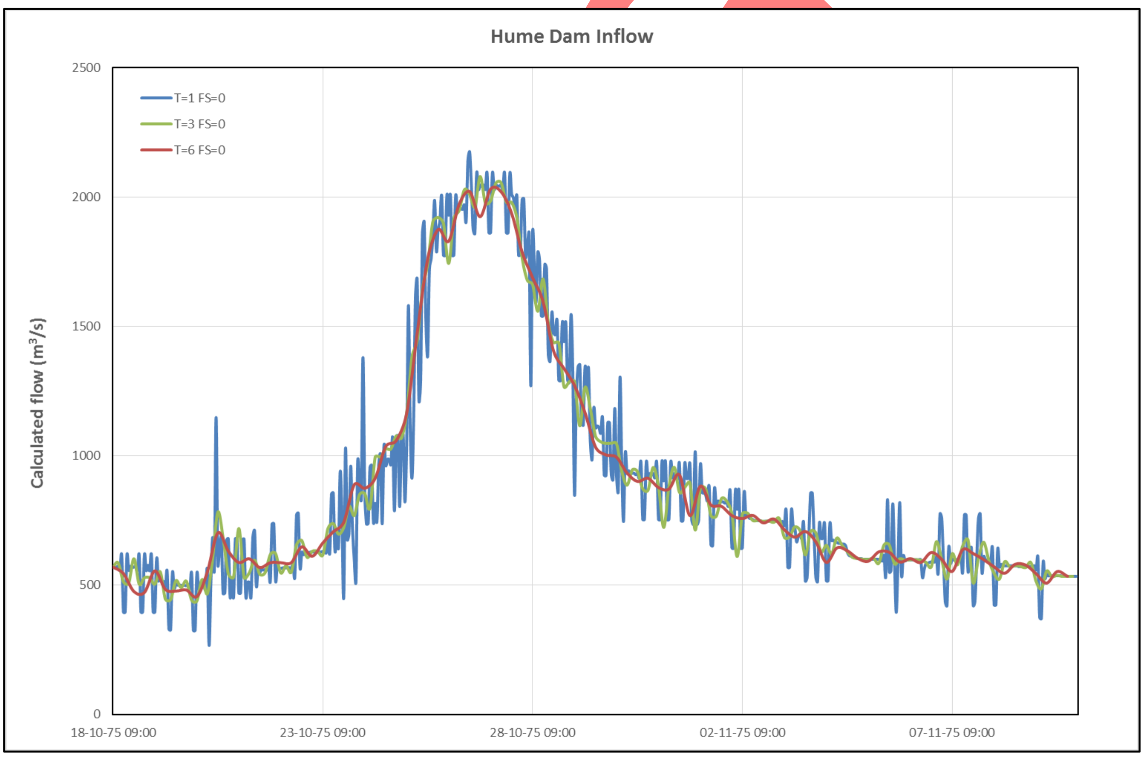

Figure 6-6~~6-6~~: Effect of Time Increment on Derived Inflow

Figure 6-6 shows the effect of varying the time increment from 1 to 6 hours on the reverse routed inflow hydrograph without any smoothing (FS=0). A time increment of 6 hours generates a much smoother reverse routed inflow hydrograph than a 1 hour time increment.

In all cases, total volume of the inflow hydrograph stayed constant.

For this study, inflows hydrographs for Dartmouth and Hume Dams were derived using a time increment of 6 hours and a smoothing factor of 1.

6.3.6 Baseflow

Baseflow is considered extremely important in this study, as it can be significant a significant component of the total inflow into Dartmouth and Hume Dams during a flood event.

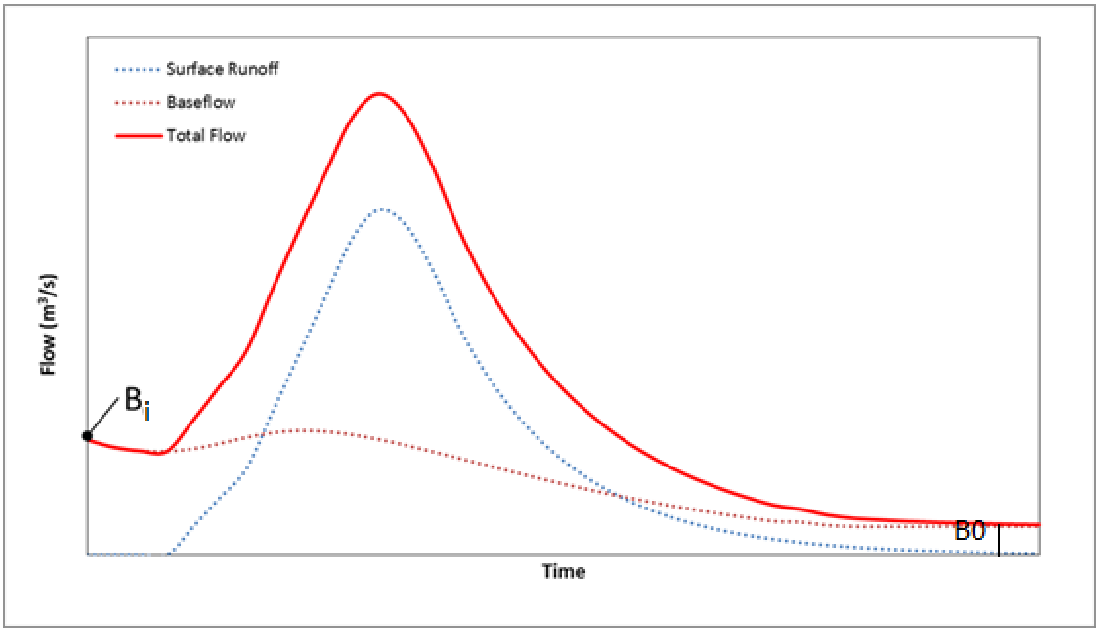

Figure 6-7~~6-7~~: Baseflow Model

Baseflow was calculated using the linear baseflow method in URBS (BM=1) which applies the following equation:

$$BF_{(t)} = B0 + (BF_{(t-1)} - B0) * BR + QF \times BC$$

B0 = persistent baseflow
BF(t) = the baseflow at time t,
BF(t-1) = the baseflow at time t-1.
BR = the baseflow recession constant (24 hour value)
QF = the quickflow component of the hydrograph.
BC = the baseflow constant.

As baseflow can be a significant component of the total inflow to Dartmouth and Hume Dams, baseflow was included in the mitta and upper models. The inclusion of baseflow was considered of value to improve model calibration or to assist dam flood operations.

The baseflow parameters were identified by adjusting the BC and BR parameters until a suitable fit between the end of the surface flow hydrograph and the shape of the baseflow recession was achieved. This procedure is described in more detail in Section 2.3 of Book V in AR&R (IEAust, 2003). Trial and error fitting of the baseflow parameters was undertaken using the same parameters for the selected events until the best fit was obtained across most of the events.

The initial baseflow (B_i) at Hume Dam at the start of each event was especially important as baseflow could account for up to 25% of the total inflow volume. In this context baseflow is not in the true meaning of the term. For an operational model, the initial baseflow at Hume Dam at the start of the event and may be a combination of residual flows from a previous event and controlled releases from upstream storages.

For gauging stations, setting URBS_BASF=TRUE means that the first value of rated flow in the corresponding '.g' file was treated as initial baseflow at that station.

For inflow to Dartmouth and Hume Dams, URBS_BF, listed in Table 6-1, was set to an appropriate initial baseflow value based on the average inflow rate (derived from the reverse routed inflow hydrograph) into the dam during the first few days of the event.

Table 6-1: Initial Baseflow at Dams

Event	Initial Baseflow (m^3/s)			
	Dartmouth Dam	Comment	Hume Dam	Comment
197401	Na		165	Releases being made at start of event. Adopt starting flow at Heywoods
197410	Na		500	Releases being made at start of event. Adopt starting flow at Heywoods
197510	Na		500	Releases being made at start of event. Adopt starting flow at Heywoods
198107	25	From derived inflow	100	From derived inflow
198308	0	From derived inflow	0	No flood releases at start of event
199210	20	Flow over spillway	525	Releases being made at start of event. Adopt starting flow at Heywoods
199310	15	From derived inflow	325	Releases being made at start of event. Adopt starting flow at Heywoods
199607	0	From derived inflow	10	Flow at Heywoods at start
199610	50	Flow at Colemans	240	Flow at Heywoods at start
199809	0	From derived inflow	0	No flood releases at start of event
201009	50	From derived inflow	150	From derived inflow
201010	25	From derived inflow	80	Flow at Heywoods at start
201012	40	From derived inflow	260	Flow at Heywoods at start
201102	0	From derived inflow	125	Flow at Heywoods at start
201109	0	From derived inflow	80	Flow at Heywoods at start
201203	5	Flow at Colemans	50	Flow at Heywoods at start

6.3.7 Inflows from Snowy Mountains Scheme

The Upper Murray River system receives releases from the Snowy Mountains Hydroelectric Scheme. These must be accounted for the upper URBS model.

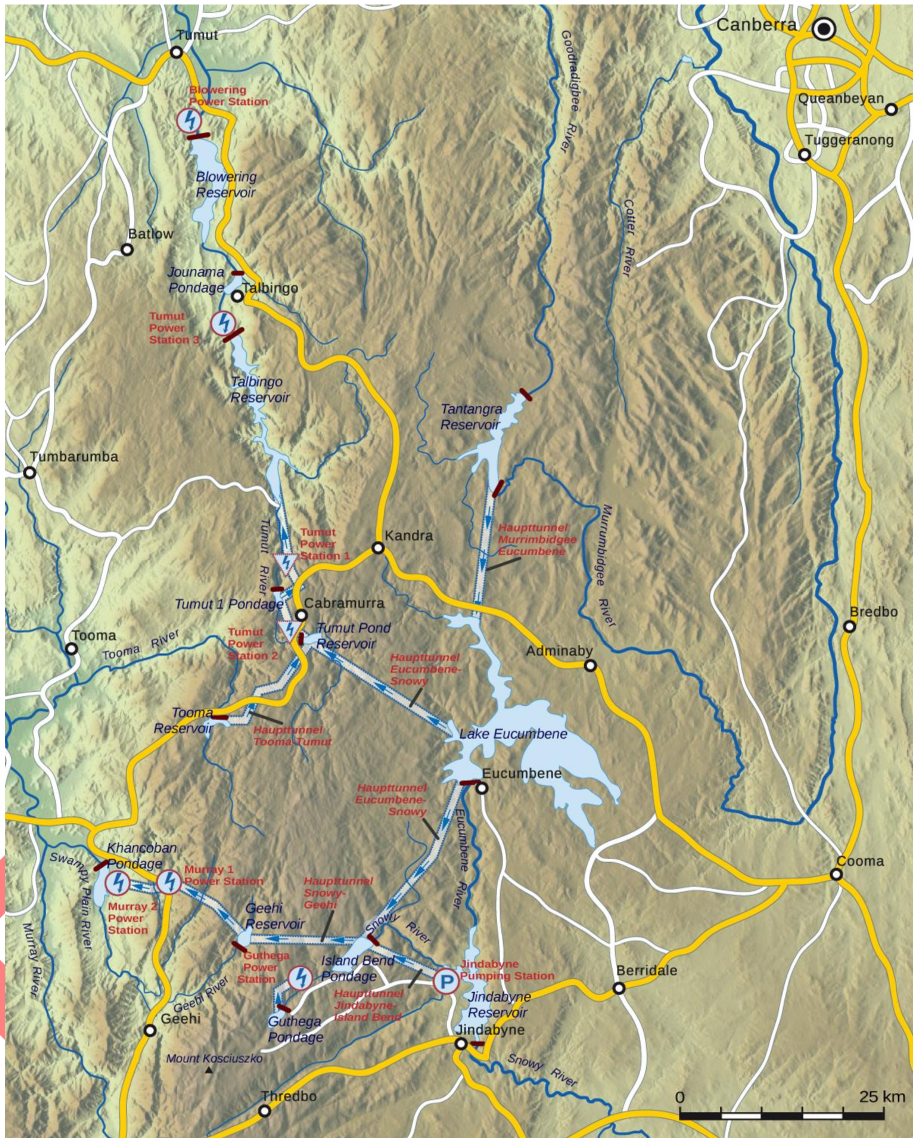

Figure 6-8~~6-8~~: Inflows into the Upper Murray from the Snowy Mountains Scheme (Source MDBA)

The following assumptions have been made in configuring the upper model:

1. Inflows to Tooma Dam are diverted via the Haupttunnel into the upper reaches of the Tumut River. In the Upper Murray model, it is assumed that all inflow to the dam is lost (i.e. diverted into the Tumut River) and that there are never any outflows from Tooma Dam into the Tooma River. Given the catchment area of Tooma Dam is only 155 km^2 (about 1% of the total catchment area to Hume Dam), this is considered a reasonable assumption.
2. Releases from Murray 1 Power Station flow into Khancoban Pondage which has a catchment area of about 780km^2. The total inflow into Khancoban Pondage is the combined releases from Murray 1 Power Station and local runoff from Swampy Plains River which is generated in the upper model. Outflow from the storage is

controlled. In the Upper Murray model, the outflows of Khancoban Pondage have been matched during calibration.

6.3.8 Drowned River Reaches

The influence of drowned reaches through the dam reservoirs can be represented by reducing the relative travel time in reservoir reaches. In the URBS model, this is achieved by using a reduced reach length factor; in this case a factor of 0.5 effectively halves the travel time in the reservoir reaches. The factor of 0.5 is similar to that adopted in studies of south east Queensland and has been tested on other large storages.

Given that Lake Hume can extend as far as 60 km upstream of the dam wall, it was considered important to simulate the reduction in travel times in the effected drowned reaches.

As Lake Dartmouth does not extend as far upstream of Dartmouth Dam, the effect of drowned reaches have been ignored.

7 Model Calibration

7.1 Calibration Methodology

Selected gauge locations were identified as primary calibration points, based on the amount of data available and the reliability of the rating at that point.

For the dam models, the dam water level was selected as the primary calibration location, with the aim of matching the rise in water level if the dam was below the fixed crest spillway at the start of the event and the outflow, if any, over the spillway crest.

Several locations, listed in Table 7-1~~Table 7-1~~, were identified as primary locations after examination of the data available and the rating reliability.

Table 7-1: Model calibration locations

Model	Calibration location	
	Primary	Secondary
mitta	• Dartmouth Dam water level and reverse routed inflow	• Hinnomunjie water level • Tallandoon water level
upper	• Murray R at Jingellic water level • Hume Dam water level and reverse routed inflow	• Bringenbrong water level • Pinegrove water level
below	• Doctors Pt water level and rated flow	• Albury water level

The general methodology in calibrating each catchment model followed the process below:

1. Dam starting level was selected from available data
2. Inflows to Dartmouth and Hume dams were derived by reverse routing
3. Initial baseflow was selected from the derived inflow hydrographs and/or immediate downstream stations
4. Initial loss was selected to match the start of rise at gauging stations
5. Continuing loss rate was selected to match volume at primary locations
6. Alpha was adjusted to match the timing of the peak at primary locations
7. Beta was adjusted to match the surface flow recession at primary locations
8. Conceptual storage parameters, alpha, and beta values were readjusted until a good match was obtained for the overall shape and timing of hydrograph at gauging stations and water levels at dams
9. Repeat until a good match was obtained

Often this process is a compromise and requires judgement of the best data and ratings as it is not always possible to match the recorded height or estimated flow at every location with a single set of parameters for the catchment.

7.2 Calibration Performance Ranking and Weighting Parameters

A ranking scheme was developed to assess the calibration performance at the primary and secondary locations for the calibration events. The criteria used to assess calibration performance considered quantitative measures of the flood hydrograph calibration and qualitative assessment of the quality of data and significance (magnitude) of the flood event. Each calibration result was assigned a class score on a five point scale ranging from zero (no data) to five (excellent calibration).

The calibration class scores were then used to weight the parameters for each event calibration to derive recommended model parameters.

Table 7-2~~Table 7-2~~ presents a summary of the criteria used to rank the quality of calibration and weight the parameters derived in the calibration events.

Table 7-2: Criteria for ranking and weighting of calibration events

Class	Score	Peak ratio	Volume ratio	Nash-Sutcliffe	Event magnitude	Quality of rainfall data
Excellent	5	<±10%	<±15%	≥0.95	90%	>2008
Good	4	<±15%	<±25%	≥0.90	75%	>2000
Fair	3			≥0.85	50%	>1990
Poor	2	<±50%	<±50%	≥0.50	25%	<1970
No data/exclude calibration	0	>±50%	>±50%	<0.5	0%	

Peak ratio (PR) represents the difference between the calculated (modelled) peak flow and the estimated (rated) peak flow. The estimated peak flow is derived using the recorded peak height and the gauge site rating curve.

Volume ratio represents the difference between calculated (modelled) event volume and the estimated event volume. The estimated event volume is calculated by converting the recorded water level hydrograph to a rated flow using the gauge site rating curve.

The Nash-Sutcliffe (NS) coefficient (or coefficient of efficiency) represents the calibration event modelled hydrograph goodness of fit (i.e. shape and timing). Nash-Sutcliffe can range from $-\infty$ to 1, with a NS value of 1 being a perfect fit. Generally, NS values greater than 0.8 are considered to be acceptable.

The magnitude weighting depended on size of the flood event in comparison with the other events in the calibration set with the top 10% of events given the highest weighting score of 5.

Data quality varied with time with far higher quality data available in later events which were weighted accordingly.

Users may choose to include or exclude a particular event from the parameter weighting by changing the User Rating from 1 (include) to 0(exclude).

7.3 Mitta Model Calibration Results

Thirteen post Dartmouth events were used to calibrate and validate the Mitta Mitta River to Tallandoon catchment model and a summary of the results is presented in this section.

Weighting of each event used to derive the model parameters is summarised in Table 7-3 ~~Table 7-3~~.

Table 7-3: Calibration Parameters Mitta Mitta River Model

Event	Calibration parameters					Calibration performance ranking				User Ranking
	IL	CL	Alpha	Beta	m	PR	VR	NS	Weight	
198107	15	3.0	0.30	6.0	0.8	0	5	0	**8%**	1
198308	10	2.3	0.30	5.0	0.8	0	5	0	**7%**	1
199210	0	2.4	0.30	5.0	0.8	0	2	0	**4%**	1
199310	35	0.9	0.25	3.0	0.8	0	4	0	**8%**	1
199607	0	2.4	0.22	5.0	0.8	0	5	2	**9%**	1
199610	0	1.7	0.40	5.0	0.8	0	5	0	**8%**	1
199809	10	2.2	0.20	3.0	0.8	0	5	2	**11%**	1
201009	25	3.0	0.30	3.0	0.8	4	5	0	**14%**	1
201010	40	7.0	0.25	3.0	0.8	0	5	0	**9%**	1
201012	35	4.0	0.25	5.0	0.8	0	2	0	**5%**	1
201102	90	6.5	0.25	3.0	0.8	0	5	0	**9%**	1
201109	5	4.2	0.25	5.0	0.8	0	5	0	**8%**	1
201203	15	7.0	0.30	4.0	0.8	0	0	0	**0%**	0

The calibration parameters were reasonably evenly weighted between all events except 201203.

The calibration of the mitta model to the rated inflow to Dartmouth Dam is shown in Table 7-4 and calibration plots in Appendix D.

Table 7-4: Calibration Performance Mitta Mitta River Model at Dartmouth Inflow

Event	Flow			Volume			Nash Sutcliffe
	Cal m^3/s	Rated m^3/s	PR	Cal ML	Rated ML	VR	
198107	636	338	1.88	241,752	224,861	1.08	0.11
198308	489	309	1.58	106,625	110,989	0.96	0.21
199210	299	225	1.33	92,001	113,631	0.81	0.15
199310	1,009	631	1.60	175,688	197,499	0.89	0.49
199607	316	238	1.33	235,519	217,967	1.08	0.76
199610	702	440	1.60	523,405	505,647	1.04	0.42
199809	1,220	779	1.57	187,452	189,708	0.99	0.62
201009	1,021	940	1.09	257,344	262,233	0.98	-0.56
201010	550	243	2.26	126,382	138,926	0.91	-0.17
201012	240	166	1.44	91,004	79,017	1.15	0.25

Event	Flow			Volume			Nash Sutcliffe
	Cal	Rated	PR	Cal	Rated	VR	
	m^3/s	m^3/s		ML	ML		
201102	357	168	2.12	150,345	153,147	0.98	-0.40
201109	127	65	1.97	31,770	32,590	0.97	-2.25
201203	404	1,278	0.32	149,921	479,200	0.31	-0.33

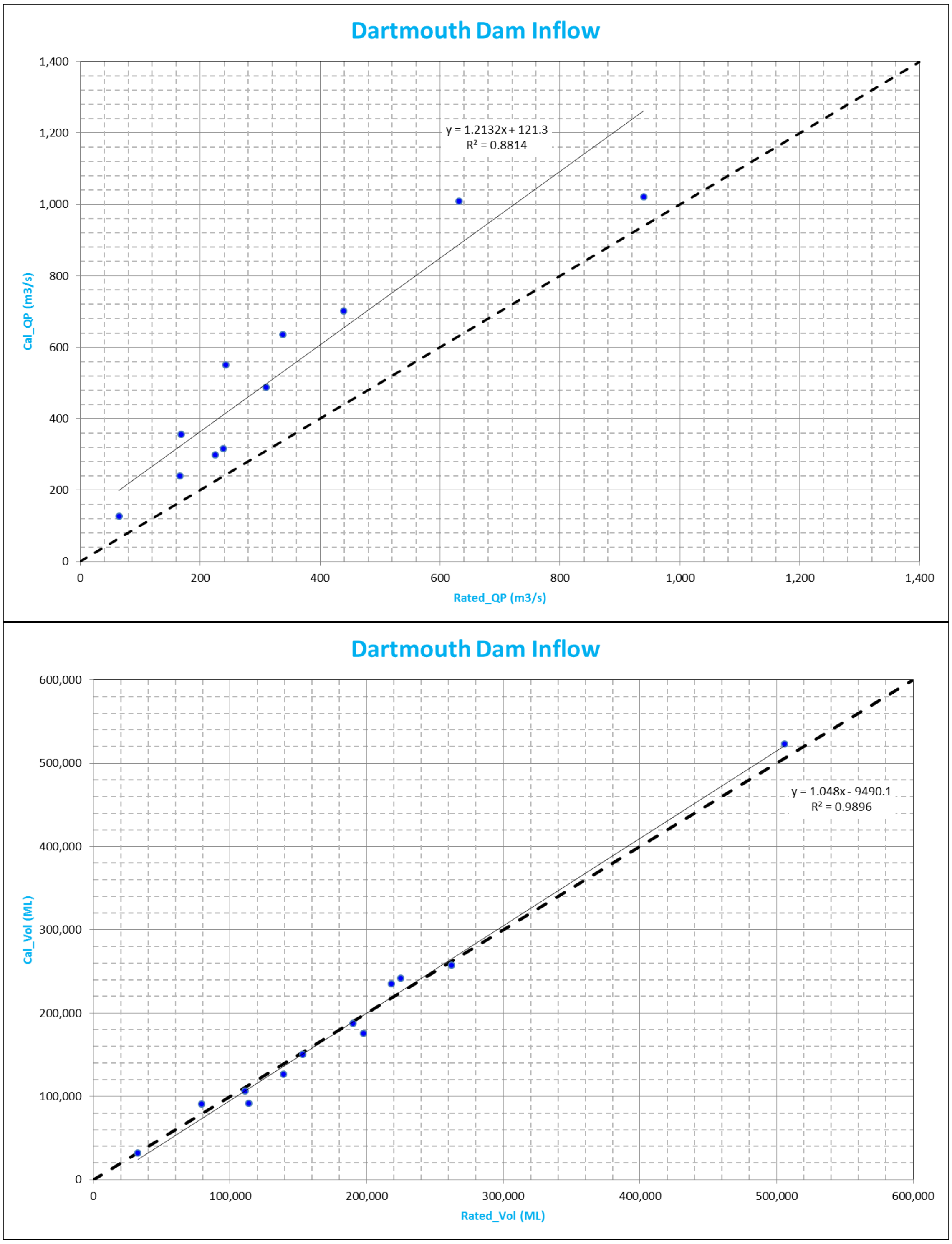

Figure 7-17~~-1~~: Model Performance at Dartmouth Dam

Figure 7-1~~Figure 7-1~~ shows a comparison of the rated and modelled peak inflow and inflow volumes to Dartmouth in each event investigated with the exception of 201203 which has been omitted due to poor rainfall definition. Overall, the model tends to overestimate the peak inflow but is considered to be well calibrated with respect to the inflow volume to Dartmouth Dam.

Examination of the calibration plots in Appendix D shows that the mitta model is reasonably well calibrated at most gauging stations with the exception of Tallandoon where the modelled water level is generally higher than the recorded water level.

As shown in Figure 7-2, this difference was highlighted by plotting the rated flows at Dartmouth Dam, Colemans and Tallandoon in three events when Dartmouth Dam spilled.

While it is appreciated that the increase in catchment area between Dartmouth Dam, Colemans and Tallandoon may account for the apparent increase, there should be reasonably consistent flows in the recessions of each of the three events. The difference cannot be readily explained but needs further investigation.

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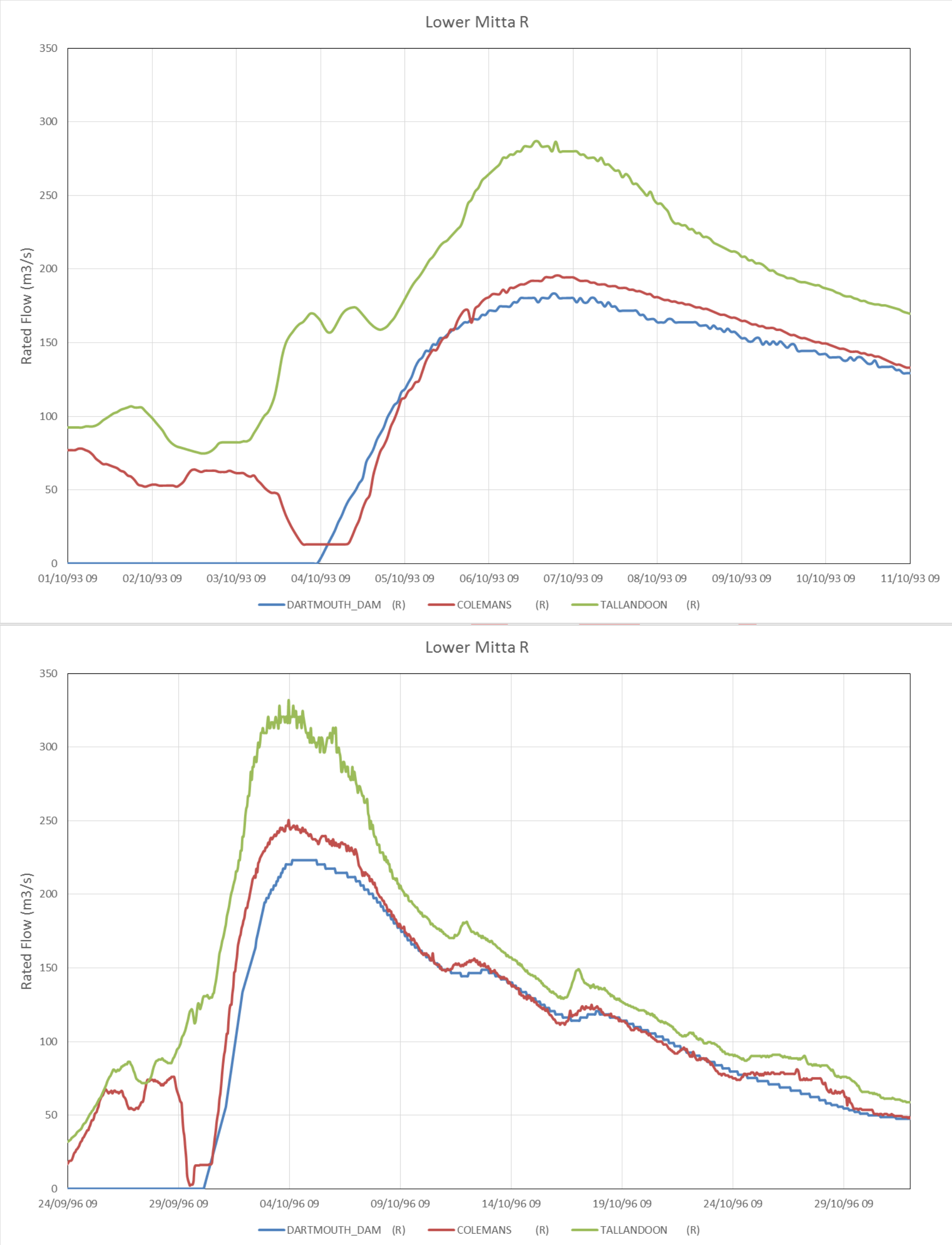


Figure 7-2~~7-2~~: Flow Inconsistency Lower Mitta Mitta River

Analysis of the rated flow volume at Tallandoon compared with the rated Hume Dam inflow shows that, in the 16 events investigated from 1974 to 2012, the Mitta Mitta River contributes between 6 and 27% of the inflow volume to Hume Dam with an average of 14%. Thus the inconsistency in rated flows between Dartmouth Dam, Colemans and Tallandoon will not be significant in terms of Hume Dam inflow.

The parameters recommended for use in the real time model are shown in Table 7-3 ~~Table 7-3~~.

Table 7-5: Recommended Model Parameters Mitta Mitta River

Percentile	IL (mm)	CL (mm/hr)	Alpha	Beta	m
5th	0	1.4	0.20	3.0	0.8
95th	68	7.3	0.43	5.3	0.8
Recommended	**To suit antecedent conditions**	**3.3**	**0.27**	**4.0**	**0.8**

7.4 Upper Model Calibration Results

Sixteen events were used to calibrate and validate the Upper Murray to Hume Dam catchment model and a summary of the results is presented in this section.

Weighting of each event used to derive the model parameters is summarised in Table 7-6~~Table 7-6~~.

Table 7-6: Calibration Parameters Upper Murray River Model

Event	Calibration parameters					Calibration performance ranking				User Ranking
	IL	CL	Alpha	Beta	m	PR	VR	NS	Weight	
197401	35	4.1	0.30	3.0	0.8	5	5	0	**6%**	1
197410	10	1.8	0.25	5.0	0.8	2	5	3	**7%**	1
197510	15	1.3	0.30	5.0	0.8	5	5	4	**8%**	1
198107	10	1.6	0.35	4.0	0.8	2	5	3	**6%**	1
198308	10	1.9	0.30	3.0	0.8	2	5	0	**5%**	1
199210	5	3.8	0.25	3.0	0.8	2	5	3	**6%**	1
199310	0	2.8	0.30	5.0	0.8	4	5	3	**7%**	1
199607	10	1.1	0.35	5.0	0.8	2	5	2	**5%**	1
199610	10	4.0	0.35	5.0	0.8	5	5	2	**7%**	1
199809	0	3.0	0.30	5.0	0.8	0	5	2	**5%**	1
201009	10	2.4	0.35	5.0	0.8	2	5	2	**7%**	1
201010	20	4.9	0.25	3.0	0.8	0	5	3	**7%**	1
201012	30	8.5	0.30	3.0	0.8	4	5	3	**7%**	1
201102	60	7.9	0.30	3.0	0.8	0	5	2	**5%**	1
201109	15	5.4	0.25	3.0	0.8	2	5	2	**6%**	1
201203	25	6.0	0.35	3.0	0.8	4	5	2	**7%**	1

The calibration parameters were reasonably evenly weighted between all sixteen events.

The calibration of the upper model to the rated flow and recorded heights at selected locations above Hume Dam and at Hume Dam itself is shown in calibration plots in Appendix D.

Table 7-7: Calibration Performance Upper Murray River Model at Jingellic

Event	Flow			Volume			Peak Height			Nash Sutcliffe
	Cal	Rated	PR	Cal	Rated	VR	Cal	Rec	δH	
	m³/s	m³/s		ML	ML		m AHD	m AHD	m	
197401	717	523	1.37	429,890	368,935	1.17	5.24	4.46	-0.78	0.50
197410	1,155	1,440	0.80	1,131,796	1,306,677	0.87	6.73	7.51	0.78	0.82
197510	1,338	1,352	0.99	982,161	984,031	1.00	7.29	7.32	0.03	0.89
198107	1,025	853	1.20	624,108	619,218	1.01	6.33	5.75	-0.58	0.68
198308	1,050	814	1.29	298,893	269,823	1.11	6.41	5.61	-0.80	0.51
199210	902	1,149	0.79	377,780	444,406	0.85	5.92	6.71	0.79	0.73

Event	Flow			Volume			Peak Height			Nash Sutcliffe
	Cal	Rated	PR	Cal	Rated	VR	Cal	Rec	δH	
	m^3/s	m^3/s		ML	ML		m AHD	m AHD	m	
199310	732	1,060	0.69	367,201	489,400	0.75	5.30	6.44	1.14	0.68
199607	605	673	0.90	1,076,965	1,058,817	1.02	4.81	5.07	0.26	0.94
199610	656	763	0.86	1,196,363	1,302,431	0.92	5.01	5.42	0.41	0.76
199809	942	869	1.08	341,024	296,449	1.15	6.06	5.81	-0.25	0.87
201009	1,416	1,273	1.11	947,160	797,694	1.19	7.46	7.10	-0.36	0.86
201010	1,549	1,495	1.04	627,284	685,908	0.91	7.75	7.63	-0.12	0.90
201012	626	847	0.74	347,005	386,685	0.90	4.89	5.73	0.84	0.81
201102	489	479	1.02	526,574	646,066	0.82	4.31	4.27	-0.04	0.49
201109	529	554	0.96	178,115	208,271	0.86	4.49	4.59	0.10	0.77
201203	1,006	1,624	0.62	440,848	554,022	0.80	6.27	7.91	1.64	0.74

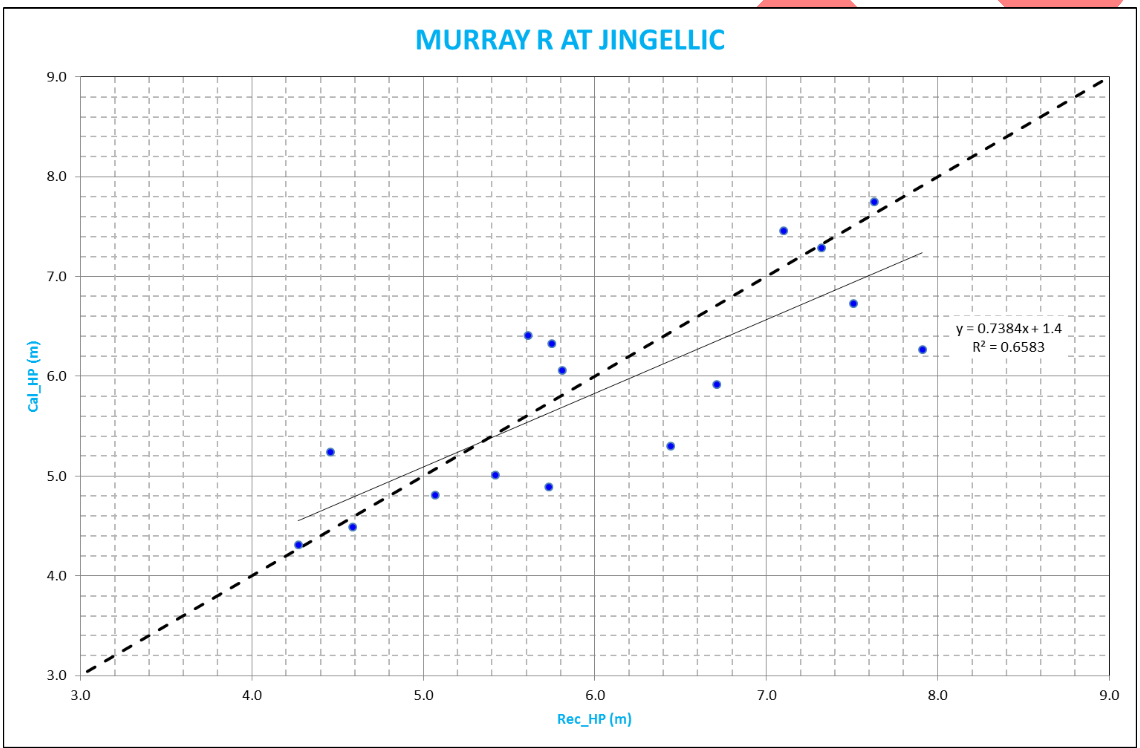
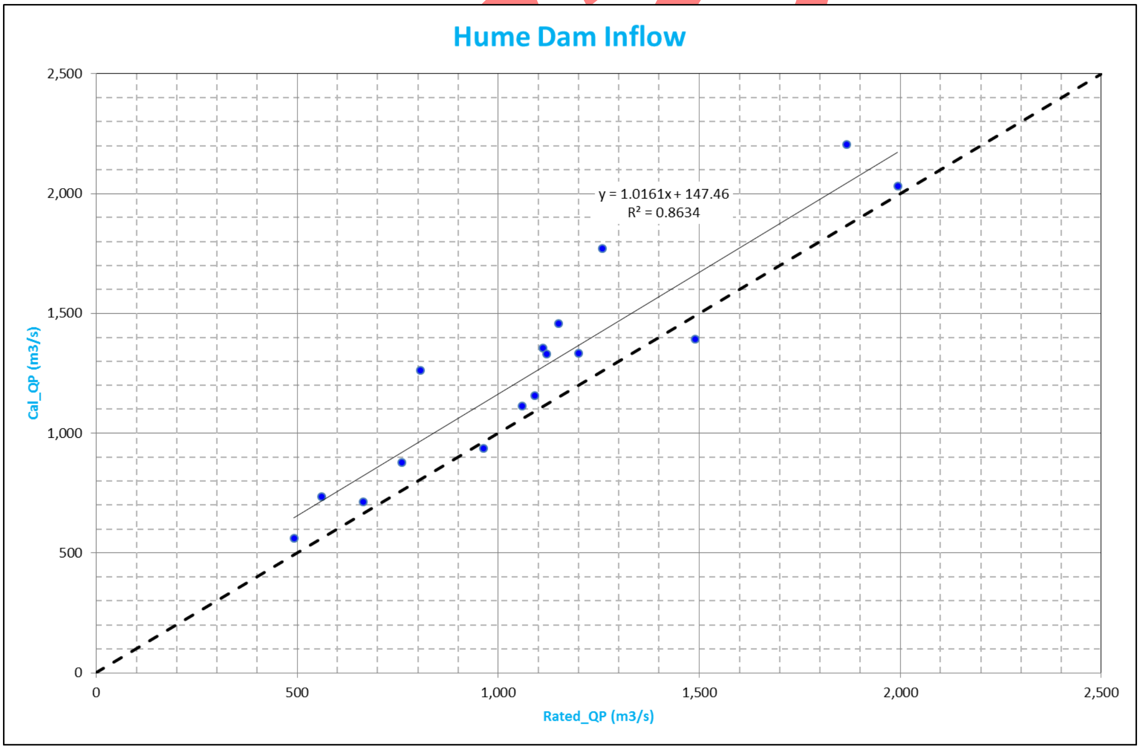


Figure 7-3~~7-3~~: Model Performance at Jingellic

Analysis of the model performance at Jingellic in Figure 7-3 shows on average there is little bias in the model as the trend line is close to the line of best fit. The average error in the replication of the peak height is less than 0.2m but may be as much as plus/minus 1.5m in any particular event.

Table 7-8: Calibration Performance Upper Murray River Model at Hume Dam Inflow

Event	Flow Cal m^3/s	Flow Rated m^3/s	PR	Volume Cal ML	Volume Rated ML	VR	Nash Sutcliffe
197401	1,113	1,060	1.05	851,320	774,736	1.10	0.35
197410	2,205	1,866	1.18	2,139,248	2,216,463	0.97	0.84
197510	2,030	1,994	1.02	1,775,667	1,735,933	1.02	0.91
198107	1,354	1,111	1.22	895,149	884,110	1.01	0.80
198308	1,331	1,121	1.19	447,664	465,349	0.96	0.38
199210	1,335	1,199	1.11	723,775	679,524	1.07	0.86
199310	1,158	1,091	1.06	788,152	799,314	0.99	0.82
199607	879	760	1.16	1,426,793	1,389,772	1.03	0.72
199610	936	964	0.97	2,029,825	1,912,541	1.06	0.76
199809	1,261	806	1.56	393,484	392,787	1.00	0.59
201009	1,458	1,149	1.27	977,370	928,445	1.05	0.80
201010	1,770	1,259	1.41	793,876	778,398	1.02	0.87
201012	713	664	1.07	424,344	411,928	1.03	0.86
201102	735	561	1.31	814,809	798,085	1.02	0.67
201109	561	492	1.14	202,403	223,524	0.91	0.79
201203	1,392	1,489	0.93	653,872	726,026	0.90	0.74



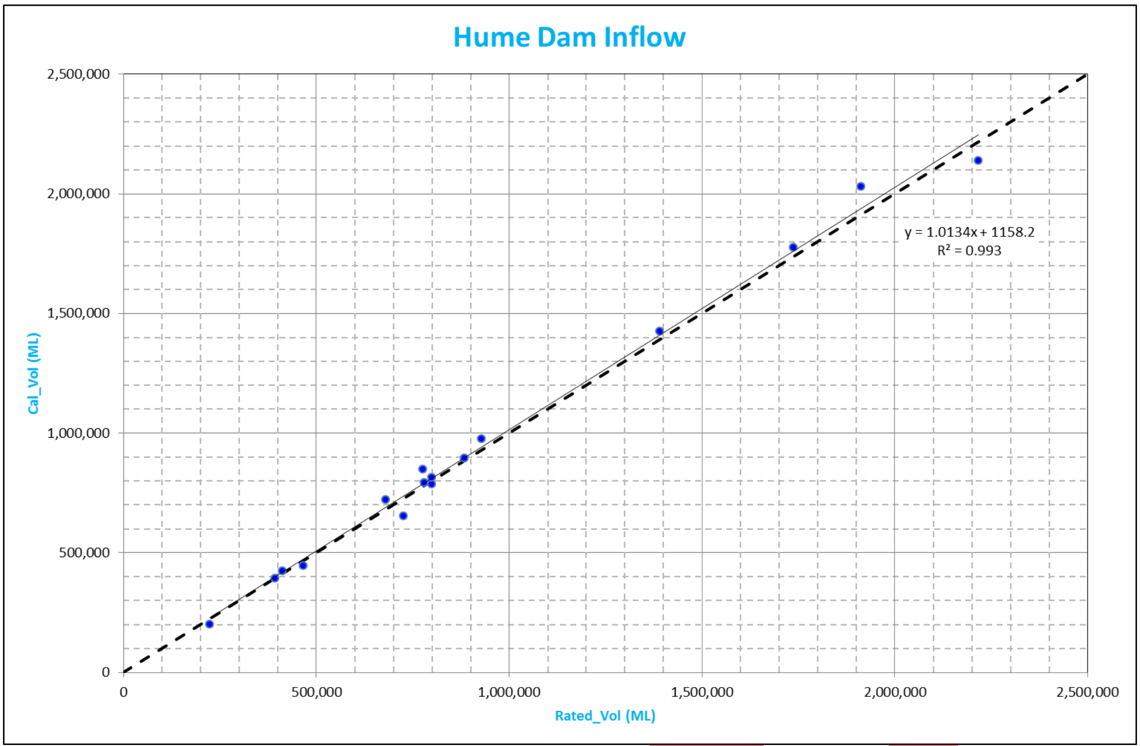
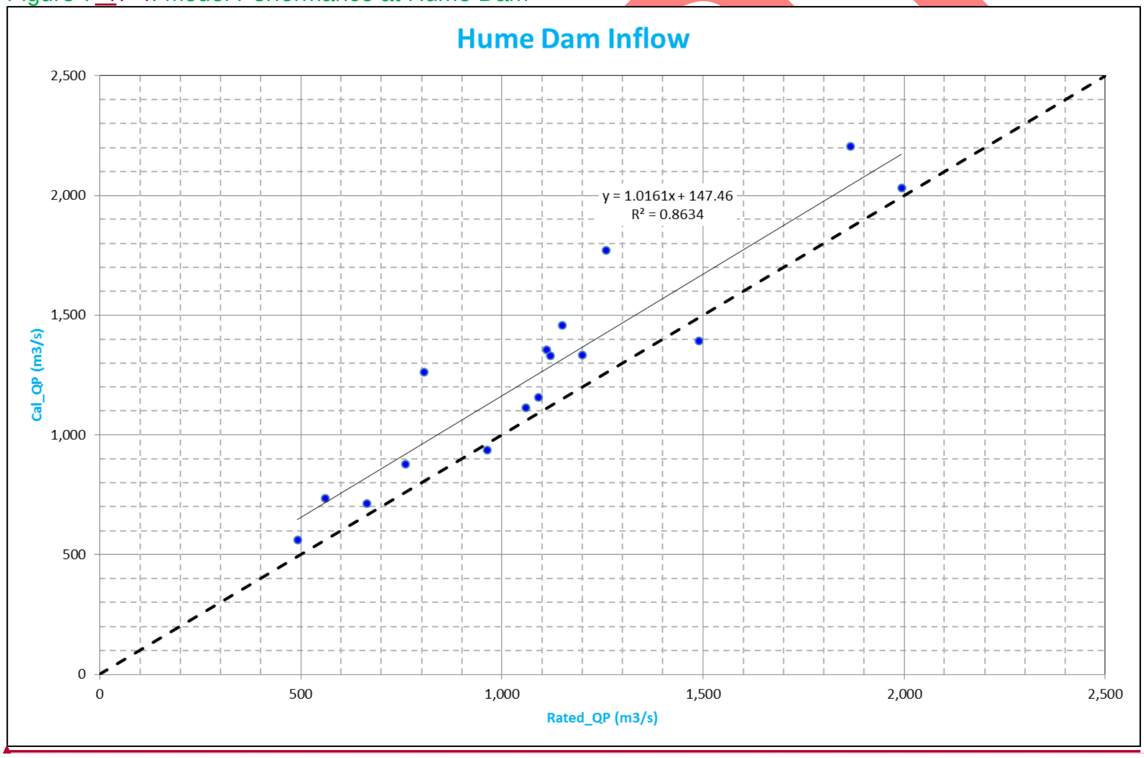


Figure 7-~~47~~-4: Model Performance at Hume Dam



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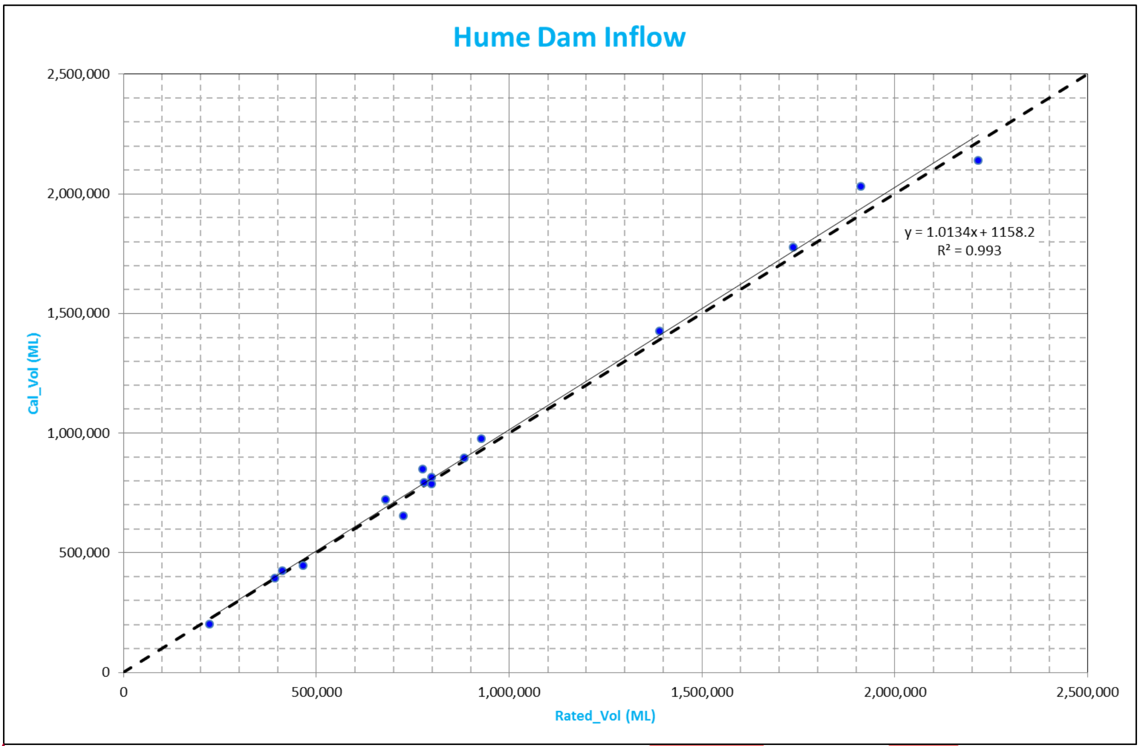
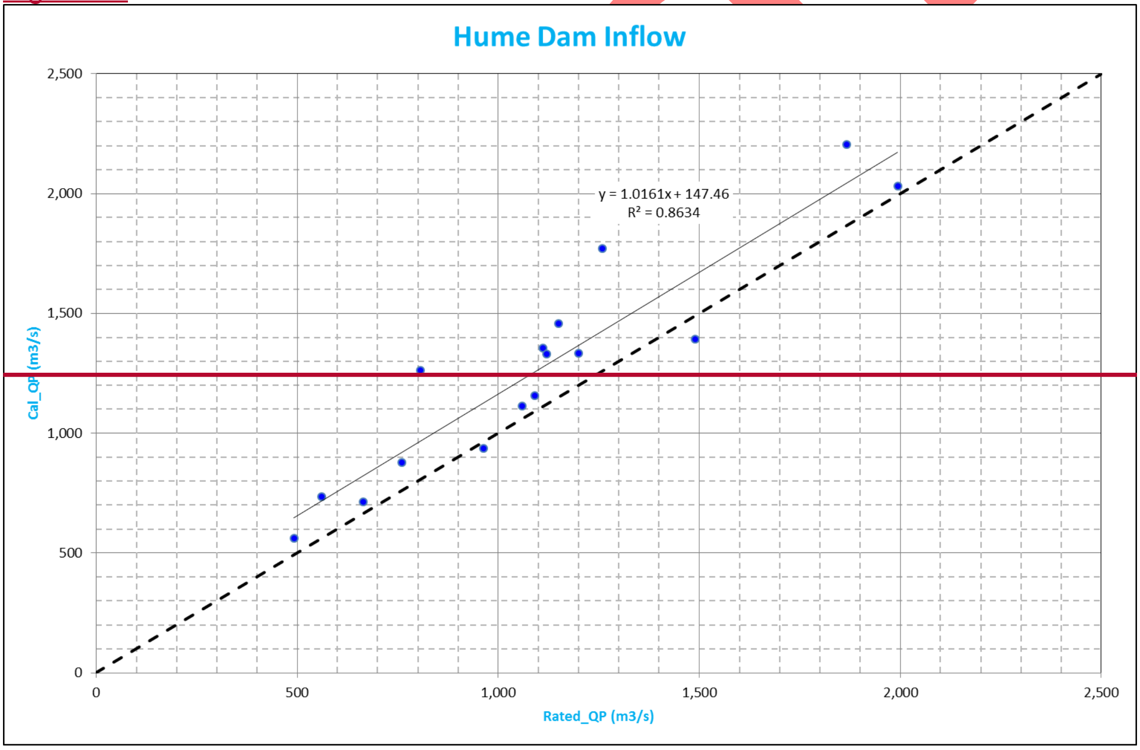


Figure 7-4



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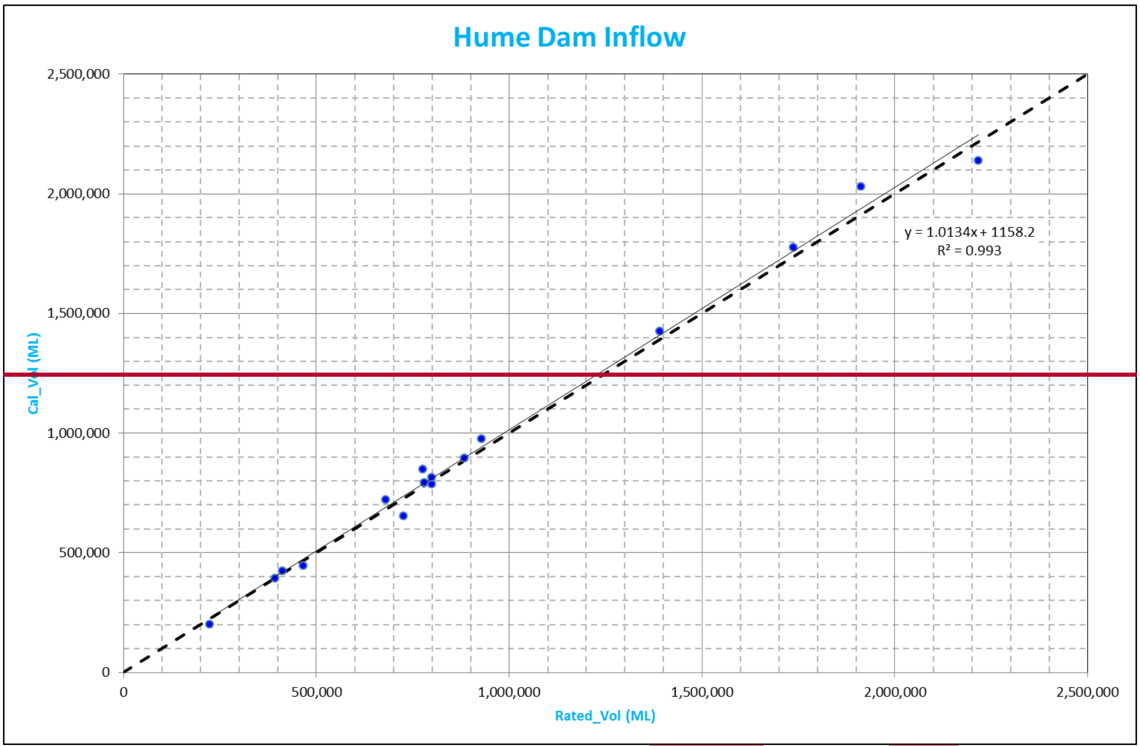

~~Figure~~ 7-4 shows a comparison of the rated and modelled peak inflows and inflow volumes to Hume Dam in each event investigated. In general, the model overestimates the peak inflow but replicates the inflows volumes reasonably well with little evidence of any bias. Plots of the modelled and recorded Hume Dam water level in Appendix D shows close correlation in most events.

Examination of the calibration plots in Appendix D shows that the upper model is reasonably well calibrated at most of the key gauging stations.

The parameters recommended for use in the real time upper model are shown in Table 7-9.

Table 7-9: Recommended Model Parameters Upper Murray River

Percentile	IL (mm)	CL (mm/hr)	Alpha	Beta	m
5th	0	1.3	0.25	3.0	0.8
95th	41	8.1	0.35	5.0	0.8
Recommended	**To suit antecedent conditions**	**3.8**	**0.30**	**4.0**	**0.8**

7.5 Below Model Calibration Results

Sixteen events were used to calibrate and validate the Upper Murray below Hume Dam to Albury catchment model and a summary of the results is presented in this section.

It should be noted that the model matches the rated flow at Heywoods and routes this flow to Albury including modelled inflows from the Kiewa River at the appropriate location.

Weighting of each event used to derive the model parameters is summarised in Table 7-10~~Table 7-10~~.

Table 7-10: Calibration Parameters Below Murray River to Albury Model

Event	Calibration parameters					Calibration performance ranking				User Ranking
	IL	CL	Alpha	Beta	m	PR	VR	NS	Weight	
197401	25	6.0	0.30	3.0	0.8	5	5	3	**7%**	1
197410	30	1.5	0.30	5.0	0.8	4	4	3	**7%**	1
197510	40	2.0	0.30	5.0	0.8	5	5	5	**8%**	1
198107	0	2.8	0.30	4.0	0.8	5	2	2	**4%**	1
198308	10	2.0	0.50	3.0	0.8	5	5	3	**6%**	1
199210	30	3.5	0.50	3.0	0.8	5	5	5	**8%**	1
199310	10	4.0	0.50	3.0	0.8	4	5	4	**7%**	1
199607	25	1.5	0.30	5.0	0.8	4	4	3	**5%**	1
199610	0	2.0	0.30	5.0	0.8	4	5	5	**8%**	1
199809	15	3.5	0.30	4.0	0.8	4	4	4	**6%**	1
201009	15	2.5	0.40	5.0	0.8	2	5	3	**6%**	1
201010	30	6.0	0.30	3.0	0.8	2	5	2	**5%**	1
201012	40	2.0	0.35	5.0	0.8	2	5	2	**6%**	1
201102	80	8.0	0.30	5.0	0.8	5	4	2	**6%**	1
201109	5	1.2	0.40	5.0	0.8	5	5	3	**7%**	1
201203	55	4.0	0.35	5.0	0.8	2	5	3	**6%**	1

The calibration parameters were reasonably evenly weighted between all sixteen events.

The calibration of the below model to the rated flow and recorded height at the Murray River at Doctors Point and Albury is shown in calibration plots in Appendix D.

Table 7-11: Calibration Performance Below Murray River Model at Doctors Point

Event	Flow			Volume			Peak Height			Nash Sutcliffe
	Cal	Rated	PR	Cal	Rated	VR	Cal	Rec	δH	
	m^3/s	m^3/s		ML	ML		m AHD	m AHD	m	
197401	1,045	1,013	1.03	710,681	672,962	1.06	6.33	6.30	-0.03	0.89
197410	1,963	1,800	1.09	2,238,106	2,030,519	1.10	7.02	6.93	-0.09	0.87
197510	2,087	2,043	1.02	1,800,482	1,668,089	1.08	7.07	7.05	-0.02	0.97
198107	330	319	1.04	176,418	224,109	0.79	4.18	4.10	-0.08	0.56

Event	Flow			Volume			Peak Height			Nash Sutcliffe
	Cal	Rated	PR	Cal	Rated	VR	Cal	Rec	δH	
	m^3/s	m^3/s		ML	ML		m AHD	m AHD	m	
198308	378	372	1.02	112,481	116,198	0.97	4.48	4.44	-0.04	0.89
199210	1,310	1,332	0.98	732,244	736,132	0.99	6.59	6.61	0.02	0.97
199310	835	767	1.09	730,217	716,981	1.02	6.10	6.01	-0.09	0.93
199607	349	387	0.90	721,700	821,036	0.88	4.29	4.53	0.24	0.88
199610	1,089	1,150	0.95	2,688,315	2,826,797	0.95	6.38	6.44	0.06	0.97
199809	479	526	0.91	120,122	139,925	0.86	5.10	5.36	0.26	0.94
201009	292	337	0.86	185,966	181,346	1.03	3.91	4.22	0.31	0.89
201010	431	372	1.16	349,470	361,311	0.97	4.80	4.44	-0.36	0.74
201012	839	715	1.17	522,433	484,541	1.08	6.10	5.92	-0.18	0.79
201102	341	327	1.05	588,258	659,600	0.89	4.24	4.15	-0.09	0.58
201109	323	316	1.02	205,581	214,284	0.96	4.13	4.08	-0.05	0.86
201203	223	249	0.90	124,303	120,911	1.03	3.40	3.59	0.19	0.83

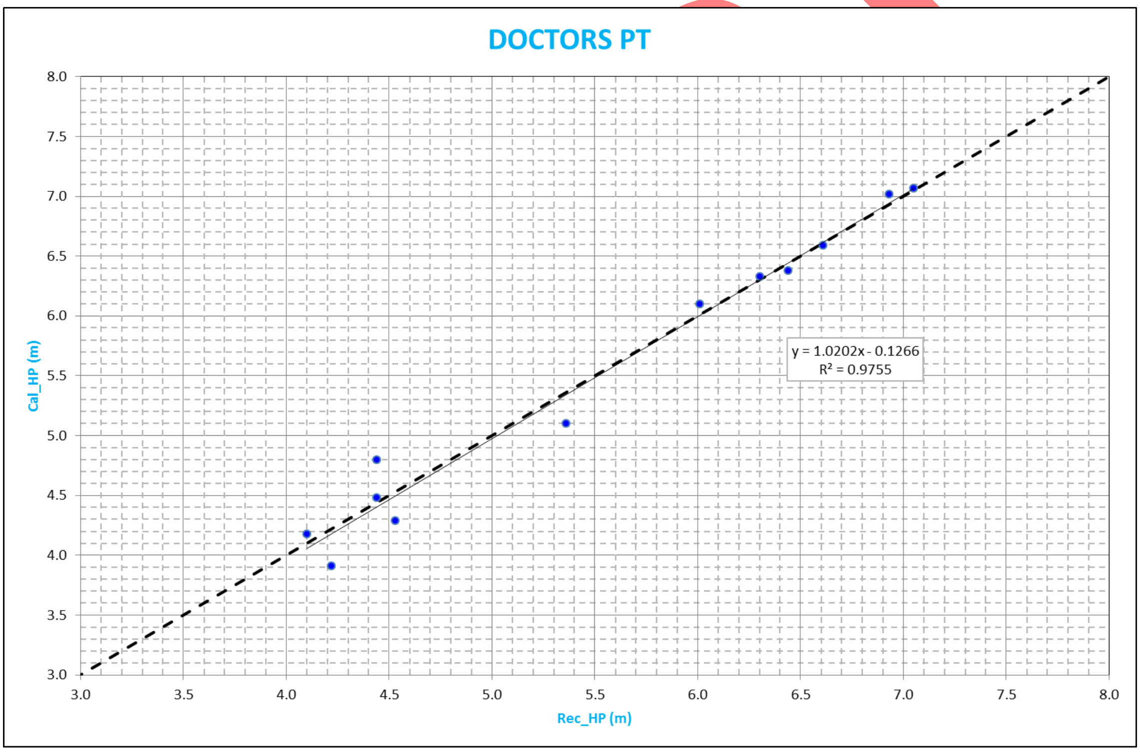

Figure 7-5~~7-5~~: Model Performance at Doctors Point

Analysis of the model performance at Doctors Point in **Error! Reference source not found.**Figure 7-5 shows on average there is little bias in the model as the trend line is close to the line of best fit. The average error in the replication of the peak height is less than 0.1m but may be as much as plus/minus 0.5m in any particular event.

This is especially true in events where the flow in the river below Hume Dam is dominated by runoff from the Kiewa River. Such events include 198308, 199809 and 201009. Each of these events is reasonably well calibrated at Doctors point suggesting that the flood runoff from the Kiewa River is modelled appropriately.

Examination of the calibration plots in Appendix D shows that the below model is reasonably well calibrated at the key gauging stations.

The parameters recommended for use in the real time upper model are shown in Table 7-12.

Table 7-12: Recommended Model Parameters Below Murray River

Percentile	IL (mm)	CL (mm/hr)	Alpha	Beta	m
5th	0	1.4	0.30	3.0	0.8
95th	54	6.5	0.50	5.0	0.8
Recommended	**To suit antecedent conditions**	**3.2**	**0.36**	**4.3**	**0.8**

8 Real Time Considerations

8.1 Estimation of Catchment Rainfall

The study showed that the model results are very sensitive to the estimation of gross and net or excess rainfall.

With relatively few real time stations available in real time, particular attention should be paid to the veracity of the rainfall data used as input to the models. Any doubtful rainfall information should be omitted from calculations.

With over 25 stations in the model there appears to be an adequate number of water level stations to support real time operations. However, with only about ten real time rainfall stations, many co-located at water level gauges located at the bottom of valleys, there could be scope for increasing the number of rain gauges to improve spatial coverage.

During real time operations, some sensitivity of model results to initial and continuing loss should be undertaken. It is suggested that initial loss be estimated to the nearest 5mm and that continuing loss rate be estimated to the nearest 0.1mm/hr.

8.2 Dam Starting Levels and Initial Baseflow

The starting level in Dartmouth and Hume Dams can have a significant impact on the flood behavior in Murray River downstream of Hume Dam.

To guide modelers in real time, an analysis of the adopted initial inflow and the initial height/flow at an upstream gauging station was undertaken.

As shown in Figure 8-1Figure 1-1, ~~In~~ in the Mitta Mitta River model, the initial baseflow into Dartmouth Dam can be assumed to be 135% of the flow at Hinnomunjie at the event start/date time to the nearest 5 m^3/s.

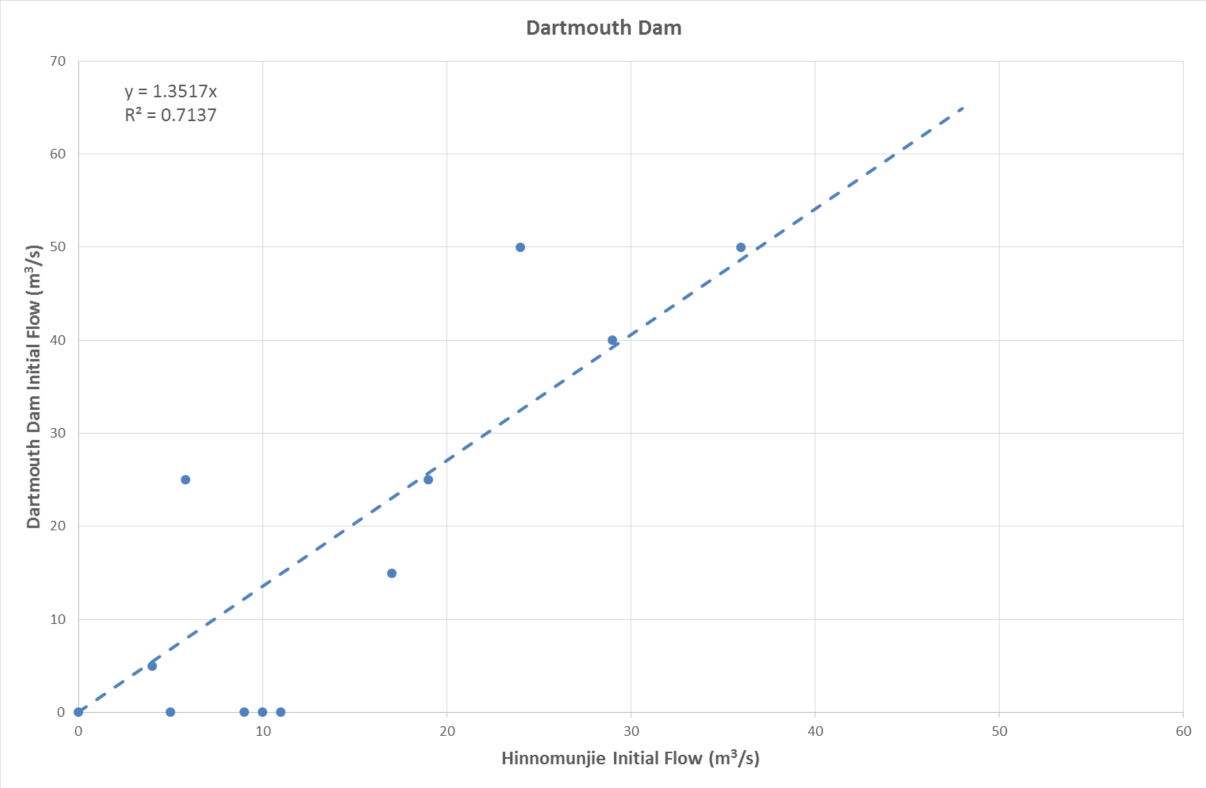

Figure 8-1: Initial Dartmouth Baseflow

~~the average flow at Colemans over a couple of days prior to the onset of the flood producing rainfall.~~

Similarly, as shown in Figure 8-2, in the Upper Murray River model, the initial baseflow into Hume Dam can be assumed to be 120% of the flow at Jingellic (Murray R) at the event start/date time to the nearest 50 m^3/s.
~~the average flow at Heywoods over a couple of days prior to the onset of the flood producing rainfall~~.

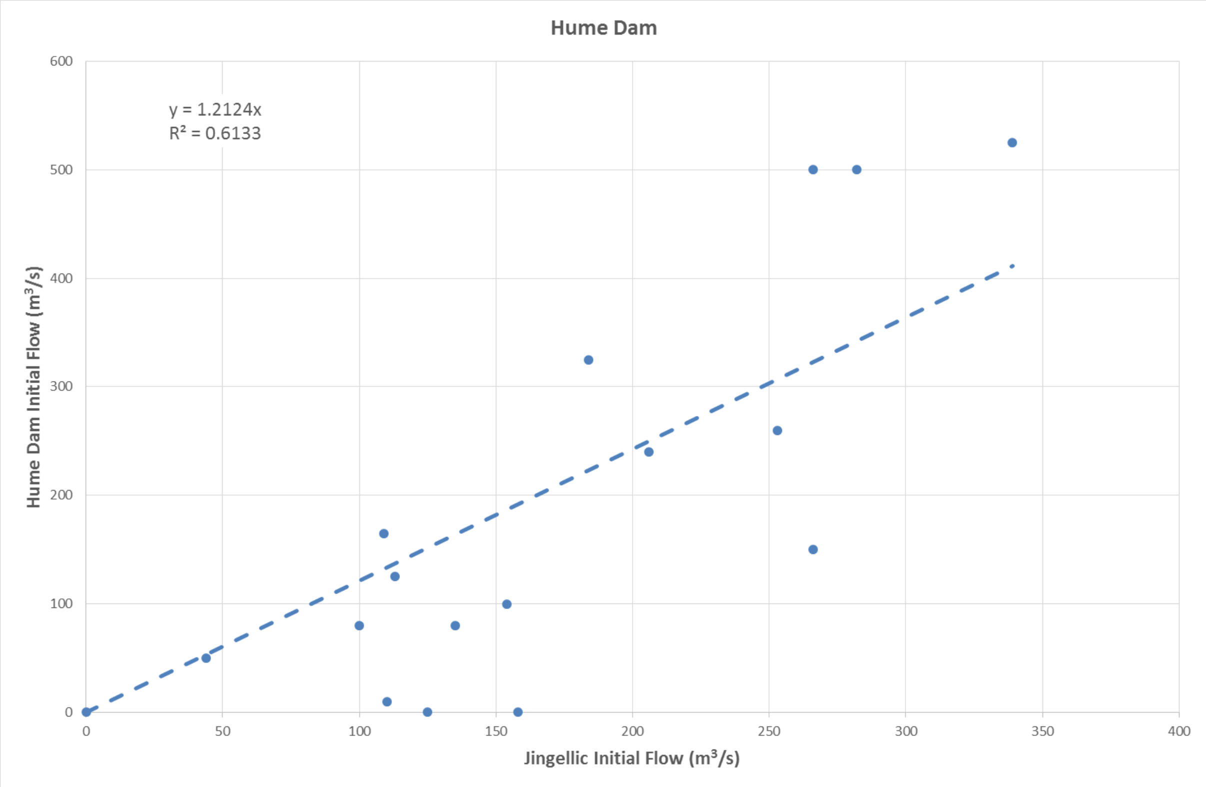

Figure 8-2: Initial Hume Dam Baseflow

8.3 Antecedent Conditions

Catchment state in the lead up to the onset of flood producing rainfall can give an indication of the initial that might be adopted.

Rainfall deciles for South East Australia in the month preceding each flood event investigated was determined from the Bureau of Meteorology Climate website with results shown in Table 8-1.

Table 8-1: Antecedent Rainfall

Event	Initial Loss (mm)		Rainfall in Preceding Month
	Mitta Mitta	Upper Murray	
197401		35	Above Average to Very Much Above Average
197410		10	Above Average
197510		15	Above Average to Very Much Above Average
198107	15	10	Above Average to Highest on Record
198308	10	10	Average to Above Average
199210	0	5	Very Much Above Average to Highest on Record
199310	35	0	Above Average to Very Much Above Average
199607	0	10	Average
199610	0	10	Above Average to Very Much Above Average
199809	10	0	Average
201009	25	10	Above Average to Very Much Above Average
201010	40	20	Average to Above Average
201012	35	30	Above Average to Very Much Above Average
201102	90	60	Average to Above Average
201109	5	15	Below Average to Average
201203	10	25	Above Average to Very Much Above Average

There does not appear to be any strong correlation in the above data between rainfall in the preceding month and initial loss. However, with one exception, initial losses tend to be less than 50mm and in many occasions equal to zero. Intuitively, it is reasonable to assume that initial loss will be closer to zero if the catchments are wet.

Rainfall decile for Queensland for the preceding month can be found on the Bureau of Meteorology web site at http://www.bom.gov.au/jsp/awap/rain/index.jsp.

Further work should be undertaken to investigate if a relationship can be established between the BoM's AWRA-L root zone soil moisture model depths and event initial loss. Some work has already been undertaken for other catchments in Tasmania and south-east Queensland and results to date are reasonably promising.

Based on the work carried out to date, at the start of an event, initial loss estimated from the information above should be adopted. As the event develops, initial losses should be adjusted to best match the recorded water level rises at primary stations and continuing losses adjusted to match rated flows.

9 Conclusions and Recommendations

An URBS model of the Upper Murray River to Albury has been developed and calibrated as an event model to the best sets of rainfall and water level data available. Sixteen events from 1974 up to March 2012 ranging from small to large events were investigated.

Three linked models were developed:

- Mitta mitta River to Tallandoon,
- Upper Murray River to Hume Dam, and,
- Murray River below Hume Dam to Albury

Rating reliability was assessed at several sites and the most reliable gauging stations selected on which to base calibration.

Models results were found to be very sensitive to the estimation of gross and net rainfall. There would appear to be an adequate number of water level stations in the model area but an insufficient number of real time rainfall stations, especially as many of the real time rain gauges are co-located at water level gauges located at the bottom of valleys.

Specific model parameters are recommended for each of the three models, including:

- Initial loss
- Continuing loss rate
- Alpha, the channel routing parameter
- Beta, the sub-catchment routing parameter
- Sub-catchment non-linearity exponent

Initial losses are highly variable depending on rainfall and climate in periods leading up to the flood events. An investigation into whether the BoM's AWRA-L root zone soil moisture model would assist in determining event initial loss should be considered. Continuing loss may be generalised to the typical continuing loss rate, however the continuing loss can also vary and is often event specific.

The models were well calibrated with respect to inflow volume and water level at Dartmouth and Hume Dams and at most of the primary calibration locations. Calibration at some gauging stations with relatively small catchment areas suffered from poor definition of spatial and temporal rainfall.

The models are considered suitable for use as a flood forecasting model but should be applied with caution provided:

- Appropriate catchment conditions at start of event (catchment state and initial baseflow and level in Dartmouth and Hume Dams) are applied, and
- Sufficient rainfall and water level data is available in real time.

After any significant event, the model calibration should be checked and reviewed.

10 References

Carroll, D. 2012. "*URBS Unified River Basin Simulator. A Rainfall Runoff Routing Model for Flood Forecasting and Design*" Version 5.00

GHD. 2003. "Albury City to Greater Murray, Murray River Flood Study", March 2012

Institution of Engineers Australia 2003. "*Australian Rainfall and Runoff, A Guide to Flood Estimation, Volume 1"*, 2003.

MDBA. 2015. "Flood Operations Manual: Dartmouth Dam Final Draft", June 2015

MDBA. 2015. "Flood Operations Manual: Hume Dam [Draft]", September 2015

Ryan. C. 2011 "*CatchmentSIM: A Terrain Processing and Hydrologic Analysis Model"*, Version 3.04, Build 2, 2011.

StateWater, SKM and SMEC. 2009. "*Hume Dam, Assessment of Hydrologic Risk, Phase 3B Development of Catchment-Wide Model*", Final Report, November 2009

Appendix A - Rainfall Stations

Appendix B - Rainfall Maps

Appendix C - URBS Vectors

Appendix D - Calibration Plots